Cavity-waveguide interplay in optical resonators and its role in optimal single-photon sources

Interfacing solid-state emitters with photonic structures is a key strategy for developing highly efficient photonic quantum technologies. Such structures are often organized into two distinct categories: nanocavities and waveguides. However, any realistic nanocavity structure simultaneously has characteristics of both a cavity and waveguide, which is particularly pronounced when the cavity is constructed using low-reflectivity mirrors in a waveguide structure with good transverse light confinement. In this regime, standard cavity quantum optics theory breaks down, as the waveguide character of the underlying dielectric is only weakly suppressed by the cavity mirrors. By consistently treating the photonic density of states of the structure, we provide a microscopic description of an emitter including the effects of phonon scattering over the full transition range from waveguide to cavity. This generalized theory lets us identify an optimal regime of operation for single-photon sources in optical nanostructures, where cavity and waveguide effects are concurrently exploited.
All-optical mapping of the position of single quantum dots embedded in a nanowire antenna

Nanowire antennas embedding single quantum dots (QDs) have recently emerged as a versatile solid-state platform for quantum optics. Within the nanowire section, the emitter position simultaneously determines the strength of the light-matter interaction, as well as the coupling to potential decoherence channels. Therefore, to quantitatively understand device performance and guide future optimization, it is highly desirable to map the emitter position with an accuracy much smaller than the waveguide diameter, on the order of a few hundreds of nanometers. We introduce here a non-destructive, all-optical mapping technique which exploits the QD emission into two guided modes with different transverse profiles. These two modes are fed by the same emitter, and thus interfere. The resulting intensity pattern, which is highly sensitive to the emitter position, is resolved in the far-field using Fourier microscopy. We demonstrate this technique on a standard micro-photoluminescence setup and map the position of individual QDs in a nanowire antenna with a spatial resolution of +/- 10 nm. This work opens important perspectives for the future development of light-matter interfaces based on nanowire antennas. Beyond single-QD devices, it will also provide a valuable tool for the investigation of collective effects which...
imply several emitters coupled to an optical waveguide.
Benchmarking five numerical simulation techniques for computing resonance wavelengths and quality factors in photonic crystal membrane line defect cavities

We present numerical studies of two photonic crystal membrane microcavities, a short line-defect cavity with relatively low quality (Q) factor and a longer cavity with high Q. We use five state-of-the-art numerical simulation techniques to compute the cavity Q factor and the resonance wavelength (\( \lambda \)) for the fundamental cavity mode in both structures. For each method, the relevant computational parameters are systematically varied to estimate the computational uncertainty. We show that some methods are more suitable than others for treating these challenging geometries.

General information

State: Published
Organisations: Department of Photonics Engineering, Nanophotonics Theory and Signal Processing, Nanophotonic Devices, Centre of Excellence for Silicon Photonics for Optical Communications, Department of Electrical Engineering, Electromagnetic Systems, Department of Mechanical Engineering, Solid Mechanics, Plasmonics and Metamaterials, Zuse Institute Berlin, St. Petersburg National Research University of Information Technologies, Mechanics and Optics (ITMO)
Pages: 11366-11392
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Peer-reviewed: Yes
Benchmarking state-of-the-art numerical simulation techniques for analyzing large photonic crystal membrane line defect cavities

In this work, we perform numerical studies of two photonic crystal membrane microcavities, a short line-defect L5 cavity with relatively low quality (Q) factor and a longer L9 cavity with high Q. We compute the cavity Q factor and the resonance wavelength $\lambda$ of the fundamental M1 mode in the two structures using five state-of-the-art computational methods. We study the convergence and the associated numerical uncertainty of Q and $\lambda$ with respect to the relevant computational parameters for each method. Convergence is not obtained for all the methods, indicating that some are more suitable than others for analyzing photonic crystal line defect cavities.

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State: Accepted/In press
Organisations: Department of Photonics Engineering, Nanophotonics Theory and Signal Processing, Nanophotonic Devices, Centre of Excellence for Silicon Photonics for Optical Communications, Department of Electrical Engineering, Electromagnetic Systems, Department of Mechanical Engineering, Solid Mechanics, Plasmonics and Metamaterials, Zuse Institute Berlin, St. Petersburg National Research University of Information Technologies, Mechanics and Optics (ITMO)
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Fundamental cavity-waveguide interplay in cavity QED

Interfacing solid-state emitters with photonic structures is a key strategy for developing highly efficient photonic quantum technologies [1]. Such structures are often organised into two distinct categories: nanocavities and waveguides. However, any realistic nanocavity structure simultaneously has characteristics of both a cavity and waveguide, which is particularly pronounced when the cavity is constructed using low-reflectivity mirrors in a waveguide structure with good transverse light confinement. In this regime, standard cavity quantum optics theory breaks down, as the waveguide character of the

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Benchmarking state-of-the-art optical simulation methods for analyzing large nanophotonic structures

Five computational methods are benchmarked by computing quality factors and resonance wavelengths inphotonic crystal membrane L5 and L9 line defect cavities. Careful convergence studies reveal that some methods are more suitable than others for analyzing these cavities.

General information
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Fundamental cavity-waveguide interplay in cavity QED

Interfacing solid-state emitters with photonic structures is a key strategy for developing highly efficient photonic quantum technologies [1]. Such structures are often organised into two distinct categories: nanocavities and waveguides. However, any realistic nanocavity structure simultaneously has characteristics of both a cavity and waveguide, which is particularly pronounced when the cavity is constructed using low-reflectivity mirrors in a waveguide structure with good transverse light confinement. In this regime, standard cavity quantum optics theory breaks down, as the waveguide character of the
underlying dielectric is only weakly suppressed by the cavity mirrors. In this work [2], we present a quantum optical model that captures the transition between a high-Q cavity and a waveguide, allowing consistent treatment of waveguides, lossy resonators, and high quality cavities. Our model constitutes a bridge between highly accurate optical simulations of nanostructures [3] and microscopic quantum dynamical calculations. This way, the quantum properties of generated light can be calculated, while fully accounting for the electromagnetic properties of the nanostructure. The generality of this theory enables us to identify an optimal regime of operation for quantum dot single-photon sources, which simultaneously harnesses the high efficiency of a waveguide and the phonon-suppressing spectral structure of a cavity [4,5].

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Organisations: Department of Photonics Engineering, Nanophotonics Theory and Signal Processing, University of Manchester
Contributors: Denning, E. V., Iles-Smith, J., Østerkryger, A. D., Gregersen, N., Mørk, J.
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**Giant nonlinear interaction between two optical beams via a quantum dot embedded in a photonic wire**
Optical nonlinearities usually appear for large intensities, but discrete transitions allow for giant nonlinearities operating at the single-photon level. This has been demonstrated in the last decade for a single optical mode with cold atomic gases, or single two-level systems coupled to light via a tailored photonic environment. Here, we demonstrate a two-mode giant nonlinearity with a single semiconductor quantum dot (QD) embedded in a photonic wire antenna. We exploit two detuned optical transitions associated with the exciton-biexciton QD level scheme. Owing to the broadband waveguide antenna, the two transitions are efficiently interfaced with two free-space laser beams. The reflection of one laser beam is then controlled by the other beam, with a threshold power as low as 10 photons per exciton lifetime (1.6 nW). Such a two-color nonlinearity opens appealing perspectives for the realization of ultralow-power logical gates and optical quantum gates, and could also be implemented in an integrated photonic circuit based on planar waveguides.

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Web of Science (2015): Impact factor 3.718
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Giant Two-Mode Non-linearity Using a Single Quantum Dot Embedded in a Photonic Wire.

Optical logic down to the single photon level holds the promise of data processing with a better energy efficiency than electronic devices. In addition, preservation of quantum coherence in such logical components would enable optical quantum logical gates. Optical logic requires optical two-modes non-linearities to allow for photon-photon interactions. Non-linearities usually appear for large intensities, but discrete transitions in a well coupled single two-level system allow for giant non-linearities operating at the single photon level.
The development of high quality factor solid-state microcavities with low mode volumes has paved the way towards on-chip cavity quantum electrodynamics experiments and the development of high-performance nanophotonic devices. Here, we report on the implementation of a new kind of solid-state vertical microcavity, which allows for confinement of the electromagnetic field in the lateral direction without deep etching. The confinement originates from a local elongation of the cavity layer imprinted in a shallow etch and epitaxial overgrowth technique. We show that it is possible to improve the quality factor of such microcavities by a specific in-plane bullseye geometry consisting of a set of concentric rings with subwavelength dimensions. This design results in a smooth effective lateral photonic potential and therefore in a reduction of lateral scattering losses, which makes it highly appealing for experiments in the framework of exciton-polariton physics demanding tight spatial confinement.

Intrinsic and environmental effects on the interference properties of a high-performance quantum dot single-photon source
We report a joint experimental and theoretical study of the interference properties of a single-photon source based on a In(Ga)As quantum dot embedded in a quasiplanar GaAs microcavity. Using resonant laser excitation with a pulse separation of 2 ns, we find near-perfect interference of the emitted photons, and a corresponding indistinguishability of I = (99.6 ± 0.4 − 1.4)%. For larger pulse separations, quasiresonant excitation conditions, increasing pump power, or with increasing temperature, the interference contrast is progressively and notably reduced. We present a systematic study of the relevant dephasing mechanisms and explain our results in the framework of a microscopic model of our system. For strictly resonant excitation, we show that photon indistinguishability is independent of pump power, but strongly influenced by virtual phonon-assisted processes which are not evident in excitonic Rabi oscillations.
General information
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Organisations: Department of Photonics Engineering, Nanophotonics Theory and Signal Processing, University of Würzburg, University of Science and Technology of China
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Scopus rating (2015): CiteScore 2.8 SJR 2.377 SNIP 1.13
Web of Science (2015): Impact factor 3.718
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Web of Science (2014): Impact factor 3.736
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Scopus rating (2012): CiteScore 3.57 SJR 3.173 SNIP 1.378
Web of Science (2012): Impact factor 3.767
ISI indexed (2012): ISI indexed yes
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Scopus rating (2010): SJR 3.318 SNIP 1.447
Web of Science (2010): Impact factor 3.774
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Scopus rating (2008): SJR 2.923 SNIP 1.516
Web of Science (2008): Indexed yes
Scopus rating (2007): SJR 2.892 SNIP 1.588
Web of Science (2007): Indexed yes
Scopus rating (2006): SJR 2.62 SNIP 1.468
Web of Science (2006): Indexed yes
Scopus rating (2005): SJR 2.126 SNIP 1.156
Web of Science (2005): Indexed yes
Which Computational Methods Are Good for Analyzing Large Photonic Crystal Membrane Cavities?
By introducing defects into an otherwise periodic photonic crystal lattice, high quality (Q) factor cavities may be formed. However, the size and the lack of simplifying symmetries in the photonic crystal membrane make these types of cavities exceptionally hard to analyze using numerical simulation methods. In this work, we consider two different line defect cavities and we compute their Q factors using state-of-the-art optical simulation tools. We show that certain simulation methods perform much better than others in the analysis of these challenging structures.

Benchmarking five computational methods for analyzing large photonic crystal membrane cavities
We benchmark five state-of-the-art computational methods by computing quality factors and resonance wavelengths in photonic crystal membrane L5 and L9 line defect cavities. The convergence of the methods with respect to resolution, degrees of freedom and number of modes is investigated. Convergence is not obtained for some of the methods, indicating that some are more suitable than others for analyzing line defect cavities.
Comparison of Five Computational Methods for Computing Q Factors in Photonic Crystal Membrane Cavities

Five state-of-the-art computational methods are benchmarked by computing quality factors and resonance wavelengths in photonic crystal membrane L5 and L9 line defect cavities. The convergence of the methods with respect to resolution, degrees of freedom and number of modes is investigated. Special attention is paid to the influence of the size of the computational domain. Convergence is not obtained for some of the methods, indicating that some are more suitable than others for analysing line defect cavities.

General information
State: Published
Organisations: Department of Photonics Engineering, Plasmonics and Metamaterials, Nanophotonic Devices, Department of Electrical Engineering, Electromagnetic Systems, Department of Mechanical Engineering, Solid Mechanics, Nanophotonics Theory and Signal Processing, Zuse Institute Berlin, St. Petersburg National Research University of Information Technologies, Mechanics and Optics (ITMO)
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Comparison of Five Numerical Methods for Computing Quality Factors and Resonance Wavelengths in Photonic Crystal Membrane Cavities

General information
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Number of pages: 1
Publication date: 2017
Determination of radial quantum dot position in trumpet nanowires from far field measurements

General information
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Organisations: Department of Photonics Engineering, Nanophotonics Theory and Signal Processing, Universite Grenoble Alpes
Contributors: Østerkryger, A. D., Gregersen, N., Fons, R., Stepanov, P., Jakubczyk, T., Bleuse, J., Gérard, J., Claudon, J.
Number of pages: 1
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Electronic versions:
FarField_needle_structures_Poster_2017.pdf
Source: PublicationPreSubmission
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Research output: Research › Poster – Annual report year: 2017

Efficient Modeling of Excitons in Type-II Nanowire Quantum Dots - Presented at: CLEO®/Europe-EQEC 2017, 2017, Munich

General information
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Organisations: Department of Photonics Engineering, Nanophotonics Theory and Signal Processing
Contributors: Taherkhani, M., Gregersen, N., Mark, J., Willatzen, M.
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Event:
Electronic versions:
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Source: PublicationPreSubmission
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Research output: Research - peer-review › Conference abstract for conference – Annual report year: 2017

Enhanced Photon Extraction from a Nanowire Quantum Dot Using a Bottom-Up Photonic Shell
Semiconductor nanowires offer the possibility to grow high-quality quantum-dot heterostructures, and, in particular, CdSe quantum dots inserted in ZnSe nanowires have demonstrated the ability to emit single photons up to room temperature. In this paper, we demonstrate a bottom-up approach to fabricate a photonic fiberlike structure around such nanowire quantum dots by depositing an oxide shell using atomic-layer deposition. Simulations suggest that the intensity collected in our NA=0.6 microscope objective can be increased by a factor 7 with respect to the bare nanowire case. Combining microphotoluminescence, decay time measurements, and numerical simulations, we obtain a fourfold increase in the collected photoluminescence from the quantum dot. We show that this improvement is due to an increase of the quantum-dot emission rate and a redirection of the emitted light. Our ex situ fabrication technique allows a precise and reproducible fabrication on a large scale. Its improved extraction efficiency is compared to state-of-the-art top-down devices.

General information
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Organisations: Department of Photonics Engineering, Nanophotonics Theory and Signal Processing, Universite Grenoble Alpes
Contributors: Jeannin, M., Cremel, T., Häyrynen, T., Gregersen, N., Bellet-Amalric, E., Nogues, G., Kheng, K.
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Publication information
Journal: Physical Review Applied
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ISSN (Print): 2331-7019
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Modeling open nanophotonic systems using the Fourier modal method: Generalization to 3D Cartesian coordinates

Recently, an open geometry Fourier modal method based on a new combination of an open boundary condition and a non-uniform $k$-space discretization was introduced for rotationally symmetric structures providing a more efficient approach for modeling nanowires and micropillar cavities [J. Opt. Soc. Am. A33, 1298 (2016)]. Here, we generalize the approach to three-dimensional (3D) Cartesian coordinates allowing for the modeling of rectangular geometries in open space. The open boundary condition is a consequence of having an infinite computational domain described using basis functions that expand the whole space. The strength of the method lies in discretizing the Fourier integrals using a non-uniform circular “dartboard” sampling of the Fourier $k$-space. We show that our sampling technique leads to a more accurate description of the continuum of the radiation modes that leak out from the structure. We also compare our approach to conventional discretization with direct and inverse factorization rules commonly used in established Fourier modal methods. We apply our method to a variety of optical waveguide structures and demonstrate that the method leads to a significantly improved convergence enabling more accurate and efficient modeling of open 3D nanophotonic structures.
Modelling open nanophotonic structures using the Fourier modal method in infinite domains

**General information**
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Organisations: Department of Photonics Engineering, Nanophotonics Theory and Signal Processing
Contributors: Østerkryger, A. D., Häyrynen, T., de Lasson, J. R., Gregersen, N.
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Title of host publication: 2017 Conference on Lasers and Electro-Optics Europe & European Quantum Electronics Conference (CLEO/Europe-EQEC)
On the Theory of Coupled Modes in Optical Cavity-Waveguide Structures

Light propagation in systems of optical cavities coupled to waveguides can be conveniently described by a general rate equation model known as (temporal) coupled mode theory (CMT). We present an alternative derivation of the CMT for optical cavity-waveguide structures, which explicitly relies on the treatment of the cavity modes as quasi-normal modes with properties that are distinctly different from those of the modes in the waveguides. The two families of modes are coupled via the field equivalence principle to provide a physically appealing yet surprisingly accurate description of light propagation in the coupled systems. Practical application of the theory is illustrated using example calculations in one and two dimensions.
Optical localization of quantum dots in tapered nanowires

In this work we have measured the far-field emission patterns of InAs quantum dots embedded in a GaAs tapered nanowire and used an open-geometry Fourier modal method for determining the radial position of the quantum dots by computing the far-field emission pattern for different quantum dot locations.

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Organisations: Department of Photonics Engineering, Universite Grenoble Alpes
Contributors: Østerkryger, A. D., Gregersen, N., Fons, R., Stepanov, P., Jakubczyk, T., Bleuse, J., Gérard, J., Claudon, J.
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Source: PublicationPreSubmission
Source-ID: 138515202
Research output: Research - peer-review › Journal article – Annual report year: 2017
Single-photon sources for quantum technologies - Results of the joint research project SIQUTE

In this presentation, the results of the joint research project “Single-Photon Sources for Quantum Technologies” (SIQUTE) [1] will be presented. The focus will be on the development of absolutely characterized single-photon sources, on the realization of an efficient waveguide-based single-photon source at the telecom wavelengths of 1.3 µm and 1.55 µm, on the implementation of the quantum-enhanced resolution in confocal fluorescence microscopy and on the development of a detector for very low photon fluxes.

Type-II quantum-dot-in-nanowire structures with large oscillator strength for optical quantum gate applications

We present a numerical investigation of the exciton energy and oscillator strength in type-II nanowire quantum dots. For a single quantum dot, the poor overlap of the electron part and the weakly confined hole part of the excitonic wave function leads to a low oscillator strength compared to type-I systems. To increase the oscillator strength, we propose a double quantum dot structure featuring a strongly localized exciton wave function and a corresponding fourfold relative enhancement of the oscillator strength, paving the way towards efficient optically controlled quantum gate applications in the type-II nanowire system. The simulations are performed using a computationally efficient configuration-interaction method suitable for handling the relatively large nanowire structures.
Type-II Quantum Dot Nanowire Structures with Large Oscillator Strengths for Optical Quantum Gating Applications

The exciton oscillator strength (OS) in type-II quantum dot (QD) nanowires is calculated by using a fast and efficient method. We propose a new structure in Double-Well QD (DWQD) nanowire that considerably increases OS of type-II QDs which is a key parameter in optical quantum gating in the stimulated Raman adiabatic passage (STIRAP) process [1] for implementing quantum gates.

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Contributors: Taherkhani, M., Gregersen, N., Willatzen, M., Mørk, J.
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Ultra-low power all-optical switch
Optical logic down to the single photon level holds the promise of data processing with a better energy efficiency than electronic devices [1]. In addition, preservation of quantum coherence in such logical components could lead to optical quantum logical gates [2–4]. Optical logic requires optical non-linearities to enable photon-photon interactions. Non-linearities usually appear for large intensities, but discrete transitions allow for giant non-linearities operating at the single photon level [5], as demonstrated for a single optical mode with cold atomic gases [6, 7], or single two-level systems coupled to light via a tailored photonic environment [8–13]. However optical logic requires two-mode non-linearities [14, 15]. Here we take advantage of the large coupling efficiency and the broadband operation of a photonic wire containing a semiconductor quantum dot (QD) [16] to implement an all-optical logical component, wherein as few as 10 photons per QD lifetime in one mode control the reflectivity of another, spectrally distinct, mode. Whether classical or quantum, optical communication has proven to be the best choice for long distance information distribution. All-optical data processing has therefore raised much interest in recent years, as it would avoid energy and coherence consuming optics-to-electronics conversion steps. Two-ports operation is a necessary requirement for the implementation of any non-trivial optical data processing. This involves a non-linear interaction between two distinct optical modes. Such a functionality operating at the single photon level can be achieved with a giant cross non-linearity obtained via resonant interactions in an atomic-like system featuring discrete energy levels [5].

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Research output: Research - peer-review > Journal article – Annual report year: 2017

Ultra-Low Power Optical Transistor Using a Single Quantum Dot Embedded in a Photonic Wire
Using a single InAs quantum dot embedded in a GaAs photonic wire, we realize a giant non-linearity between two optical modes to experimentally demonstrate an all-optical transistor triggered by 10 photons.

General information
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A broadband tapered nanocavity for efficient nonclassical light emission

We present the design of a tapered nanocavity, obtained by sandwiching a photonic wire section between a planar gold reflector and a few-period Bragg mirror integrated into the tapered wire. Thanks to its ultrasmall mode volume \((0.71 \lambda^3/n^3)\), this hybrid nanocavity largely enhances the spontaneous emission rate of an embedded quantum dot (Purcell factor: 6), while offering a wide operation bandwidth (full-width half-maximum: 20 nm). In addition, the top tapered section shapes the cavity far-field emission into a very directive output beam, with a Gaussian spatial profile. For realistic taper dimensions, a total outcoupling efficiency to a Gaussian beam of 0.8 is predicted. Envisioned applications include bright sources of non-classical states of light, such as widely tunable sources of indistinguishable single photons and polarization-entangled photon pairs.
A fiber-coupled quantum-dot on a photonic tip
We present the experimental realization of a quantum fiber-pigtail. The device consists of a semiconductor quantum-dot embedded into a conical photonic wire that is directly connected to the core of a fiber-pigtail. We demonstrate a photon collection efficiency at the output of the fiber of 5.8% and suggest realistic improvements for the implementation of a useful device in the context of quantum information. We also discuss potential applications in scanning probe microscopy. The approach is generic and transferable to other materials including diamond and silicon.

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Scopus rating (2016): CiteScore 2.67 SJR 1.673 SNIP 1.249
Web of Science (2016): Impact factor 3.411
Web of Science (2016): Indexed yes
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Web of Science (2015): Impact factor 3.142
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BFI (2014): BFI-level 2
Scopus rating (2014): CiteScore 3.25 SJR 1.861 SNIP 1.492
Web of Science (2014): Impact factor 3.302
Web of Science (2014): Indexed yes
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Web of Science (2012): Indexed yes
BFI (2011): BFI-level 2
Scopus rating (2011): CiteScore 4.04 SJR 2.814 SNIP 1.917
Web of Science (2011): Impact factor 3.844
ISI indexed (2011): ISI indexed yes
Web of Science (2011): Indexed yes
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Scopus rating (2010): SJR 2.92 SNIP 1.775
A modal approach to light emission and propagation in coupled cavity waveguide systems

We theoretically investigate systems of optical cavities coupled to waveguides, which necessitates the introduction of non-trivial radiation conditions and normalization procedures. In return, the approach provides simple and accurate modeling of Green functions, Purcell factors and perturbation corrections, as well as an alternative approach to the so-called coupled mode theory. In combination, these results may form part of the foundations for highly efficient, yet physically transparent models of light emission and propagation in both classical and quantum integrated photonic circuits.

General information
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Organisations: Department of Photonics Engineering, Nanophotonics Theory and Signal Processing, Humboldt University of Berlin
Contributors: Gregersen, N., Kristensen, P. T., de Lasson, J. R., Gregersen, N., Merk, J.
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Source: PublicationPreSubmission
Source-ID: 125482284
Research output: Research - peer-review › Article in proceedings – Annual report year: 2016
Broadband Purcell enhancement in highly efficient photonic nanowire-based single-photon sources

The photonic nanowire single-photon source design approach allows for efficient broadband coupling between a quantum dot and a 1D photonic environment. In this work, we introduce weak cavity effects to the design by implementing a distributed Bragg reflector in the inverted taper. This leads to broadband enhancement of the photon emission rate with a Purcell factor of 6 over a full-width half-maximum range of 20 nm while maintaining a total outcoupling efficiency of 0.8 to a Gaussian profile.

CdSe quantum dot in vertical ZnSe nanowire and photonic wire for efficient single-photon emission

We've recently demonstrated that a CdSe quantum dot (QD) in a ZnSe nanowire (NW) can emit triggered single photons up to room temperature [1]. In this contribution, we present the possibilities of enhancing the photon emission and collection in such NW-QDs structures for a realistic application as a single photon source. We have grown vertically oriented ZnSe NWs (with typical diameter of 10 nm) by molecular beam epitaxy on a ZnSe(111)B buffer layer. The growth of a ZnMgSe passivating shell increases the (otherwise weak) ZnSe near-band-edge luminescence by two orders of magnitude. This has allowed us to observe luminescence for the first time from CdSe/ZnSe NW-QDs in the (111) direction. We managed to obtain a low NW density (~ 1 NW/μm²) so that single NW-QDs can be directly studied on the as-grown sample. Exciton, biexciton and charged exciton lines are clearly identified. Then we obtained conformal dielectric coating of Al₂O₃ on the NW-QDs using Atomic Layer Deposition so that a photonic wire is formed with the CdSe QD deterministically positioned on its axis. The collection enhancement effect is studied by measuring the emission (with pulse excitation, at saturation intensity) of single vertical NW-QDs with Al₂O₃ coating thickness ranging from 20 nm to 110 nm. Decay time measurements interestingly evidence an inhibition effect of the QD emission for thin Al₂O₃ coating, indicating that the optical dipole is orthogonal to the NW axis, in agreement with our calculations.

Comparison of four computational methods for computing Q factors and resonance wavelengths in photonic crystal membrane cavities

We benchmark four state-of-the-art computational methods by computing quality factors and resonance wavelengths in photonic crystal membrane L5 and L9 line defect cavities. The convergence of the methods with respect to resolution, degrees of freedom and number of modes is investigated. Special attention is paid to the influence of the size of the computational domain. Convergence is not obtained for some of the methods, indicating that some are more suitable than others for analyzing line defect cavities.
Efficient formalism for treating tapered structures using the Fourier modal method
We investigate the development of the mode occupations in tapered structures using the Fourier modal method. In order to use the Fourier modal method, tapered structures are divided into layers of uniform refractive index in the propagation direction and the optical modes are found within each layer. This is not very efficient and in this proceeding we take the first steps towards a more efficient formalism for treating tapered structures using the Fourier modal method. We show that the coupling coefficients through the structure are slowly varying and that only the first few modes are occupied. We exploit both of these properties in the developing of a more efficient formalism.

Efficient Modeling of Coulomb Interaction Effect on Exciton in Crystal-Phase Nanowire Quantum Dot
The binding energy and oscillation strength of the ground-state exciton in type-II quantum dot (QD) is calculated by using a post Hartree-Fock method known as the configuration interaction (CI) method which is significantly more efficient than conventional methods like ab initio method. We show that the Coulomb interaction between electron and holes in these structures considerably affects the transition dipole moment which is the key parameter of optical quantum gating in STIRAP (stimulated Raman adiabatic passage) process for implementing quantum gates [1], [2].
Highly indistinguishable on-demand resonance fluorescence photons from a deterministic quantum dot micropillar device with 74% extraction efficiency

The implementation and engineering of bright and coherent solid state quantum light sources is key for the realization of both on chip and remote quantum networks. Despite tremendous efforts for more than 15 years, the combination of these two key prerequisites in a single, potentially scalable device is a major challenge. Here, we report on the observation of bright single photon emission generated via pulsed, resonance fluorescence conditions from a single quantum dot (QD) deterministically centered in a micropillar cavity device via cryogenic optical lithography. The brightness of the QD fluorescence is greatly enhanced on resonance with the fundamental mode of the pillar, leading to an overall device efficiency of $\eta = (74 \pm 4)\%$ for a single photon emission as pure as $g(2)(0) = 0.0092 \pm 0.0004$. The combination of large Purcell enhancement and resonant pumping conditions allows us to observe a two-photon wave packet overlap up to $\nu = (88 \pm 3)\%$.

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Contributors: Gregersen, N.
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Scopus rating (2016): CiteScore 3.48 SJR 1.532 SNIP 1.544
Web of Science (2016): Impact factor 3.307
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BFI (2015): BFI-level 2
Scopus rating (2015): CiteScore 3.78 SJR 1.91 SNIP 1.674
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 2
Scopus rating (2014): CiteScore 4.18 SJR 2.313 SNIP 2.124
Web of Science (2014): Impact factor 3.488
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BFI (2013): BFI-level 2
Scopus rating (2013): CiteScore 4.38 SJR 2.337 SNIP 2.196
Web of Science (2013): Impact factor 3.525
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
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Scopus rating (2012): CiteScore 3.85 SJR 2.562 SNIP 2.108
Web of Science (2012): Impact factor 3.546
ISI indexed (2012): ISI indexed yes
Web of Science (2012): Indexed yes
BFI (2011): BFI-level 2
Scopus rating (2011): CiteScore 4.04 SJR 2.58 SNIP 2.572
Web of Science (2011): Impact factor 3.587
Modeling cavities exhibiting strong lateral confinement using open geometry Fourier modal method
We have developed a computationally efficient Fourier-Bessel expansion based open geometry formalism for modeling the optical properties of rotationally symmetric photonic nanostructures. The lateral computation domain is assumed infinite so that no artificial boundary conditions are needed. Instead, the leakage of the modes due to an imperfect field confinement is taken into account by using a basis functions that expand the whole infinite space. The computational efficiency is obtained by using a non-uniform discretization in the frequency space in which the lateral expansion modes are more densely sampled around a geometry specific dominant transverse wavenumber region. We will use the developed approach to investigate the Q factor and mode confinement in cavities where top DBR mirror has small rectangular defect confining the modes laterally on the defect region.

General information
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Organisations: Department of Photonics Engineering, Nanophotonics Theory and Signal Processing
Contributors: Häyrynen, T., Gregersen, N.
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Volume: 9900
On-Demand Single Photons with High Extraction Efficiency and Near-Unity Indistinguishability from a Resonantly Driven Quantum Dot In a Micropillar

Scalable photonic quantum technologies require on-demand single-photon sources with simultaneously high levels of purity, indistinguishability, and efficiency. These key features, however, have only been demonstrated separately in previous experiments. Here, by s-shell pulsed resonant excitation of a Purcellenhanced quantum dot-micropillar system, we deterministically generate resonance fluorescence single photons which, at π pulse excitation, have an extraction efficiency of 66%, single-photon purity of 99.1%, and photon indistinguishability of 98.5%. Such a single-photon source for the first time combines the features of high efficiency and near-perfect levels of purity and indistinguishability, and thus opens the way to multiphoton experiments with semiconductor quantum dots.

General information
State: Published
Organisations: Department of Photonics Engineering, Nanophotonics Theory and Signal Processing, University of Science and Technology of China, University of Würzburg, Universität Würzburg
Contributors: Ding, X., He, Y., Duan, Z., Gregersen, N., Chen, M., Unsleber, S., Maier, S., Schneider, C., Kamp, M., Höfling, S., Lu, C., Pan, J.
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BFI (2016): BFI-level 2
Scopus rating (2016): CiteScore 6.33 SJR 4.196 SNIP 2.61
Web of Science (2016): Impact factor 8.462
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 2
Scopus rating (2015): CiteScore 5.76 SJR 4.656 SNIP 2.538
Web of Science (2015): Impact factor 7.645
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 2
Scopus rating (2014): CiteScore 6.62 SJR 5.232 SNIP 2.71
Web of Science (2014): Impact factor 7.512
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 2
Scopus rating (2013): CiteScore 7.46 SJR 5.675 SNIP 2.781
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 2
Scopus rating (2012): CiteScore 7.19 SJR 6.292 SNIP 2.867
We present an open-geometry Fourier modal method based on a new combination of open boundary conditions and an efficient k-space discretization. The open boundary of the computational domain is obtained using basis functions that expand the whole space, and the integrals subsequently appearing due to the continuous nature of the radiation modes are handled using a discretization based on nonuniform sampling of the k space. We apply the method to a variety of photonic structures and demonstrate that our method leads to significantly improved convergence with respect to the number of degrees of freedom, which may pave the way for more accurate and efficient modeling of open nanophotonic structures.
Quantum dot-micropillars: a bright source of coherent single photons
We present the efficient generation of coherent single photons based on quantum dots in micropillars. We utilize a scalable lithography scheme leading to quantum dot-micropillar devices with 74% extraction efficiency. Via pulsed strict resonant pumping, we show an indistinguishability of consecutively emitted photons up to 98.5%.

General information
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Organisations: Department of Photonics Engineering, Nanophotonics Theory and Signal Processing, University of Würzburg, Technical University of Denmark
Contributors: Unsleber, S., He, Y., Maier, S., Gerhardt, S., Ding, X., He, Y., Duan, Z., Gregersen, N., Chen, M., Lu, C., Pan, J., Schneider, C., Hofling, S.
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Research output: Research - peer-review › Article in proceedings – Annual report year: 2017

Quantum optics with quantum dots in photonic wires
We present an exploration of the spectroscopy of a single quantum dot in a photonic wire. The device presents a high photon extraction efficiency, and strong hybrid coupling to mechanical modes. We use resonance fluorescence to probe the emitter's properties with the highest sensitivity, allowing the detection of thermal excitation of the mechanical mode at 4 K.

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Research output: Research - peer-review › Article in proceedings – Annual report year: 2016

Quantum photonics with quantum dots in photonic wires
We present results from the spectroscopy of a single quantum dot in a photonic wire. The device presents a high photon extraction efficiency, and strong hybrid coupling to mechanical modes. We use resonance fluorescence to probe the emitter’s properties with the highest sensitivity. We perform a detailed analysis of the noise in the device and reveal in
particular the thermal excitation of mechanical modes at 4 K.

Site-controlled quantum dots coupled to photonic crystal waveguides
We demonstrate selective optical coupling of multiple, site controlled semiconductor quantum dots (QDs) to photonic crystal waveguide structures. The impact of the exact position and emission spectrum of the QDs on the coupling efficiency is elucidated. The influence of optical disorder and end-reflections on photon transport in these systems are discussed.

Spectral symmetry of Fano resonances in a waveguide coupled to a microcavity
We investigate the symmetry of transmission spectra in a photonic crystal (PhC) waveguide with a side-coupled cavity and a partially transmitting element (PTE). We demonstrate, through numerical calculations, that by varying the cavity-PTE distance the spectra vary from being asymmetric with the minimum blueshifted relative to the maximum, to being symmetric (Lorentzian), to being asymmetric with the minimum redshifted relative to the maximum. For cavity-PTE distances larger than five PhC lattice constants, we show that the transmission spectrum is accurately described as the transmission spectrum of a Fabry–Perot etalon with a single propagating Bloch mode and that the symmetry of the transmission spectrum correlates with the Fabry–Perot round-trip phase.
BFI (2017): BFI-level 2
Scopus rating (2017): CiteScore 3.89 SJR 1.79 SNIP 1.597
Web of Science (2017): Impact factor 3.589
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 2
Scopus rating (2016): CiteScore 3.54 SJR 1.769 SNIP 1.549
Web of Science (2016): Impact factor 3.416
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 2
Scopus rating (2015): CiteScore 3.53 SJR 2.013 SNIP 1.53
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 2
Scopus rating (2014): CiteScore 3.86 SJR 2.429 SNIP 1.997
Web of Science (2014): Impact factor 3.292
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 2
Scopus rating (2013): CiteScore 3.95 SJR 2.441 SNIP 2.058
Web of Science (2013): Impact factor 3.179
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 2
Scopus rating (2012): CiteScore 3.52 SJR 2.577 SNIP 1.92
Web of Science (2012): Impact factor 3.385
ISI indexed (2012): ISI indexed yes
Web of Science (2012): Indexed yes
BFI (2011): BFI-level 2
Scopus rating (2011): CiteScore 3.69 SJR 2.519 SNIP 2.453
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ISI indexed (2011): ISI indexed yes
Web of Science (2011): Indexed yes
BFI (2010): BFI-level 2
Scopus rating (2010): SJR 2.637 SNIP 2.263
Web of Science (2010): Impact factor 3.318
Web of Science (2010): Indexed yes
BFI (2009): BFI-level 1
Scopus rating (2009): SJR 3.077 SNIP 2.658
Web of Science (2009): Indexed yes
BFI (2008): BFI-level 1
Scopus rating (2008): SJR 3.354 SNIP 2.384
Web of Science (2008): Indexed yes
Scopus rating (2007): SJR 3.443 SNIP 2.157
Web of Science (2007): Indexed yes
Scopus rating (2006): SJR 3.126 SNIP 2.319
Web of Science (2006): Indexed yes
Scopus rating (2005): SJR 3.245 SNIP 2.451
Web of Science (2005): Indexed yes
Scopus rating (2004): SJR 3.523 SNIP 2.726
Web of Science (2004): Indexed yes
Scopus rating (2003): SJR 3.725 SNIP 2.626
Web of Science (2003): Indexed yes
Scopus rating (2002): SJR 3.571 SNIP 2.415
Web of Science (2002): Indexed yes
We present experimental results on two-mode optical giant non-linearity of a single InAs quantum dot (QD) embedded in a GaAs tapered photonic wire (fig. 1a). This system, in which the QD is efficiently coupled to a single guided mode, has been exploited to realize ultrabright single-photon sources [1,2]. We exploit here its broad operation bandwidth (>100 nm around 950 nm) to efficiently address two different transitions of the QD with two cw laser beams (fig. 1b). The laser coupled to the upper transition leads to a Rabi splitting of the intermediate state (Autler-Townes effect), affecting the resonant reflectivity of the laser coupled to the lower transition (see fig. 1c). By performing reflectivity experiment, we show that a coupling laser of 10 nW (50 photons per emitter lifetime) can modify the transmission of the probe laser, realizing an ultra-low power all-optical switch.

Ultra-low power all-optical switch using a single quantum dot embedded in a photonic wire

We present experimental results on two-mode optical giant non-linearity of a single InAs quantum dot (QD) embedded in a GaAs tapered photonic wire (fig. 1a). This system, in which the QD is efficiently coupled to a single guided mode, has been exploited to realize ultrabright single-photon sources [1,2]. We exploit here its broad operation bandwidth (>100 nm around 950 nm) to efficiently address two different transitions of the QD with two cw laser beams (fig. 1b). The laser coupled to the upper transition leads to a Rabi splitting of the intermediate state (Autler-Townes effect), affecting the resonant reflectivity of the laser coupled to the lower transition (see fig. 1c). By performing reflectivity experiment, we show that a coupling laser of 10 nW (50 photons per emitter lifetime) can modify the transmission of the probe laser, realizing an ultra-low power all-optical switch.

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Organisations: Department of Photonics Engineering, Nanophotonics Theory and Signal Processing, Université Grenoble Alpes, Vienna University of Technology, CEA–Grenoble and Université Joseph Fourier–Grenoble
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Source: PublicationPreSubmission
Source-ID: 119756240
Research output: Research - peer-review › Conference abstract for conference – Annual report year: 2016

Ultra-low power all-optical switch using a single quantum dot embedded in a photonic wire

We present experimental results on two-mode optical giant non-linearity of a single InAs quantum dot (QD) embedded in a GaAs tapered photonic wire (fig. 1a). This system, in which the QD is efficiently coupled to a single guided mode, has been exploited to realize ultrabright single-photon sources [1,2]. We exploit here its broad operation bandwidth (>100 nm around 950 nm) to efficiently address two different transitions of the QD with two cw laser beams (fig. 1b). The laser coupled to the upper transition leads to a Rabi splitting of the intermediate state (Autler-Townes effect), affecting the resonant reflectivity of the laser coupled to the lower transition (see fig. 1c). By performing reflectivity experiment, we show that a coupling laser of 10 nW (50 photons per emitter lifetime) can modify the transmission of the probe laser, realizing an ultra-low power all-optical switch.

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Organisations: Department of Photonics Engineering, Nanophotonics Theory and Signal Processing, Université Grenoble Alpes, Vienna University of Technology, CEA–Grenoble and Université Joseph Fourier–Grenoble, CNRS
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A Hybrid Photonic Nanowire-Cavity Design for a Single-Indistinguishable-Photon Source

General information
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Organisations: Department of Photonics Engineering, Nanophotonics Theory and Signal Processing, CNRS
Contributors: Gregersen, N., Mørk, J., Claudon, J., Gerard, J.
Number of pages: 1
Publication date: 2015

Design and simulations of highly efficient single-photon sources
The realization of the highly-efficient single-photon source represents not only an experimental, but also a numerical challenge. We will present the theory of the waveguide QED approach, the design challenges and the current limitations. Additionally, the important numerical challenges in the simulations of sources with in-plane emission will be discussed.

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Organisations: Department of Photonics Engineering, Nanophotonics Theory and Signal Processing
Contributors: Gregersen, N., de Lasson, J. R., Mørk, J.
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Source: PublicationPreSubmission
Source-ID: 112568909
Research output: Research - peer-review › Paper – Annual report year: 2015

Design of Slow and Fast Light Photonic Crystal Waveguides for Single-photon Emission Using a Bloch Mode Expansion Technique
We design slow and fast light photonic crystal waveguides for single-photon emission using a Bloch mode expansion and scattering matrix technique. We propose slow light designs that increase the group index-waveguide mode volume ratio for larger Purcell enhancement, and address efficient slow-to-fast-light waveguide coupling.

General information
State: Published
Organisations: Department of Photonics Engineering, Nanophotonics Theory and Signal Processing, Swiss Federal Institute of Technology Lausanne
Contributors: de Lasson, J. R., Rigal, B., Kapon, E., Mørk, J., Gregersen, N.
Number of pages: 1
Publication date: 2015
Peer-reviewed: Yes
Event: Abstract from 2015 Progress In Electromagnetics Research Symposium, Prag, Czech Republic.
Electronic versions: PIERS2015_Final.pdf
Source: PublicationPreSubmission
Source-ID: 113012703
Research output: Research - peer-review › Conference abstract for conference – Annual report year: 2015

Highly directive and Gaussian far-field emission from "giant" photonic trumpets
Photonic trumpets are broadband dielectric antennas that efficiently funnel the emission of a pointlike quantum emitter—such as a semiconductor quantum dot—into a Gaussian free-space beam. After describing guidelines for the taper design, we present a "giant" photonic trumpet. The device features a bottom diameter of 210 nm and a 5 lm wide top facet. Using Fourier microscopy, we show that 95% of the emitted beam is intercepted by a modest numerical aperture of 0.35. Furthermore, far-field measurements reveal a highly Gaussian angular profile, in agreement with the predicted overlap to a Gaussian beam $M_g \approx 0.98$. Future application prospects include the direct coupling of these devices to a
cleaved single-mode optical fiber. The calculated transmission from the taper base to the fiber already reaches 0.59, and we discuss strategies to further improve this figure of merit.

**General information**

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Organisations: Department of Photonics Engineering, Nanophotonics Theory and Signal Processing, University of Grenoble, Universite Grenoble Alpes, University of Basel, CNRS
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- BFI (2017): BFI-level 2
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- Scopus rating (2017): CiteScore 3.25 SJR 1.382 SNIP 1.167
- Web of Science (2017): Indexed yes
- BFI (2016): BFI-level 2
- Web of Science (2016): Impact factor 3.411
- Web of Science (2016): Indexed yes
- BFI (2015): BFI-level 2
- Web of Science (2015): Indexed yes
- BFI (2014): BFI-level 2
- Web of Science (2014): Impact factor 3.302
- Web of Science (2014): Indexed yes
- BFI (2013): BFI-level 2
- Web of Science (2013): Impact factor 3.515
- ISI indexed (2013): ISI indexed yes
- Web of Science (2013): Indexed yes
- BFI (2012): BFI-level 2
- Web of Science (2012): Impact factor 3.794
- ISI indexed (2012): ISI indexed yes
- Web of Science (2012): Indexed yes
- BFI (2011): BFI-level 2
- Web of Science (2011): Impact factor 3.844
- ISI indexed (2011): ISI indexed yes
- Web of Science (2011): Indexed yes
- BFI (2010): BFI-level 2
- Web of Science (2010): SJR 2.92 SNIP 1.775
- Web of Science (2010): Impact factor 3.841
- Web of Science (2010): Indexed yes
Highly indistinguishable photons from a QD-microcavity with a large Purcell-factor

We demonstrate the emission of highly indistinguishable photons from a quasi-resonantly pumped coupled quantum dot-microcavity system operating in the weak coupling regime. Furthermore we model the degree of indistinguishability with our novel microscopic theory.

**General information**

State: Published
Organisations: Department of Photonics Engineering, Nanophotonics Theory and Signal Processing, Department of Micro- and Nanotechnology, University of Würzburg
Contributors: Unsleber, S., McCutcheon, D., Dambach, M., Lermer, M., Gregersen, N., Hofling, S., Mørk, J., Schneider, C., Kamp, M.
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Impact of slow-light enhancement on optical propagation in active semiconductor photonic crystal waveguides

We derive and validate a set of coupled Bloch wave equations for analyzing the reflection and transmission properties of active semiconductor photonic crystal waveguides. In such devices, slow-light propagation can be used to enhance the material gain per unit length, enabling, for example, the realization of short optical amplifiers compatible with photonic integration. The coupled wave analysis is compared to numerical approaches based on the Fourier modal method and a frequency domain finite element technique. The presence of material gain leads to the build-up of a backscattered field, which is interpreted as distributed feedback effects or reflection at passive-active interfaces, depending on the approach taken. For very large material gain values, the band structure of the waveguide is perturbed, and deviations from the simple coupled Bloch wave model are found.
Investigations on the parity of Fano resonances in photonic crystals

We investigate the relation between the parity of Fano resonances and field distribution in a photonic crystal structure using Fourier modal method, establishing a correlation between Fano parity and field profile.

Modeling and simulations of light emission and propagation in open nanophotonic systems

Light emission and propagation in photonic crystal membranes are studied theoretically, with an emphasis on waveguides, slow light effects, and coupled cavity-waveguide systems. A Bloch mode expansion formalism for optical modeling of photonic crystal membranes is presented, and perfectly matched layer boundary conditions are introduced to emulate the inherent openness of the photonic crystal membrane. The impact of the computational domain size and perfectly matched layer parameters on dipole emission in a photonic crystal membrane waveguide is investigated, and we find the associated computational uncertainty to be of larger magnitude than typical estimates found in literature. A photonic crystal waveguide with one or two side-coupled cavities is considered, and the local density of states is described using a semi-analytical quasi-normal mode theory. We propose original techniques for computing and normalizing quasi-normal modes in extended systems, and comparing to numerically exact calculations, the theory correctly predicts a slight asymmetry (one cavity) and a peak and a dip (two cavities) in the local density of states spectra. Next, the photonic crystal waveguide is interfaced with a side-coupled cavity and a scattering site in the waveguide, and we demonstrate that the shape of the transmission spectrum can be controlled by the cavity-scattering site distance, for example to exhibit a
symmetric Fano shapes. Subsequently, we investigate an active photonic crystal waveguide in the slow light region and present an original coupled Bloch mode model, with material gain treated as a perturbation, that includes back-coupling between the counter propagating passive Bloch modes. We show that this gives rise to distributed feedback, which puts fundamental limitations on the maximum achievable gain of the slow light amplifier. Finally, dipole emission in photonic crystal membrane waveguides is analyzed, where we design slow and fast light waveguides for enhanced single-photon emission into a guided mode. We investigate spectra and spatial maps of dipole emission and find that the relative coupling into the guided mode, β, remains in excess of 50%, even in non-optimum situations, and quickly approaches unity towards the band edge. Preliminary experimental results that build on the theoretical designs demonstrate emission from position-controlled quantum dots into the waveguide mode. In a disjoint chapter, we study the localized surface plasmon modes of plasmonic nanodimers, and both theoretically and experimentally, we find an almost-inverse scaling of the relative shift of the plasmon wavelength with particle distance in the sub-radius range.

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Contributors: de Lasson, J. R., Gregersen, N., Kristensen, P. T., Mørk, J.
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PhDThesis_Jakobrdl_Oct2015.pdf

Observation of resonance fluorescence and the Mollow triplet from a coherently driven site-controlled quantum dot
Resonant excitation of solid state quantum emitters has the potential to deterministically excite a localized exciton while ensuring a maximally coherent emission. In this work, we demonstrate the coherent coupling of an exciton localized in a lithographically positioned, site-controlled semiconductor quantum dot to an external resonant laser field. For strong continuous-wave driving we observe the characteristic Mollow triplet and analyze the Rabi splitting and sideband widths as a function of driving strength and temperature. The sideband widths increase linearly with temperature and the square of the driving strength, which we explain via coupling of the exciton to longitudinal acoustic phonons. We also find an increase of the Rabi splitting with temperature, which indicates a temperature induced delocalization of the excitonic wave function resulting in an increase of the oscillator strength. Finally, we demonstrate coherent control of the exciton excited state population via pulsed resonant excitation and observe a damping of the Rabi oscillations with increasing pulse area, which is consistent with our exciton-photon coupling model. We believe that our work outlines the possibility to implement fully scalable platforms of solid state quantum emitters. The latter is one of the key prerequisites for more advanced, integrated nanophotonic quantum circuits.

General information
State: Published
Organisations: Department of Photonics Engineering, Nanophotonics Theory and Signal Processing, Department of Micro- and Nanotechnology, Universität Würzburg, Technische Universität Berlin
Contributors: Unsleber, S., Maier, S., McCutcheon, D., He, Y., Dambach, M., Gschrey, M., Gregersen, N., Merk, J., Reitzenstein, S., Höfling, S., Schneider, C., Kamp, M.
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Scopus rating (2016): CiteScore 8.05
Web of Science (2016): Impact factor 7.727
Web of Science (2016): Indexed yes
Semi-analytical quasi-normal mode theory for the local density of states in coupled photonic crystal cavity-waveguide structures

We present and validate a semi-analytical quasi-normal mode (QNM) theory for the local density of states (LDOS) in coupled photonic crystal (PhC) cavity-waveguide structures. By means of an expansion of the Green's function on one or a few QNMs, a closed-form expression for the LDOS is obtained, and for two types of two-dimensional PhCs, with one and two cavities side-coupled to an extended waveguide, the theory is validated against numerically exact computations. For the single cavity, a slightly asymmetric spectrum is found, which the QNM theory reproduces, and for two cavities a non-trivial spectrum with a peak and a dip is found, which is reproduced only when including both the two relevant QNMs in the theory. In both cases, we find relative errors below 1% in the bandwidth of interest.
Two-photon interference from a quantum dot-microcavity: Persistent pure-dephasing and suppression of time-jitter

We demonstrate the emission of highly indistinguishable photons from a quasi-resonantly pumped coupled quantum dot–microcavity system operating in the regime of cavity quantum electrodynamics. Changing the sample temperature allows us to vary the quantum dot–cavity detuning and, on spectral resonance, we observe a threefold improvement in the Hong-Ou-Mandel interference visibility, reaching values in excess of 80%. Our measurements off-resonance allow us to investigate varying Purcell enhancements, and to probe the dephasing environment at different temperatures and energy scales. By comparison with our microscopic model, we are able to identify pure dephasing and not time jitter as the dominating source of imperfections in our system.
Two-photon interference from a quantum dot-microcavity: Persistent pure-dephasing and suppression of time-jitter

We demonstrate the emission of highly indistinguishable photons from a quasiresonantly pumped coupled quantum dot–microcavity system operating in the regime of cavity quantum electrodynamics. Changing the sample temperature allows us to vary the quantum dot–cavity detuning, and on spectral resonance we observe a three-fold improvement in the Hong–Ou–Mandel interference visibility, reaching values in excess of 80%. By comparison with our microscopic model, we are able to identify pure-dephasing and not time-jitter as the dominating source of imperfections in our system.

A Bloch modal approach for engineering waveguide and cavity modes in two-dimensional photonic crystals

In open nanophotonic structures, the natural modes are so-called quasi-normal modes satisfying an outgoing wave boundary condition. We present a new scheme based on a modal expansion technique, a scattering matrix approach and Bloch modes of periodic structures for determining these quasi-normal modes. As opposed to spatial discretization methods like the finite-difference time-domain method and the finite element method, the present approach satisfies automatically the outgoing wave boundary condition in the propagation direction which represents a significant advantage of our new method. The scheme uses no external excitation and determines the quasi-normal modes as unity eigenvalues of the cavity roundtrip matrix. We demonstrate the method and the quasi-normal modes for two types of two-dimensional photonic crystal structures, and discuss the quasi-normal mode field distributions and Q-factors in relation to the transmission spectra of these structures.
A Bloch mode expansion approach for analyzing quasi-normal modes in open nanophotonic structures

We present a new method for determining quasi-normal modes in open nanophotonic structures using a modal expansion technique. The outgoing wave boundary condition of the quasi-normal modes is satisfied automatically without absorbing boundaries, representing a significant advantage compared to conventional techniques. The quasi-normal modes are determined by constructing a cavity roundtrip matrix and iterating the complex mode wavelength towards a unity eigenvalue. We demonstrate the method by determining quasi-normal modes of cavities in two-dimensional photonic crystals side-coupled to W1 waveguides.

General information
State: Published
Organisations: Department of Photonics Engineering, Nanophotonics Theory and Signal Processing
Contributors: de Lasson, J. R., Kristensen, P. T., Mørk, J., Gregersen, N.
Number of pages: 3
Publication date: 2014

Bright quantum dot single photon source based on a low Q defect cavity

The quasi-planar single photon source presented in this paper shows an extraction efficiency of 42% without complex photonic resonator geometries or lithography steps as well as a high purity with a g2(0) value of 0.023.

General information
State: Published
Organisations: Department of Photonics Engineering, Nanophotonics Theory and Signal Processing, Universität Würzburg, University of Würzburg
Contributors: Maier, S., Gold, P., Forchel, A., Gregersen, N., Höfling, S., Schneider, C., Kamp, M.
Number of pages: 3
Publication date: 2014

Bright single photon source based on self-aligned quantum dot–cavity systems

We report on a quasi-planar quantum-dot-based single-photon source that shows an unprecedented high extraction efficiency of 42% without complex photonic resonator geometries or post-growth nanofabrication. This very high efficiency originates from the coupling of the photons emitted by a quantum dot to a Gaussian shaped nanohill defect that naturally arises during epitaxial growth in a self-aligned manner. We investigate the morphology of these defects and characterize the photonic operation mechanism. Our results show that these naturally arising coupled quantum dot-defects provide a new avenue for efficient (up to 42% demonstrated) and pure (g2(0) value of 0.023) single-photon emission.

General information
State: Published
Organisations: Department of Photonics Engineering, Nanophotonics Theory and Signal Processing, Universität Würzburg
Contributors: Maier, S., Gold, P., Forchel, A., Gregersen, N., Mørk, J., Höfling, S., Schneider, C., Kamp, M.
We show how one can use a non-local boundary condition, which is compatible with standard frequency domain methods, for numerical calculation of quasinormal modes in optical cavities coupled to waveguides. In addition, we extend the definition of the quasinormal mode norm by use of the theory of divergent series to provide a framework for modeling of optical phenomena in such coupled cavity-waveguide systems. As an example, we apply the framework to study perturbative changes in the resonance frequency and Q value of a photonic crystal cavity coupled to a defect waveguide.
Indistinguishable photons from a quantum dot–cavity system: competing roles of timing-jitter and pure-dephasing

General information
State: Published
Organisations: Department of Photonics Engineering, Nanophotonics Theory and Signal Processing, University of Würzburg
Contributors: McCutcheon, D., Gregersen, N., Mørk, J., Unslab, S., Dambach, M., Lermer, M., Höfling, S., Schneider, C., Kamp, M.
Publication date: 2014
Peer-reviewed: Yes
Event: Poster session presented at International Conference on Nonlinear Optics and Excitation Kinetics in Semiconductors, Bremen, Germany.
Source: PublicationPreSubmission
Source-ID: 100889514
Research output: Research - peer-review › Poster – Annual report year: 2014

Indistinguishable single photons generated by quantum dots in adiabatic micropillar cavities

General information
State: Published
Organisations: Department of Photonics Engineering, Nanophotonics Theory and Signal Processing, University of Würzburg
Contributors: Unslab, S., McCutcheon, D., Dambach, M., Lermer, M., Gregersen, N., Höfling, S., Mørk, J., Schneider, C., Kamp, M.
Publication date: 2014
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Source-ID: 100889504
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Numerical Methods in Photonics

General information
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Organisations: Department of Photonics Engineering, Plasmonics and Metamaterials, Fiber Optics, Devices and Nonlinear Effects, Nanophotonics Theory and Signal Processing, Zuse Institute Berlin, Aalborg University
Contributors: Lavrinenko, A., Lægsgaard, J., Gregersen, N., Schmidt, F., Søndergaard, T.
Number of pages: 362
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Research output: Research - peer-review › Book – Annual report year: 2015

Random nanolasers in the Anderson localized regime

The development of nanoscale optical devices for classical and quantum photonics is affected by unavoidable fabrication imperfections that often impose performance limitations. However, disorder may also enable new functionalities, for
example in random lasers, where lasing relies on random multiple scattering. The applicability of random lasers has been limited due to multidirectional emission, lack of tunability, and strong mode competition with chaotic fluctuations due to a weak mode confinement. The regime of Anderson localization of light has been proposed for obtaining stable multimode random lasing, and initial work concerned macroscopic one-dimensional layered media. Here, we demonstrate on-chip random nanolasers where the cavity feedback is provided by the intrinsic disorder. The strong confinement achieved by Anderson localization reduces the spatial overlap between lasing modes, thus preventing mode competition and improving stability. This enables highly efficient, stable and broadband wavelength-controlled lasers with very small mode volumes. Furthermore, the complex interplay between gain, dispersion-controlled slow light, and disorder is demonstrated experimentally for a non-conservative random medium. The statistical analysis shows a way towards optimizing random-lasing performance by reducing the localization length, a universal parameter.

General information
State: Published
Organisations: Department of Photonics Engineering, Nanophotonics Theory and Signal Processing, University of Copenhagen
Contributors: Liu, J., Garcia, P. D., Ek, S., Gregersen, N., Skovgård, T. S., Schubert, M., Mørk, J., Stobbe, S., Lodahl, P.
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Web of Science (2017): Indexed yes
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Web of Science (2016): Impact factor 38.986
Web of Science (2016): Indexed yes
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Web of Science (2015): Impact factor 35.267
Web of Science (2015): Indexed yes
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Web of Science (2014): Impact factor 34.048
Web of Science (2014): Indexed yes
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Web of Science (2013): Impact factor 33.265
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
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Scopus rating (2012): CiteScore 17.55 SJR 15.706 SNIP 7.569
Web of Science (2012): Impact factor 31.17
ISI indexed (2012): ISI indexed yes
Web of Science (2012): Indexed yes
BFI (2011): BFI-level 2
Scopus rating (2011): CiteScore 17.25 SJR 14.582 SNIP 8.354
Web of Science (2011): Impact factor 27.27
ISI indexed (2011): ISI indexed yes
Resonant excitation of a quantum dot in a photonic wire

General information
State: Published
Organisations: Department of Photonics Engineering, Nanophotonics Theory and Signal Processing, Universite Grenoble Alpes, French Alternative Energies and Atomic Energy Commission
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Source: PublicationPreSubmission
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Research output: Research - peer-review » Poster – Annual report year: 2014

Roundtrip matrix method for calculating the leaky resonant modes of open nanophotonic structures

We present a numerical method for calculating quasi-normal modes of open nanophotonic structures. The method is based on scattering matrices and a unity eigenvalue of the roundtrip matrix of an internal cavity, and we develop it in detail with electromagnetic fields expanded on Bloch modes of periodic structures. This procedure is simpler to implement numerically and more intuitive than previous scattering matrix methods, and any routine based on scattering matrices can benefit from the method. We demonstrate the calculation of quasi-normal modes for two-dimensional photonic crystals where cavities are side-coupled and in-line-coupled to an infinite W1 waveguide and show that the scattering spectrum of these types of cavities can be reconstructed from the complex quasi-normal mode frequency.

General information
State: Published
Organisations: Department of Photonics Engineering, Nanophotonics Theory and Signal Processing
Contributors: de Lasson, J. R., Kristensen, P. T., Mørk, J., Gregersen, N.
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Single-photon source engineering using a Modal Method

Solid-state sources of single indistinguishable photons are of great interest for quantum information applications. The semiconductor quantum dot embedded in a host material represents an attractive platform to realize such a single-photon source (SPS). A near-unity efficiency, defined as the number of detected photons by the collection optics per trigger, is
desired, and to obtain this high efficiency the photonic environment must be engineered \cite{1} such that all the emitted light couples to the collection optics. A recent design approach is based on a quantum dot placed inside a photonic nanowire (Fig. 1). This structure does not feature a cavity but instead relies on a geometrical screening effect to efficiently couple photons to the fundamental waveguide mode. Furthermore, the photonic nanowire SPS implements a bottom metal mirror and exploits tapering strategies based on conical tapers to ensure efficient in- and out-coupling. However, the performance of the photonic nanowire SPS depends critically on the geometrical parameters, and exact optical simulations of the scattering coefficients of the fundamental waveguide mode are required to obtain a detailed understanding of the various subcomponents. The natural choice of simulation method for the SPS design is thus a Modal Method, which allows for a determination of scattering coefficients in an elegant way. In this presentation, I will describe the Modal Method as well as its application to novel designs of highly efficient photonic nanowire SPSs.

**General information**

State: Published  
Organisations: Department of Photonics Engineering, Nanophotonics Theory and Signal Processing  
Contributors: Gregersen, N.  
Publication date: 2014  
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Event: Abstract from Photonics North 2014, Montreal, Canada.  
Source: PublicationPreSubmission  
Source-ID: 99520696  
Research output: Research - peer-review › Conference abstract for conference – Annual report year: 2014

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**The photonic nanowire: A highly efficient single-photon source**

The photonic nanowire represents an attractive platform for a quantum light emitter. However, careful optical engineering using the modal method, which elegantly allows access to all relevant physical parameters, is crucial to ensure high efficiency.

**General information**

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Organisations: Department of Photonics Engineering, Nanophotonics Theory and Signal Processing  
Contributors: Gregersen, N.  
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Publication date: 2014  
Host publication information  
Title of host publication: Advanced Photonics for Communications  
Publisher: Optical Society of America (OSA)  
Source: PublicationPreSubmission  
Source-ID: 99520672  
Research output: Research - peer-review › Article in proceedings – Annual report year: 2014

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**The photonic nanowire: An emerging platform for a highly efficient quantum light source**

The single-photon source capable of emitting single indistinguishable photons on demand represents a key component in quantum information applications. The photonic nanowire represents an attractive platform to construct a source with near-unity efficiency.

**General information**

State: Published  
Organisations: Department of Photonics Engineering, Nanophotonics Theory and Signal Processing, French Alternative Energies and Atomic Energy Commission  
Contributors: Gregersen, N., Claudon, J., Munsch, M., Bleuse, J., Delga, A., Mørk, J., Gerard, J. M.  
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Event: Abstract from 35th Progress In Electromagnetics Research Symposium, Guangzhou (Canton), China.  
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**Two-photon interference from a quantum dot-microcavity: Persistent pure-dephasing and suppression of time-jitter**

**General information**

State: Published
Very Efficient Single-Photon Sources Based on Quantum Dots in Photonic Wires

We review the recent development of high efficiency single photon sources based on a single quantum dot in a photonic wire. Unlike cavity-based devices, very pure single photon emission and efficiencies exceeding 0.7 photon per pulse are jointly demonstrated under non-resonant pumping conditions. By placing a tip-shaped or trumpet-like tapering at the output end of the wire, a highly directional Gaussian far-field emission pattern is obtained. More generally, a photonic wire containing a quantum dot appears as an attractive template to explore and exploit in a solid-state system the unique optical properties of "one-dimensional atoms".

A photonic nanowire trumpet for interfacing a quantum dot and a Gaussian free-space mode

Efficient coupling between a localized quantum emitter and a well defined optical channel represents a powerful route to realize single-photon sources and spin-photon interfaces. The tailored fiber-like photonic nanowire embedding a single quantum dot has recently demonstrated an appealing potential. However, the device requires a delicate, sharp needle-like taper with performance sensitive to minute geometrical details. To overcome this limitation we demonstrate the photonic trumpet, exploiting an opposite tapering strategy. The trumpet features a strongly Gaussian far-field emission. A first implementation of this strategy has lead to an ultra-bright single-photon source with a first-lens external efficiency of 0.75 ± 0.1 and a predicted coupling to a Gaussian beam of 0.61 ± 0.08.
Bloch-wave engineered submicron-diameter quantum-dot micropillars for cavity QED experiments

The semiconductor micropillar is attractive for cavity QED experiments. For strong coupling, the figure of merit is proportional to $Q/\sqrt{V}$, and a design combining a high $Q$ and a low mode volume $V$ is thus desired. However, for the standard submicron diameter design, poor mode matching between the cavity and the DBR Bloch mode limits the $Q$. We present a novel adiabatic design where Bloch-wave engineering is employed to improve the mode matching, allowing the demonstration of a record-high vacuum Rabi splitting of 85 $\mu$eV and a $Q$ of 13600 for a 850 nm diameter micropillar.
Dielectric GaAs Antenna Ensuring an Efficient Broadband Coupling between an InAs Quantum Dot and a Gaussian Optical Beam

We introduce the photonic trumpet, a dielectric structure which ensures a nearly perfect coupling between an embedded quantum light source and a Gaussian free-space beam. A photonic trumpet exploits both the broadband spontaneous emission control provided by a single-mode photonic wire and the expansion of this mode within a conical taper. Numerical simulations highlight the performance and robustness of this concept. As a first application in the field of quantum optics, we report the realization of an ultrabright single-photon source. The device, a high aspect ratio GaAs photonic trumpet containing a few InAs quantum dots, demonstrates a first-lens external efficiency of 0.75±0.1 and an external coupling efficiency to a Gaussian beam as high as 0.58±0.08.
Erratum: Dielectric GaAs Antenna Ensuring an Efficient Broadband Coupling between an InAs Quantum Dot and a Gaussian Optical Beam [Phys. Rev. Lett. 110, 177402 (2013)]

General information
State: Published
Organisations: Department of Photonics Engineering, Nanophotonics Theory and Signal Processing, Centre National de la Recherche Scientifique
Contributors: Munsch, M., Malik, N. S., Dupuy, E., Delga, A., Bleuse, J., Gerard, J., Claudon, J., Gregersen, N., Merk, J.
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ISSN (Print): 0031-9007
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BFI (2017): BFI-level 2
Scopus rating (2017): CiteScore 7.58 SJR 3.622 SNIP 2.464
Web of Science (2017): Impact factor 8.839
Harnessing Light with Photonic Nanowires: Fundamentals and Applications to Quantum Optics

The efficient feeding of spontaneous emission (SE) into a controlled optical mode lies at the heart of a new generation of advanced optoelectronic devices, such as low-threshold microlasers and bright sources of quantum light. In the solid state, single-mode emission was first demonstrated by using the Purcell effect that arises in a resonant microcavity. Recently, the need to relax the constraints inherent to such a narrow-band approach has motivated large effort to develop structures ensuring broadband and efficient SE control. This minireview deals with fiber-like photonic nanowires, a class of high-index waveguides that features key assets in this context. Combining theoretical predictions and experimental results, the paper details the SE dynamics in such tiny wires. In addition, it shows how the far-field emission of a single wire can be tailored through proper engineering of the two wire ends. As an application in the field of quantum optics, we review the realization of an ultrabright single-photon source. This first device was based on a self-assembled quantum dot embedded in a wire antenna realized with a top-down fabrication process. Considering recent advances in the direct growth of tapered photonic wires, we also propose a bottom-up fabrication route to realize a complete device. In particular, this proposal ensures the optimal 3D positioning of a single emitter inside the antenna. Finally, future research and application prospects are also reviewed.

Artist view of an optical antenna based on a tailored photonic wire, as it is discussed by J. Claudon et al. on p. 2393. The antenna exploits both the broadband spontaneous emission control offered by a single-mode photonic wire and the engineering of its far-field emission, using a planar mirror and a top conical taper. By inserting a quantum dot inside the wire, one realizes a very bright single-photon source. Beyond this first application, such a structure opens appealing perspectives for the future developments of solid-state quantum optics.

General information
State: Published
Organisations: Department of Photonics Engineering, Nanophotonics Theory and Signal Processing, CNRS, University of Bordeaux
Contributors: Claudon, J., Gregersen, N., Lalanne, P., Gérard, J.
Number of pages: 1
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High beta lasing in micropillar cavities with adiabatic layer design
We report on lasing in optically pumped adiabatic micropillar cavities, based on the AlAs/GaAs material system. A detailed study of the threshold pump power and the spontaneous emission $\beta$ factor in the lasing regime for different diameters $d_c$ is presented. We demonstrate a reduction of the threshold pump power by over 2 orders of magnitude from $d_c=2.25\mu m$ down to $0.95\mu m$. Lasing with $\beta$ factors exceeding 0.5 shows that adiabatic micropillars are operating deeply in the cavity quantum electrodynamics regime.

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Web of Science (2017): Impact factor 3.495
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 2
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Web of Science (2016): Impact factor 3.411
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 2
Scopus rating (2015): CiteScore 2.47 SJR 1.499 SNIP 1.226
Web of Science (2015): Impact factor 3.142
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 2
Scopus rating (2014): CiteScore 3.25 SJR 1.861 SNIP 1.492
Web of Science (2014): Impact factor 3.302
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Web of Science (2013): Impact factor 3.515
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 2
Scopus rating (2012): CiteScore 3.76 SJR 2.57 SNIP 1.739
Web of Science (2012): Impact factor 3.794
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Highly efficient photonic nanowire single-photon sources for quantum information applications

Within the emerging field of optical quantum information processing, the current challenge is to construct the basic building blocks for the quantum computing and communication systems. A key component is the singlephoton source (SPS) capable of emitting single photons on demand. Ideally, the SPS must feature near-unity efficiency, where the efficiency is defined as the number of detected photons per trigger, the probability $g(2)(τ=0)$ of multi-photon emission events should be 0 and the emitted photons are required to be indistinguishable.

An optically or electrically triggered quantum light emitter, e.g. a nitrogen-vacancy center or a semiconductor quantum dot (QD), embedded in a solid-state semiconductor host material appears as an attractive platform for generating such single photons. However, for a QD in bulk material, the large index contrast at the semiconductor-air interface leads to a collection efficiency of only 1-2 %, and efficient light extraction thus poses a major challenge in SPS engineering.
Initial efforts to improve the efficiency have exploited cavity quantum electrodynamics (cQED) to efficiently couple the emitted photons to the optical cavity mode. An alternative approach based on QDs in a photonic nanowire (Fig. 1a) was recently proposed, and the first experimental demonstration featured an efficiency of 0.72. [1] This geometry does not employ a cavity but instead relies on a geometrical screening effect to efficiently couple the emitted photons to the optical mode of interest. [2] The photonic nanowire “trumpet” design based on an inverted taper and compatible with metal contacts, shown in Fig. 1(b), very recently resulted in an efficiency of 0.75 under optical pumping. [3] These designs do not employ a cavity and do not rely on resonant cQED effects to ensure a high factor, meaning that efficient coupling from the QD to the guided mode is obtained over a broad spectral range of ~ 50-100 nm. [4] This means that spectral alignment between the emitter line and a narrow cavity line is not required, which represents a huge practical advantage in the fabrication. Furthermore, for a given dot density, the smaller area of the nanowire QD layer compared to that of e.g. micropillars means that fewer dots are present, and very pure photon emission with a measured g(2)(τ=0) as low as 0.008 [1] has been obtained.
of tailoring it as well as the mechanisms governing the coherence are elucidated. The major design strategies pursued to optimize the single-photon source performance and the remaining challenges are reviewed.
Modeling of optical fields in laser microcavities using a modal method

A compact microlaser featuring a high-Q cavity with a low mode volume V is of interest as it allows for a near-unity factor, thresholdless lasing and reduced energy consumption. However, whereas a high Q and a low V are easily achieved separately, combining the two poses a challenge. Furthermore, the cavity should allow for efficient out-coupling of light, which in low-V systems represents an additional design challenge. Engineering a microcavity meeting these demands requires a in-depth physical understanding of the governing physical mechanisms of the system. In the low-V cavity, a central mechanism limiting the Q factor is the poor modal overlap between the cavity Bloch mode and the mirror Bloch mode. Also, the strong confinement will generally lead to highly divergent far field patterns and thus low collection efficiency. In this scenario, Bloch-wave engineering [1] and the introduction of adiabatic transitions emerge as powerful design tools to control the optical mode.

In the modal method, the field is expanded on the eigenmodes of z-invariant layers and on the Bloch modes of periodic sections. Using mode matching at the interfaces, the method gives direct access to reflection and transmission coefficients describing the scattering of the optical modes, and the method is thus highly suitable for Bloch-wave engineering of the low-V cavity. As example we have used the modal method to propose the high-Q submicron-diameter micropillar geometry implementing an adiabatic cavity design as illustrated in Fig. 1, which recently lead to the experimental demonstration of high-lasing in fabricated devices with factors exceeding 0.5. [2]

Photonic wires and trumpets for ultrabright single photon sources

Photonic wires have recently demonstrated very attractive assets in the field of high-efficiency single photon sources. After presenting the basics of spontaneous emission control in photonic wires, we compare the two possible tapering strategies that can be applied to their output end so as to tailor their radiation diagram in the far-field. We highlight the novel “photonic trumpet” geometry, which provides a clean Gaussian beam, and is much less sensitive to fabrication imperfections than the more common needle-like taper geometry. S4Ps based on a single QD in a PW with integrated...
bottom mirror and tapered tip display jointly a record-high efficiency (0.75±0.1 photon per pulse) and excellent single
phon purity. Beyond single photon sources, photonic wires and trumpets appear as a very attractive resource for solid-
state quantum optics experiments.

**General information**

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Organisations: Department of Photonics Engineering, Nanophotonics Theory and Signal Processing, French Alternative
Energies and Atomic Energy Commission
Contributors: Gérard, J., Claudon, J., Bleuse, J., Munsch, M., Malik, N. S., Gregersen, N., Mørk, J.
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Quantum Optics with Photonic Nanowires and Photonic Trumpets: Basics and Applications

Optimizing the coupling between a localized quantum emitter and a single-mode optical channel represents a powerful route to realise bright sources of non-classical light states. Reversely, the efficient absorption of a photon impinging on the emitter is key to realise a spin-photon interface, the node of future quantum networks. Besides optical microcavities [1], photonic wires have recently demonstrated in this context an appealing potential [2, 3]. For instance, single photon sources (SPS) based on a single quantum dot in a vertical photonic wire with integrated bottom mirror and tapered tip have enabled for the first time to achieve simultaneously a very high efficiency (0.72 photon per pulse) and a very pure single photon emission \( g(2)(0) < 0.01 \). Furthermore, photonic wires with an elongated cross-section provide polarization control of the spontaneous emission of embedded emitters [4]. However, the performance of photonic wire SPS with tapered tips is sensitive to minute geometrical details and optimum behaviour is only obtained for ultra-sharp tips. Photonic trumpets [5], which exploit the opposite tapering strategy, overcome this important limitation. Moreover, they feature a Gaussian far-field emission, a strong asset for most applications. We report on the first implementation of this strategy and demonstrate an ultra-bright SPS (first-lens external efficiency: 0.75 ± 0.1) [5]. More generally, photonic trumpets appear as a very promising template to explore and exploit in a solid-state system the unique optical properties of 'one-dimensional atoms'.

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Theory of nanolaser devices: Rate equation analysis versus microscopic theory

A rate equation theory for quantum-dot-based nanolaser devices is developed. We show that these rate equations are capable of reproducing results of a microscopic semiconductor theory, making them an appropriate starting point for complex device simulations of nanolasers. The input-output characteristics and the modulation response are investigated and the limits of the rate equation approach are discussed.

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The photonic nanowire: an emerging platform for highly efficient single-photon sources for quantum information applications

Efficient coupling between a localized quantum emitter and a well defined optical channel represents a powerful route to realize single-photon sources and spin-photon interfaces. The tailored fiber-like photonic nanowire embedding a single quantum dot has recently demonstrated an appealing potential. However, the device requires a delicate, sharp needle-like taper with performance sensitive to minute geometrical details. To overcome this limitation we demonstrate the photonic trumpet, exploiting an opposite tapering strategy. The trumpet features a strongly Gaussian far-field emission. A first implementation of this strategy has lead to an ultra-bright single-photon source with a first-lens external efficiency of 0.75 ± 0.1 and a predicted coupling to a Gaussian beam of 0.61 ± 0.08.

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The role of phonon scattering in the indistinguishability of photons emitted from semiconductor cavity QED systems

A solid-state single-photon source emitting indistinguishable photons on-demand is an essential component of linear optics quantum computing schemes. However, the emitter will inevitably interact with the solid-state environment causing decoherence and loss of indistinguishability. In this paper, we present a comprehensive theoretical treatment of the influence of phonon scattering on the coherence properties of single photons emitted from semiconductor quantum dots. We model decoherence using a full microscopic theory and compare with standard Markovian approximations employing Lindblad-type relaxation terms. Significant differences between the two approaches are found.

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A bright single-photon source based on a photonic trumpet

Fiber-like photonic nanowires, which are optical waveguides made of a high refractive index material \(n\), have recently emerged as non-resonant systems providing an efficient spontaneous emission (SE) control. When they embed a quantum emitter like a quantum dot (QD), they find application to the realization of bright sources of quantum light and, reversibly, provide an efficient interface between propagating photons and the QD. For a wire diameter \(\sim \lambda/n\) (\(\lambda\) is the operation wavelength), the fraction of QD SE coupled to the fundamental guided mode exceeds 90%. The collection of the photons can be brought close to unity with a proper engineering of the wire ends. In particular, a tapering of the top wire end is necessary to achieve a directive far-field emission pattern [1].
Recently, we have realized a single-photon source featuring a needle-like taper. The source efficiency, though record-high, was found to be limited by the geometry of the taper [2]. Here, we propose an alternative, high performance, trumpet-like tapering of the wire and demonstrate its implementation in a bright single-photon source. Specifically, we consider a GaAs structure, for which the wire diameter is progressively increased from 220 nm to 1.5 µm, for a total height of 12 µm. Such trumpet-like tapers present a number of key assets: i) a nearly perfect adiabatic expansion (less than 5% losses) of the fundamental mode is achieved for tapering angle as large as 7°. ii) the emitted mode features a Gaussian profile with a divergence controlled by the top-facet diameter: for a top diameter of 1.5 µm, less than 5% of the light is scattered outside the collection cone of a lens with a 0.75 NA. iii) the large top facet also simplifies the implementation of a top electrode, to achieve an electrical driving of the device [3].

Using top-down fabrication techniques, we have fabricated a single photon source based on this geometry. The trumpet lies on an integrated mirror and embeds a single layer of InAs QDs, located 110 nm above the mirror. We obtain collection efficiencies higher than 40% for a bunch of QDs spread over 35 nm in a single wire, with a maximum of 65%. This result, which approaches the state of the art (70%), is also close to the predicted value of 80%, obtained for a perfect emitter [4]. Eventually, we map the field profile at the top facet and evidence its Gaussian profile. This is desirable to achieve a good coupling to a monomode fiber, in view of the long range distribution of single photons. This is also crucial to increase the mode matching when addressing a single QD with an optical Gaussian beam.

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Bloch-wave engineering of quantum dot-micropillars for cavity quantum electrodynamics experiments
We have employed Bloch-wave engineering to realize submicron diameter ultra-high quality factor GaAs/AlAs micropillars (MPs). The design features a tapered cavity in which the fundamental Bloch mode is subject to an adiabatic transition to match the Bragg mirror Bloch mode. The resulting reduced scattering loss leads to record-high visibility of the strong coupling in MPs with modest oscillator strength quantum dots. A quality factor of 13,600 and a Rabi splitting of 85 \mueV with an estimated visibility v of 0.38 are observed for a small mode volume MP with a diameter dc of 850 nm.

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Controlling light emission from single-photon sources using photonic nanowires

The photonic nanowire has recently emerged as an promising alternative to microcavity-based single-photon source designs. In this simple structure, a geometrical effect ensures a strong coupling between an embedded emitter and the optical mode of interest and a combination of tapers and mirrors are used to tailor the far-field emission pattern. This non-resonant approach relaxes the demands to fabrication perfection, allowing for record-high measured efficiency of fabricated nanowire single-photon sources. We review recent progress in photonic nanowire technology and present next generation designs allowing for electrical contacting, polarization control, improved efficiency and simplified fabrication.

Efficient and broadband spontaneous emission control in fiber-like photonic nanowires

Funneling a large fraction of the spontaneous emission (SE) of a quantum emitter into a single optical mode is a powerful strategy for improving the brightness of quantum light sources or developing an efficient spin-photon interface. In the solid state, preferential emission into a single localized mode has been first achieved taking advantage of the Purcell effect that arises in semiconductor optical microcavities. In the last years, the need to overcome the limited operation bandwidth inherent to a resonant approach has triggered intense research on SE control in waveguide structures. Among the investigated platforms, fiber-like photonic nanowires are particularly appealing, as shown by the recent development of a very bright single-photon source based on a wire with carefully engineered ends [1,2].

Here we focus on the mechanisms governing the SE dynamics of the embedded emitter and consider a photonic nanowire made of GaAs (refractive index n=3.5) and surrounded by air (n=1). It features a circular section (diameter d), and contains spectrally isolated single InAs quantum dots (QD) with a free space emission wavelength around 920 nm. The large refractive index contrast between the wire and the air cladding has two important consequences: i) The coupling to the 3D continuum of non-guided modes is strongly inhibited, thanks to a pronounced dielectric screening effect. Experimentally, the coupling to these modes can be probed by studying the luminescence decay of QDs embedded in ‘small’ wires (d=120 nm), for which the coupling to the guided mode is vanishingly small. In that case, we measure a slowdown of the SE rate by a factor 16, a value which is comparable to the one obtained in state-of-the-art photonic crystal structures. ii) For larger structures (d=220 nm), the fundamental guided mode is tightly confined in the wire. The emitter is well coupled to this mode, and the SE rate becomes comparable to the one measured on a QD embedded in bulk GaAs. These experimental results demonstrate the ability of these simple structures to funnel a large fraction (>90%) of the SE into the guided mode [3]. For some applications (e.g. polarization encoded quantum key distribution, generation of indistinguishable photons), it is desirable to control the polarization of the emitted photon. This control can be efficiently implemented in a wire featuring an elliptical section with a moderate aspect ratio (~2). In that case, calculations show that the local density of optical modes is largely dominated by a single guided mode, with a linear polarization oriented along the major axis of the ellipse. Polarization-resolved measurements conducted on elliptical GaAs photonic nanowires embedding spectrally isolated InAs QDs fully confirm the predicted performances: the fraction of collected photons with the desired polarization can be as high as 95% [4].
Efficient and broadband spontaneous emission control in fiber-like photonic nanowires.pdf

High-Q AlAs/GaAs adiabatic micropillar cavities with submicron diameters for cQED experiments
Quantum dot (QD) micropillar cavities represent an interesting class of microresonator systems aiming at the observation and application of cavity quantum electrodynamics (cQED) on a semiconductor platform. They combine valuable properties i.e. a highly directional and approximately Gaussian shaped emission pattern, efficient electrical operation, high quality (Q) factors up to 165,000 at large diameters [1].
To overcome the trade-off between high Q and low Vmode, we designed and implemented a novel adiabatic AlAs/GaAs cavity design (MC1) with 3 taper segments (Fig. 1 (a)) as it was suggested by Zhang et al. for SiO2/TiO2 micropillar cavities [3]. Comparative measurements of the Q factor were performed between a standard one-λ microcavity structure (MC2) and MC1 for pillars with diameters ranging from 0.70 μm to 1.50 μm (Fig. 1 (b; bottom)). As can be seen in Fig. 1(b), MC1 shows significantly higher Q-factors exceeding 10,000 in the submicron diameter range due to the adiabatic cavity design. Purcell factors FP between 225 and 325 can be expected in the diameter range between 0.70 μm and 1.00 μm as it is indicated by the shaded box in Fig. 1 (b; top). Moreover, strong coupling between a standard InGaAs QD and an 850 nm diameter adiabatic micropillar with quality factor of 13,600 has been achieved.

High-Q submicron-diameter quantum-dot microcavity pillars for cavity QED experiments
The semiconductor quantum dot – microcavity pillar system represents an attractive platform for studying fundamental light-matter interaction as well as for demonstrating novel quantum devices, ultra-low threshold lasers and sub-ps optical switching. In this work we present a novel tapered GaAs/AlAs micropillar design where Bloch-wave engineering is employed to signficantly enhance the cavity mode confinement in the submicron diameter regime. We demonstrate a record-high vacuum Rabi splitting of 85 µeV of the strong coupling for pillars incorporating quantum dots with modest oscillator strength f ≈ 10. It is well-known that light-matter interaction depends on the photonic environment, and thus proper engineering of the optical mode in microcavity systems is central to obtaining the desired functionality. In the strong coupling regime, the visibility of the Rabi splitting is described by the light-matter coupling constant g proportional to Q/√V, where Q is the quality factor and V is the mode volume. A high Q and a low V are thus desirable. The mode volume V can be minimized by reducing the pillar diameter. However, for the standard micropillar design, the poor mode matching between the cavity mode and the DBR Bloch mode limits the Q to about 2000. In our optimized design we have replaced the standard λ-spacer with a 3 segment tapered region. The layer thicknesses of these GaAs/AlAs segments are gradually reduced towards the center, effectively detuning the bandgap relative to that of the DBRs and allowing for a single localized mode inside the cavity. The fundamental Bloch mode experiences an adiabatic transition, leading to an improved mode matching and a reduced coupling to propagating Bloch modes in the DBRs. The
central GaAs layer incorporating quantum dots is only 60 nm thick corresponding to \( \approx \lambda/5 \), and regular cavity concepts are thus insufficient to explain the localization of the cavity mode, demonstrating the necessity of Bloch-wave formalism in the analysis of the design.

We compare our adiabatic design to a reference incorporating a \( \lambda \)-spacer. A theoretical improvement of \( Q \) of two orders of magnitude and an experimentally measured improvement of \( f \approx 5 \), limited by fabrication imperfections, are obtained. Thus our novel approach allows us to demonstrate remarkably high quality factors exceeding 10,000 for MP cavities with diameters below 1 \( \mu m \). [2]

Whereas previous studies of strong coupling in micropillars relied on quantum dots with high oscillator strengths \( f > 50 \), our advanced design allows for the observation of strong coupling for submicron diameter quantum dot-pillars with standard \( f \approx 10 \) oscillator strength. A quality factor of 13600 and a vacuum Rabi splitting of 85 \( \mu eV \) are observed for a small mode volume micropillar with a diameter of 850 nm.

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Linearly Polarized, Single-Mode Spontaneous Emission in a Photonic Nanowire
We introduce dielectric elliptical photonic nanowires to funnel efficiently the spontaneous emission of an embedded emitter into a single optical mode. Inside a wire with a moderate lateral aspect ratio, the electromagnetic environment is largely dominated by a single guided mode, with a linear polarization oriented along the ellipse major axis. The resulting monomode spontaneous emission is maintained over a broad wavelength range, a key asset of this 1D photonic structure. Our theoretical analysis is completed by an experimental study of GaAs elliptical photonic wires with embedded InAs quantum dots. In particular, the fraction of collected photons with the desired linear polarization can exceed 95%.

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Modeling of cavities using the analytic modal method and an open geometry formalism

We present an eigenmode expansion technique for calculating the properties of a dipole emitter inside a micropillar. We consider a solution domain of infinite extent, implying no outer boundary conditions for the electric field, and expand the field on analytic eigenmodes. In contrast to finite-sized simulation domains, this avoids the issue of parasitic reflections from artificial boundaries. We compute the Purcell factor in a two-dimensional micropillar and explore two discretization techniques for the continuous radiation modes. Specifically, an equidistant and a nonequidistant discretization are employed, and while both converge, only the nonequidistant discretization exhibits uniform convergence. These results demonstrate that the method leads to more accurate results than existing simulation techniques and constitutes a promising basis for further work.

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Web of Science (2011): Indexed yes
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BFI (2009): BFI-level 1
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Modeling of Coupled Nano-Cavity Lasers

Modeling of nanocavity light emitting semiconductor devices is done using the semiconductor laser rate equations with spontaneous and stimulated emission terms modified for Purcell enhanced recombination. The modified terms include details about the optical and electronic density-of-states and it is argued that Purcell enhancement should also be included in stimulated recombination term, contrary to the common practice in the literature. It is shown that for quantum well devices, the Purcell enhancement is effectively independent of the cavity quality factor due to the broad electronic density-of-states relative to the optical density-of-states. The low effective Purcell effect for quantum well devices limits the highest possible modulation bandwidth to a few tens of gigahertz, which is comparable to the performance of conventional diode lasers.

Compared to quantum well devices, quantum dot devices have narrower electronic density-of-states and are not affected by the reduction of the Purcell enhancement to the same degree. The highest modulation bandwidth is found for below threshold operation, where the bandwidth is not cavity-limited. Using finite-difference time-domain methods, systems of passive, coupled photonic crystal nanocavity structures are simulated. The resonance frequencies of in-phase and out-of-phase coupled quadrupole modes in rectangular photonic crystal H1 cavities are extracted and are found to vary non-trivially with the intercavity separation. A qualitative explanation is given in terms of the in-plane mode profiles. Farfield emission patterns for the structures are calculated based on the finite-difference time-domain simulations. It is found that only systems with an even number of holes separating the cavities show clear signs of being coupled. This non-trivial coupling behavior is useful for design of coupled systems.

A tight-binding description for coupled nanocavity lasers is developed and employed to investigate the phase-locking behavior for the system of two coupled cavities. Phase-locking is found to be critically dependent on exact parameter values and to be difficult to achieve for systems with large linewidth enhancement factors and low Purcell enhancement such as quantum well based lasers.

Realistic numbers for the coupling strength are extracted from finite-difference time-domain simulations.

Near-unity efficiency, single-photon sources based on tapered photonic nanowires

Single-photon emission from excitons in InAs Quantum Dots (QD) embedded in GaAs Tapered Photonic Wires (TPW) already demonstrated a 0.72 collection efficiency, with TPWs were the apex is the sharp end of the cone. Going to alternate designs, still based on the idea of the adiabatic deconfinement of the quasi-Gaussian emission mode, but with inverted TPW where the apex is the cone's base, leads to even larger efficiencies. In addition, these inverted TPWs make the electric pumping of the emitters compatible with these large efficiencies.
Photonic nanowires for quantum optics

Photonic nanowires (PWs) are simple dielectric structures for which a very efficient and broadband spontaneous emission (SE) control has been predicted [1]. Recently, a single photon source featuring a record high efficiency was demonstrated using this geometry [2]. Using time-resolved micro-photoluminescence, we investigate directly the SE of single InAs quantum dots (QDs) embedded in GaAs PWs and demonstrate performances that fully confirm the theoretical predictions [3]. In addition, we discuss recent results obtained on elliptical wires that ensure an efficient control of the photon polarization [4].

We first consider cylindrical PWs, defined within a top-down fabrication process. For diameters leading to the optimal confinement of the fundamental guided mode HE11 (d/\lambda~0.25, \lambda~950nm), the coupling to HE11 (2-time polarization degenerated) dominates the SE process and a maximum enhancement of the SE rate by a factor of 1.5 is reached. When the diameter is decreased by 100nm, the guided mode is completely deconfined. The coupling to this mode vanishes, thus allowing the coupling to the other radiation modes to be probed [3]. In these conditions, a SE inhibition factor of 16, equivalent to the one obtained in state-of-the-art 2D photonic crystals, is measured.

Moreover, a PW featuring an elliptical section provides a very efficient control over the polarization of the emitted photon. In that case, only one guided mode, with a linear polarization oriented along the major axis, is confined in the semiconductor. Polarization-resolved experiments show that the coupling to this single mode can exceed 95% for optimum structures [4]. These results confirm the high potential of PWs for the realization of efficient sources of quantum light.

Quantum-dot nano-cavity lasers with Purcell-enhanced stimulated emission

We present a rate equation model for quantum-dot light-emitting devices that take into account Purcell enhancement of both spontaneous emission and stimulated emission as well as the spectral profile of the optical and electronic density-of-states. We find that below threshold the b-factor in a quantum-dot nanolaser depends strongly on the pump. For quantum dots with linewidth comparable to that of the cavity, we then show that an otherwise non-lasing device can lase due to Purcell enhancement of the stimulated emission. Finally, we compare the rate equation model to a microscopic model and obtain good agreement.
Quantum optics with quantum dots in photonic nanowires

Besides microcavities and photonic crystals, photonic nanowires have recently emerged as a novel resource for solid-state quantum optics. We will review recent studies which demonstrate an excellent control over the spontaneous emission of InAs quantum dots (QDs) embedded in single-mode GaAs photonic wires. On the basic side, we have demonstrated a strong inhibition (x 1/16) of QD SpE in thin wires (d0.95 for d~λ/n), and polarization control in elliptical nanowires. A single QD in a photonic wire is thus an attractive system to explore the physics of the "one-dimensional atom" and build novel quantum optoelectronic devices. Quite amazingly, this approach has for instance permitted (unlike microcavity-based approaches) to combine for the first time a record-high efficiency (72%) and a negligible g(2) in a QD single photon source.

General information
State: Published
Organisations: Department of Photonics Engineering, Nanophotonics Theory and Signal Processing, CNRS, Universite Paris-Sud
Contributors: Claudon, J., Munsch, M., Bleuse, J., Lalanne, P., Gregersen, N., Gerard, J.
Pages: 82681J
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Web of Science (2017): Indexed yes
BFI (2016): BFI-level 1
Scopus rating (2016): CiteScore 0.42 SJR 0.226 SNIP 0.258
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 1
Scopus rating (2015): CiteScore 0.3 SJR 0.212 SNIP 0.239
Quantum Optics with Quantum Dots in Photonic Nanowires
We review recent experimental and theoretical results, which highlight the strong interest of the photonic wire geometry for solid-state quantum optics and quantum optoelectronic devices.

General information
State: Published
Organisations: Department of Photonics Engineering, Nanophotonics Theory and Signal Processing, CNRS, Laboratoire Charles Fabry de l’Institut d’Optique
Contributors: Gérard, J. M., Claudon, J., Bleuse, J., Munsch, M., Gregersen, N., Lalanne, P. ...
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Publication date: 2012

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This paper was published in CLEO Technical Digest and is made available as an electronic reprint with the permission of OSA. The paper can be found at the following URL on the OSA website: http://www.opticsinfobase.org/abstract.cfm?URI=CLEO:%20S%20and%20I-2012-CTh3M.1. Systematic or multiple reproduction or distribution to multiple locations via electronic or other means is prohibited and is subject to penalties under law.
Recent Advances for High-Efficiency Sources of Single Photons Based on Photonic Nanowires

Photonic nanowires have recently been used to tailor the spontaneous emission of embedded quantum dots, and to develop record efficiency single-photon sources. We will present recent developments in this field mainly 1) the observation of a strong inhibition of the spontaneous emission of quantum dots in ultrathin photonic wires 2) the control of the linear polarization of the single photons by photonic wires with an elliptical section, 3) the joint observation (unlike-cavity-based devices) of a record high efficiency and pure single photon emission process in a photonic wire single photon source, 4) progress toward high-efficiency electrical-driven sources.

General information
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Organisations: Department of Photonics Engineering, Nanophotonics Theory and Signal Processing, Universite Paris-Sud
Contributors: Gerard, J. M., Claudon, J., Munsch, M., Bleuse, J., Gregersen, N.
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DOIs: 10.1109/ICTON.2012.6253783
Source: dtu
Source-ID: n::oai:DTIC-ART:compendex/371443832::20235
Research output: Research - peer-review › Article in proceedings – Annual report year: 2012

A High-Efficiency Photonic Nanowire Single-Photon Source Featuring An Inverted Conical Taper

A photonic nanowire single-photon source design incorporating an inverted conical tapering is proposed. The inverted taper allows for easy electrical contacting and a high photon extraction efficiency of 89 %. Unlike cavity-based approaches, the photonic nanowire features broadband spontaneous emission control and an improved tolerance towards fabrication imperfections.

General information
State: Published
Organisations: Nanophotonics Theory and Signal Processing, Department of Photonics Engineering, CNRS
Contributors: Gregersen, N., Nielsen, T. R., Mørk, J., Claudon, J., Gérard, J.
Pages: 5-6
Publication date: 2011

Host publication information
Title of host publication: 2011 11th International Conference on Numerical Simulation of Optoelectronic Devices (NUSOD)
ISBN (Print): 978-1-61284-876-1
Keywords: Inverted conical tapering, Electrical pumping, Single-photon source, Photonic nanowire
Electronic versions:
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DOIs: 10.1109/NUSOD.2011.6041136
URLs: http://www.nusod.org/2011/
Source: orbit
Source-ID: 283022
Research output: Research - peer-review › Conference abstract in proceedings – Annual report year: 2012

An Electrically Driven Single Photon Source

General information
**Bloch-Wave Engineered Submicron Diameter Micropillars with Quality Factors Exceeding 10,000**

Adiabatic design submicron diameter quantum-dot micropillars have been designed and implemented for cavity quantum electrodynamics experiments. Ultra-high experimental quality factors (>10,000) are obtained for submicron diameters and strong light-matter interaction is observed.

**General information**

State: Published
Organisations: Nanophotonics Theory and Signal Processing, Department of Photonics Engineering, University of Würzburg
Pages: 69-70
Publication date: 2011

**Host publication information**

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DOIs: 10.1109/PHO.2011.6110429

**Bibliographical note**

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Source: orbit
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**Design for an Electrically-Pumped Photonic Nanowire Single-Photon Source with an Efficiency of 89 %**

We propose an electrically-pumped singlephoton source design based on a photonic nanowire. For realistic geometrical parameters, a collection efficiency of 89 % is predicted. Initial fabrication results confirming the feasibility of the design are presented.

**General information**

State: Published
Organisations: Nanophotonics Theory and Signal Processing, Department of Photonics Engineering, CNRS
Contributors: Gregersen, N., Nielsen, T. R., Mørk, J., Claudon, J., Gérard, J.
Pages: CK6.3
Publication date: 2011

**Host publication information**

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Publisher: IEEE
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URLs: http://www.cleoeurope.org/
Source: orbit
Source-ID: 277447
Efficient and broadband control of the spontaneous emission in photonic nanowires

General information
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Organisations: Nanophotonics Theory and Signal Processing, Department of Photonics Engineering, CNRS, Université Paris-Sud
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URLs:
http://www.oecs12.org/OECS12/Home.html
Source: orbit
Source-ID: 283650
Research output: Research - peer-review › Conference abstract for conference – Annual report year: 2011

Electrically pumped photonic nanowire single-photon source with an efficiency of 89%
We propose a new electrically-pumped single-photon source design based on a quantum dot in a photonic nanowire. For realistic parameters, the design features an efficiency of 89% predicted by numerical simulations. Unlike cavity-based designs, our approach allows for broadband spontaneous emission control and has high tolerance towards surface roughness. In the nanowire, a geometrical effect ensures good coupling between the quantum dot and the optical mode, and an inverted tapering section is introduced to adiabatically expand the mode waist and control the far field emission profile while minimizing the relative modal overlap with the metal contacts.

General information
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Organisations: Nanophotonics Theory and Signal Processing, Department of Photonics Engineering, CNRS
Contributors: Gregersen, N., Nielsen, T. R., Mørk, J., Claudon, J., Gérard, J.
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Peer-reviewed: Yes

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BFI (2017): BFI-level 1
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BFI (2016): BFI-level 1
Scopus rating (2016): CiteScore 0.42 SJR 0.226 SNIP 0.258
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 1
Scopus rating (2015): CiteScore 0.3 SJR 0.212 SNIP 0.239
BFI (2014): BFI-level 1
Scopus rating (2014): CiteScore 0.3 SJR 0.217 SNIP 0.249
BFI (2013): BFI-level 1
Scopus rating (2013): CiteScore 0.26 SJR 0.234 SNIP 0.273
ISI indexed (2013): ISI indexed no
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 1
Scopus rating (2012): CiteScore 0.27 SJR 0.219 SNIP 0.275
ISI indexed (2012): ISI indexed no
Finite element modeling of plasmon based single-photon sources

A finite element method (FEM) approach of calculating a single emitter coupled to plasmonic waveguides has been developed. The method consists of a 2D model and a 3D model: (I) In the 2D model, we have calculated the spontaneous emission decay rate of a single emitter into guided plasmonic modes by using the translation symmetry of the waveguides; (II) In the 3D model, we have implemented the FEM calculation to include the radiation modes and the nonradiative contributions by solving the wave equation with a harmonic source terms. The FEM approach is rather flexible, and can handle the plasmonic waveguides with different geometries, as long as only one guided plasmonic mode is predominantly excited.

Modulation response of quantum dot nano-LEDs and nano-lasers

NanoLEDs and nanolasers are light emitting devices with characteristic length scales comparable to the wavelength of the emitted light. They are expected to operate at significantly lower powers and higher speeds than their conventional counterparts, which makes them interesting candidates for light emitters in ultrahigh speed optical communication. This is mainly due to the Purcell effect, which increases the spontaneous emission into the nanocavity mode. Early investigations of nanoscale light emitters [1,2] suggest modulation speeds in excess of 100 GHz, however, more work is needed to fully understand the limits and possibilities of these devices.
The modulation bandwidth for a quantum dot light-emitting device is calculated using a detailed model for the spontaneous emission including the optical and electronic density-of-states. We show that the Purcell enhancement of the spontaneous emission rate depends critically on the degree of inhomogeneous broadening relative to the cavity linewidth and can improve the modulation speed only within certain parameter regimes.

Modulation response of quantum dot nanolight-emitting-diodes exploiting purcell-enhanced spontaneous emission
Quantum Dots in Tapered Photonic Wires: towards Unit-Efficiency Single-Photon Sources

General information
State: Published
Organisations: Nanophotonics Theory and Signal Processing, Department of Photonics Engineering, CNRS, Universite Paris-Sud
Contributors: Claudon, J., Bleuse, J., Malik, N. S., Gregersen, N., Sauvan, C., Lalanne, P., Gerard, J.
Publication date: 2011
Peer-reviewed: Yes
URLs:
Source: orbit
Source-ID: 278345
Research output: Research - peer-review » Conference abstract for conference – Annual report year: 2011

Quantum Optics with Quantum Dots in Photonic Nanowires
We review recent studies performed on InAs quantum dots embedded in GaAs photonic wires, which highlight the strong interest of the photonic wire geometry for quantum optics experiments and quantum optoelectronic devices.

General information
State: Published
Organisations: Department of Photonics Engineering, Nanophotonics Theory and Signal Processing, French Alternative Energies and Atomic Energy Commission, Laboratoire Charles Fabry de l'Institut d'Optique
Contributors: Gérard, J., Claudon, J., Bleuse, J., Singh, N., Gregersen, N., Lalanne, P.
Pages: EI4.1
Publication date: 2011

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Title of host publication: 2011 Conference on and 12th European Quantum Electronics Conference Lasers and Electro-Optics Europe (CLEO EUROPE/EQEC)
Publisher: IEEE
DOIs:
10.1109/CLEOE.2011.5943588
URLs:
http://www.cleoeurope.org/
Source: orbit
Source-ID: 277449
Research output: Research - peer-review » Article in proceedings – Annual report year: 2011

Quantum Optics with Quantum Dots in Photonic Wires: Basics and Application to "Ultrabright" Single Photon Sources
We review recent experimental and theoretical results, which highlight the strong interest of the photonic wire (PW) geometry for quantum optics experiments with solid-state emitters, and for quantum optoelectronic devices. By studying single InAs QDs embedded within single-mode cylindrical GaAs PW, we have noticeably observed a very strong (16 fold) inhibition of their spontaneous emission rate in the thin-wire limit, and a nearly perfect funnelling of their spontaneous emission into the guided mode for larger PWs. We present a novel single-photon-source based on the emission of a quantum dot embedded in an engineered PW, comprising a tapered tip so as to control the radiation pattern, and an integrated hybrid bottom mirror. Unlike microcavity-based devices, this source displays for the first time simultaneously a record-high efficiency (0.73 photon per pulse) and a very low g(2) parameter. Numerical simulations show that an efficiency higher than 0.9 can be obtained for optimized structures, under either optical or electrical pumping.

General information
State: Published
Organisations: Nanophotonics Theory and Signal Processing, Department of Photonics Engineering, Universite Paris-Sud
Contributors: Gérard, J. M., Claudon, J., Bleuse, J., Malik, N. S., Munsch, M., Dupuy, E., Lalanne, P., Gregersen, N.
Pages: Mo.B5.4
Publication date: 2011

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Publisher: IEEE
ISBN (Print): 978-1-4577-0881-7
ISBN (Electronic): 978-1-4577-0880-0
Modeling of plasmon mediated single-photon devices
The thesis describes the theoretical study of optical plasmons mediated light-matter interaction. We develop a finite element method to study spontaneous emission from emitters coupled to plasmonic waveguides. The numerical method is applied to calculate the coupling of a emitter coupled to a cylindrical nanowire, a square metallic nanowire and a metallic slot waveguide with inhomogenous dielectric environment. We also examine a quantum emitter coupled to optical nanoantennas. We mimic the conventional Yagi-Uda to realize its optical analogy for directional emission. We also propose a plasmon-based reconfigurable antenna to controllably distribute emission from a single emitter in spatially separated channels.

General information
State: Published
Organisations: Nanophotonics Theory and Signal Processing, Department of Photonics Engineering, Quantum Photonics
Contributors: Chen, Y., Mørk, J., Gregersen, N., Nielsen, T. R., Lodahl, P.
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Source: orbit
Source-ID: 268652
Research output: Research - peer-review › Article in proceedings – Annual report year: 2011

A high-efficiency electrically-pumped single-photon source based on a photonic nanowire
An electrically-pumped single-photon source design with a predicted efficiency of 89% is proposed. The design is based on a quantum dot embedded in a photonic nanowire with tailored ends and optimized contact electrodes. Unlike cavity-based approaches, the photonic nanowire features broadband spontaneous emission control and an improved tolerance towards fabrication imperfections. The various building blocks of the design are analyzed using an elements-splitting approach.

General information
State: Published
Organisations: Nanophotonics Theory and Signal Processing, Department of Photonics Engineering, French Alternative Energies and Atomic Energy Commission
Contributors: Gregersen, N., Nielsen, T. R., Mørk, J., Claudon, J., Gérard, J.
Publication date: 2010
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Source-ID: 269127
Research output: Research - peer-review › Paper – Annual report year: 2010

A highly efficient single-photon source based on a quantum dot in a photonic nanowire

General information
State: Published
Organisations: Nanophotonics Theory and Signal Processing, Department of Photonics Engineering, French Alternative Energies and Atomic Energy Commission, Universite Paris-Sud
A highly efficient single-photon source based on a quantum dot in a photonic nanowire

The development of efficient solid-state sources of single photons is a major challenge in the context of quantum communication, optical quantum information processing and metrology. Such a source must enable the implementation of a stable, single-photon emitter, like a colour centre in diamond or a semiconductor quantum dot. Achieving a high extraction efficiency has long been recognized as a major issue, and both classical solutions and cavity quantum electrodynamics effects have been applied. We adopt a different approach, based on an InAs quantum dot embedded in a GaAs photonic nanowire with carefully tailored ends. Under optical pumping, we demonstrate a record source efficiency of 0.72, combined with pure single-photon emission. This non-resonant approach also provides broadband spontaneous emission control, thus offering appealing novel opportunities for the development of single-photon sources based on spectrally broad emitters, wavelength-tunable sources or efficient sources of entangled photon pairs.
A highly efficient single-photon source based on a quantum dot in a photonic nanowire

General information
State: Published
Organisations: Nanophotonics Theory and Signal Processing, Department of Photonics Engineering, French Alternative Energies and Atomic Energy Commission, Laboratoire Charles Fabry de l'Institut d'Optique

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Source-ID: 258920
Research output: Research - peer-review › Journal article – Annual report year: 2010

10.1038/nphoton.2009.287
URLs:
Designs for high-efficiency electrically pumped photonic nanowire single-photon sources

We propose and analyze three electrically-pumped nanowire single-photon source structures, which achieve output efficiencies of more than 80%. These structures are based on a quantum dot embedded in a photonic nanowire with carefully tailored ends and optimized contact electrodes. Contrary to conventional cavity-based sources, this non-resonant approach provides broadband spontaneous emission control and features an improved fabrication tolerance towards surface roughness and imperfections. Using an element-splitting approach, we analyze the various building blocks of the designs with respect to realistic variations of the experimental fabrication parameters.
Finite-element modeling of spontaneous emission of a quantum emitter at nanoscale proximity to plasmonic waveguides

We develop a self-consistent finite-element method to quantitatively study spontaneous emission from emitters in nanoscale proximity of plasmonic waveguides. In the model, it is assumed that only one guided mode is dominantly excited by the quantum emitter, while the cross section of the plasmonic waveguide can be arbitrary. The fraction of the energy coupled to the plasmonic mode can be calculated exactly, which can be used to determine the efficiency with which single optical plasmons are generated. We apply our numerical method to calculate the coupling of a quantum emitter to a cylindrical metallic nanowire and a square metallic waveguide, and compare the cylindrical metallic nanowire with previous work that employs quasistatic approximation. For the cylindrical metallic nanowire we observe good agreement with the quasistatic approximation for radii below 10 nm, but for increasing radius the spontaneous emission $\beta$ factor and the plasmonic decay rate deviate substantially, by factors of up to 5–10 for a radius of $\sim$100 nm, from the values obtained in the quasistatic approximation. We also show that the quasistatic approximation is typically valid when the radius is less than the skin depth of the metals at optical frequencies. For the square metallic waveguide we estimate an optimized value for the spontaneous emission $\beta$ factor up to 80%.

General information
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Organisations: Nanophotonics Theory and Signal Processing, Department of Photonics Engineering, Quantum Photonics
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Publication information
Journal: Physical Review B Condensed Matter
Volume: 81
Issue number: 12
ISSN (Print): 0163-1829
Ratings:
Modeling of mode-locked coupled-resonator optical waveguide lasers

Coupled-resonator optical waveguides made from coupled high-Q photonic crystal nanocavities are investigated for use as cavities in mode-locked lasers. Such devices show great potential in slowing down light and can serve to reduce the cavity length of a mode-locked laser. An explicit expression for the cold-cavity transmission spectrum is derived and used to interpret numerical investigations performed to characterize the parameter regime of active mode-locked operation. It is found that the modulation frequency relative to the centerband nearest supermode (SM) frequency shift determines the quality of the emerging pulse train. A range of tuning around this frequency allows for effective mode locking. Finally, noise is added to the generalized single-cavity eigenfrequencies in order to evaluate the effects of fabrication imperfections on the cold-cavity transmission properties and consequently on the locking of SMs.
Modulation response of nanoLEDs and nanolasers exploiting Purcell enhanced spontaneous emission

The modulation bandwidth of quantum well nanoLED and nanolaser devices is calculated from the laser rate equations using a detailed model for the Purcell enhanced spontaneous emission. It is found that the Purcell enhancement saturates when the cavity quality-factor is increased, which limits the maximum achievable spontaneous recombination rate. The modulation bandwidth is thereby limited to a few tens of GHz for realistic devices.

General information
State: Published
Organisations: Nanophotonics Theory and Signal Processing, Department of Photonics Engineering, Nanophotonic Devices
Contributors: Skovgård, T. S., Gregersen, N., Yvind, K., Mørk, J.
Pages: 11230-11241
Publication date: 2010
Peer-reviewed: Yes

Publication information
Journal: Optics Express
Volume: 18
Numerical and Experimental Study of the Q Factor of High-Q Micropillar Cavities

Micropillar cavities are potential candidates for high-efficiency single-photon sources and are testbeds for cavity quantum electrodynamics experiments. In both applications a high quality (Q) factor is desired. It was recently shown that the Q of high-Q semiconductor micropillar cavities exhibit pronounced quasi-periodic variations in the regime from 1 to 4 μm, and a detailed understanding of the variational behavior of the Q is required. Here, we study the origin of these variations using a multi-mode Fabry-Perot model appropriate for this regime. We analyze in detail contributions to the effective reflectivity of the fundamental mode arising from coupling to scattering channels involving higher-order cavity modes and propagating Bloch modes in the distributed Bragg reflectors (DBRs). We show how these weak contributions lead to strong variations of the Q factor, and we relate the average periodicity of these variations to the thickness of the DBRs and the derivative of the effective indices of the guided Bloch modes. We also examine the influence of various geometrical parameters, including the number of DBR layers pairs, the amplitude of the corrugation of the pillar sidewalls and the number of etched layer pairs in the bottom DBR on the Q versus diameter relation. Comparisons are made between extensive numerical simulations and experimental measurements, and a good qualitative agreement is found.

**General information**

State: Published
Organisations: Nanophotonics Theory and Signal Processing, Department of Photonics Engineering
Pages: 1470-1483
Publication date: 2010
Peer-reviewed: Yes

**Publication information**

Journal: IEEE Journal of Quantum Electronics
Volume: 46
Issue number: 10
ISSN (Print): 0018-9197
Ratings:
- BFI (2018): BFI-level 2
- Web of Science (2018): Indexed yes
- BFI (2017): BFI-level 2
- Scopus rating (2017): CiteScore 1.79 SJR 0.65 SNIP 0.891
- Web of Science (2017): Impact factor 2.069
- Web of Science (2017): Indexed yes
- BFI (2016): BFI-level 2
- Scopus rating (2016): CiteScore 1.74 SJR 0.723 SNIP 1.071
- Web of Science (2016): Impact factor 1.852
- BFI (2015): BFI-level 2
- Scopus rating (2015): CiteScore 1.99 SJR 0.968 SNIP 1.162
Spontaneous decay of a single quantum dot coupled to a metallic slot waveguide in the presence of leaky plasmonic modes

We numerically investigate the coupling efficiency of a single self-assembled quantum dot to a metallic slot waveguide in the presence of leaky plasmonic modes. Leaky plasmonic modes refer to radiation modes with plasmonic features, resulting from the inhomogeneity of the electric environment in which the metallic slot waveguide is embedded. Compared
to the ideal case of a homogenous dielectric environment, the coupling efficiency of an emitter to a metallic slot waveguide is significantly reduced. We attribute the reduction to the coupling to leaky plasmonic modes. By increasing the refractive index of the coating layer to minimize the impacts from the leaky plasmonic modes, we find that the coupling efficiency of the quantum dot to the single mode supported by the metallic slot waveguide can be enhanced by more than a factor 2.
Une source de photons uniques efficace basée sur une boîte quantique intégrée dans un fil photonique

General information
State: Published
Organisations: Nanophotonics Theory and Signal Processing, Department of Photonics Engineering, French Alternative Energies and Atomic Energy Commission, Laboratoire Charles Fabry de l'Institut d'Optique
Publication date: 2010

Event information
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Location: Troyes, France
Source: orbit
Source-ID: 270523
Research output: Research › Sound/Visual production (digital) – Annual report year: 2010

A highly efficient monomode single photon source in the photonic wire geometry

General information
State: Published
Organisations: Nanophotonics Theory and Signal Processing, Department of Photonics Engineering
High brightness single photon sources based on photonic wires

We present a novel single-photon-source based on the emission of a semiconductor quantum dot embedded in a single-mode photonic wire. This geometry ensures a very large coupling (> 95%) of the spontaneous emission to the guided mode. Numerical simulations show that a photon collection efficiency as large as 90% can be obtained for engineered nanowires with a tapered tip and a metallic bottom mirror coated by a thin dielectric layer. Experimentally, a record-high efficiency of 75 ± 10% (for a NA = 0.75 collection optics) has been measured for an InAs quantum dot embedded in such a nanowire, made of GaAs and defined by reactive-ion etching.

General information
State: Published
Organisations: Nanophotonics Theory and Signal Processing, Department of Photonics Engineering, CNRS, Universite Paris-Sud
Pages: We.A4.2
Publication date: 2009

High-efficiency single-photon source: The photonic wire geometry

We present a single-photon-source design based on the emission of a quantum dot embedded in a semiconductor (GaAs) nanowire. The nanowire ends are engineered (efficient metallic mirror and tip taper) to reach a predicted record-high collection efficiency of 90% with a realistic design. Preliminary experimental results already show a measured efficiency of 44%.

General information
State: Published
Organisations: Nanophotonics Theory and Signal Processing, Department of Photonics Engineering, CNRS, Universite Paris-Sud
Pages: ITuM1
Publication date: 2009

Nonlinear dynamics in photonic crystal nanocavity lasers

We model coupled nanolasers by adding phase-dependent coupling terms to the Purcell-enhanced laser rate equations. Transitions between phase-locking and complex oscillatory behavior are observed at critical coupling strengths in detuned two-laser systems.

General information
Optimizing the spontaneous-emission β factor for single optical plasmon generation

In applications like quantum cryptography and quantum computation, it is desirable to obtain single photon sources which can produce a train of single photons on demand at a high repetition rate, especially at or near room temperature. Such single-photon sources can be realized by tailoring the photonic environment of the quantum emitter. The photonic environment determines the local density of states, into which the photon can be emitted. A number of structures such as interfaces, cavities and waveguides have already been used to modify the spontaneous emission (SE) rate; nevertheless there is still room for improving the overall efficiency of the single-photon sources, e.g., by inventing new ways of enhancing light-matter interaction.

Oscillatory variations in the Q factors of high quality micropillar cavities

We report on the observation of oscillatory variations in the quality Q factor of quantum dot-micropillar cavities based on planar Bragg reflectors. The oscillatory behavior in the Q versus diameter dependence appears in the diameter range between 1.0 and 4.0 μm, has a characteristic period of a few hundred nanometers and increases in amplitude with increasing reflectivity of the planar microcavity structures. The experimental results are well reproduced by numerical calculations which support the interpretation that the Q oscillations are caused by coupling of propagating Bloch modes of different orders at the mirror interfaces.
Quantitative analysis of oscillatory variations in the quality factor of micropillar cavities

The influence of the pillar radius on the Q factor of a micropillar cavity is investigated numerically. The relation between Q factor and pillar radius shows an advanced oscillatory behavior which cannot be explained in a 1D model. We propose a multi-mode Fabry-Perot model to quantify the oscillation period observed and we show that the governing mechanism behind the oscillation is coupling to higher-order propagating Bloch modes in the distributed Bragg reflectors. We demonstrate that even though the Q factor is an advanced function involving many oscillating contributions, the model still allows for the determination of a characteristic oscillation period.

General information
State: Published
Organisations: Nanophotonics Theory and Signal Processing, Department of Photonics Engineering
Contributors: Gregersen, N., Nielsen, T. R., Mørk, J.
Pages: 115-117
Publication date: 2009

Host publication information
Title of host publication: Conference proceedings, TaCoNa-Photonics
Publisher: American Institute of Physics
Keywords: Q factor, Micropillar, Bloch modes, resonator, optical microcavity
Source: orbit
Source-ID: 252354
Research output: Research - peer-review › Article in proceedings – Annual report year: 2009
Controlling the emission profile of a nanowire with a conical taper

The influence of a tapering on nanowire light-emission profiles is studied. We show that, for nanowires with divergent output beams, the introduction of a conical tapering with a small opening angle reduces the beam divergence and increases transmission. This results in a dramatic increase in the collection efficiency of the detection optics. For a realistic tapering and a modest NA, the collection efficiency is enhanced by more than a factor of 2. This improvement is ensured by the adiabatic expansion of the guided mode in the tapering.

General information
State: Published
Organisations: Nanophotonics Theory and Signal Processing, Department of Photonics Engineering
Pages: 1693-1695
Publication date: 1 Aug 2008
Peer-reviewed: Yes

Publication information
Journal: Optics Letters
Volume: 33
Issue number: 15
ISSN (Print): 0146-9592
Ratings:
BFI (2018): BFI-level 2
Web of Science (2018): Indexed yes
BFI (2017): BFI-level 2
Scopus rating (2017): CiteScore 3.89 SJR 1.79 SNIP 1.597
Web of Science (2017): Impact factor 3.589
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 2
Scopus rating (2016): CiteScore 3.54 SJR 1.769 SNIP 1.549
Web of Science (2016): Impact factor 3.416
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 2
Scopus rating (2015): CiteScore 3.53 SJR 2.013 SNIP 1.53
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 2
Scopus rating (2014): CiteScore 3.86 SJR 2.429 SNIP 1.997
Web of Science (2014): Impact factor 3.292
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 2
Scopus rating (2013): CiteScore 3.95 SJR 2.441 SNIP 2.058
An improved perfectly matched layer for the eigenmode expansion technique

When performing optical simulations for rotationally symmetric geometries using the eigenmode expansion technique, it is necessary to place the geometry under investigation inside a cylinder with perfectly conducting walls. The parasitic reflections at the boundary of the computational domain can be suppressed by introducing a perfectly matched layer (PML) using e.g. complex coordinate stretching of the cylinder radius. However, the traditional PML suffers from an artificial field divergence limiting its usefulness. We show that the choice of a constant cylinder radius leads to mode profiles with exponentially increasing field amplitudes resulting in numerical instability. As a remedy we propose an improved PML based on a mode-dependent cylinder radius and mode profiles with stable field amplitudes. The new PML formulation eliminates the artificial field divergence and ensures numerical stability.
An improved perfectly matched layer in the eigenmode expansion technique

When employing the eigenmode expansion technique (EET), parasitic reflections at the boundary of the computational domain can be suppressed by introducing a perfectly matched layer (PML). However, the traditional PML, suffers from an artificial field divergence limiting its usefulness. We propose a remedy.

A novel high-efficiency single-mode quantum dot single photon source

We present a novel single-mode single photon source exploiting the emission of a semiconductor quantum dot (QD) located inside a photonic wire. Besides an excellent coupling (>95%) of QD spontaneous emission to the fundamental guided mode [1], we show that a single photon collection efficiency above 80% within a 0.5 numerical aperture can be achieved using a bottom Bragg mirror and a tapering of the nanowire tip. Because this photon collection strategy does not exploit the Purcell effect, it could also be efficiently applied to broadband single photon emitters such as F-centers in diamond.
Controlling nanowire emission profile using conical taper
The influence of a conical taper on nanowire light emission is studied. For nanowires with divergent output beams, the introduction of tapers improves the emission profile and increase the collection efficiency of the detection optics.

General information
State: Published
Organisations: Nanophotonics Theory and Signal Processing, Department of Photonics Engineering
Contributors: Gregersen, N., Nielsen, T. R., Mørk, J., Claudon, J., Gerard, J.
Pages: ITuB2
Publication date: 2008

Host publication information
Title of host publication: Integrated Photonics and Nanophotonics Research and Applications
Place of publication: Boston, Massachusetts, USA
Publisher: Optical Society of America
Source: orbit
Source-ID: 220532
Research output: Research - peer-review › Article in proceedings – Annual report year: 2008

Controlling the emission profile of a nanowire with a conical taper

General information
State: Published
Organisations: Nanophotonics Theory and Signal Processing, Department of Photonics Engineering
Contributors: Gregersen, N., Nielsen, T. R., Mørk, J., Claudon, J., Gerard, J.
Publication date: 2008
Peer-reviewed: Yes
Event: Poster session presented at Danish Optical Society/Danish Physical Society annual meeting 2008, Nyborg, Denmark.
Source: orbit
Source-ID: 228445
Research output: Research - peer-review › Poster – Annual report year: 2008

Optical methods for characterization of surface structures on a nanometer scale
When studying a sample with subwavelength features using conventional microscopy, the diffraction limit sets a lower bound to the resolution achievable. In this work the possibility of circumventing the diffraction limit by employing a scanning near-field optical microscope (SNOM) to perform the characterization is investigated. Experimental SNOM images of the optical field distribution above a deep grating are analyzed with the purpose of identifying the grating topography, and transfer functions describing the coupling of the free-space field to the guided mode of the SNOM fiber are determined numerically.

General information
State: Published
Organisations: Nanophotonics, Department of Photonics Engineering, Optical Sensor Technology, Nanophotonics Theory and Signal Processing
Contributors: Gregersen, N., Hanson, S. G., Mørk, J., Tromborg, B.
Publication date: Mar 2007

Publication information
Original language: English
Electronic versions:
Gregersen 06 Optical methods for characterization of surface structures on a nanometer scale v4.pdf
Source: orbit
Source-ID: 197558
Research output: Research › Ph.D. thesis – Annual report year: 2007

Influence of geometry on the quality factor of a micro pillar

General information
State: Published
Organisations: Nanophotonics, Department of Photonics Engineering
Contributors: Gregersen, N., Nielsen, T. R., Mørk, J.
Number of pages: 1
Publication date: 2007
Influence of geometry on the quality factor of a micro-pillar

General information
State: Published
Organisations: Nanophotonics, Department of Photonics Engineering
Contributors: Gregersen, N., Nielsen, T. R., Mørk, J.
Publication date: 2007
Peer-reviewed: Yes
Source: orbit
Source-ID: 209849
Research output: Research - peer-review › Poster – Annual report year: 2007

Modelling Q-factors of micro pillars
The influence of fabrication induced imperfections on quality factors for a microcavity pillar is studied numerically. The dependence on side-wall inclination and etch variations is quantified.

General information
State: Published
Organisations: Nanophotonics, Department of Photonics Engineering
Contributors: Nielsen, T. R., Gregersen, N., Tromborg, B., Mørk, J.
Publication date: 2007

Host publication information
Title of host publication: 9th International Conference on Transparent Optical Networks, 2007. ICTON '07.
Publisher: IEEE
ISBN (Print): 1-4244-1249-8
Electronic versions:
Nielsen.pdf
DOIs:
10.1109/ICTON.2007.4296176

Bibliographical note
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Source: orbit
Source-ID: 209793
Research output: Research - peer-review › Article in proceedings – Annual report year: 2007

Quality factors of nonideal micro pillars
The influence of fabrication-induced imperfections and material absorption on the quality (Q) factor of a microcavity pillar is studied numerically. The dependence on sidewall inclination, selective underetch, and intrinsic loss is quantified. The authors show that imperfections can lead to an improvement in Q and that a sidewall inclination angle of less than 1° causes a dramatic change in the Q factor. The variations in Q can be attributed to a delicate balance between effective index contrasts, mode overlap, and higher-order mode contributions.

General information
State: Published
Organisations: Nanophotonics Theory and Signal Processing, Department of Photonics Engineering
Contributors: Gregersen, N., Nielsen, T. R., Tromborg, B., Mørk, J.
Pages: 011116
Publication date: 2007
Peer-reviewed: Yes
Quality factors of nonideal micro pillars

General information
State: Published
Organisations: Nanophotonics Theory and Signal Processing, Department of Photonics Engineering
Contributors: Nielsen, T. R., Gregersen, N., Tromborg, B., Mørk, J.
PUBLICATION DATE: 2007

Host publication information
Title of host publication: Integrated photonics and nanophotonics research and applications
Place of publication: Salt Lake City, USA
Source: orbit
Source-ID: 209789
Research output: Research - peer-review | Article in proceedings | Annual report year: 2007

Topography characterization of a deep grating using near-field imaging

Using near-field optical microscopy at the wavelength of 633 nm, we image light intensity distributions at several distances above an ~2-mm deep and a 1-mm-period glass grating illuminated from below under the condition of total internal reflection. The intensity distributions are numerically modeled, and an inversion procedure based on a least-squares-fit optimization is employed to extract the grating geometry from the optical images.

General information
State: Published
Organisations: Nanophotonics, Department of Photonics Engineering, Center for Nanoteknologi, Aalborg University, Ibsen Photonics A/S
Contributors: Gregersen, N., Tromborg, B., Volkov, V. S., Bozhevolnyi, S. I., Holm, J.
Pages: 117-121
Publication date: 2006
Peer-reviewed: Yes

Publication information
Journal: Applied Optics
Volume: 45
Transfer function and near-field detection of evanescent waves

We consider characterization of a near-field optical probe in terms of detection efficiency of different spatial frequencies associated with propagating and evanescent field components. The former are both detected with and radiated from an etched single-mode fibertip, showing reciprocity of collection and illumination modes. Making use of a collection near-field microscope with a similar fiber tip illuminated by an evanescent field, we measure the collected power as a function of the field spatial frequency in different polarization configurations. Considering a two-dimensional probe configuration, numerical simulations of detection efficiency based on the eigenmode expansion technique are carried out for different tip apex angles. The detection roll-off for high spatial frequencies observed in the experiment and obtained during the simulations is fitted using a simple expression for the transfer function, which is derived by introducing an effective pointof (dipolelike) detection inside the probe tip. It is found to be possible to fit reasonably well both the experimental and the simulation data for evanescent field components, implying that the developed approximation of the near-field transfer function can serve as a simple, rational, and sufficiently reliable means of fiber probe characterization.
Vectorial modeling of near-field imaging with uncoated fiber probes: Transfer function and resolving power

General information
State: Published
Organisations: Nanophotonics, Department of Photonics Engineering
Contributors: Gregersen, N., Tromborg, B., Bozhevolnyi, S.
Pages: 8739-8747
Publication date: 2006
Peer-reviewed: Yes
Vectorial modeling of transfer functions of fiber tips in collection mode SNOM

General information
State: Published
Organisations: Nanophotonics, Department of Photonics Engineering, Center for Nanoteknologi
Contributors: Gregersen, N., Tromborg, B.
Publication date: 2006
Peer-reviewed: Yes
Event: Poster session presented at International Conference on Near-field Optics, Nanophotonics and Related Techniques, Lausanne, Switzerland.
Source: orbit
Source-ID: 191228
Research output: Research - peer-review › Poster – Annual report year: 2006

Study of Photosensitivity as a Function of Polarization for UV-Light in Optical Fibre using Blue Luminescence
The difference in photosensitivity between S and P polarized light is investigated. Polarisation dependent scattering at the fibre-air surface and UV-induced alignment are shown to be of no importance, but indications of radially parasitic defects sites are found.

General information
State: Published
Organisations: Nanophotonics, Department of Photonics Engineering
Contributors: Sørensen, H. R., Canning, J., Gregersen, N., Kristensen, M.
Pages: 152-154
Publication date: 2005

Host publication information
Title of host publication: Bragg Gratings, Poling and Photosensitivity (BGPP/ACOFT 2005)
Volume: Conference CD-ROM
ISBN (Print): 18-77-04033-9
Source: orbit
Source-ID: 181896
Research output: Research - peer-review › Article in proceedings – Annual report year: 2005

Transfer functions for uncoated SNOM fiber tips

General information
State: Published
Organisations: Nanophotonics, Department of Photonics Engineering
Contributors: Gregersen, N.
Publication date: 2005
Peer-reviewed: No
Event: Poster session presented at Annual meeting of the Danish Optical Society 2005, Roskilde, Denmark.
Source: orbit
Source-ID: 183046
Research output: Research › Poster – Annual report year: 2005
Projects:

**Nano-Photonic Circuits for Optical Communication (provisional)**
Gür, U. M., PhD Student, Department of Electrical Engineering
Mattes, M., Main Supervisor, Department of Electrical Engineering
Arslanagic, S., Supervisor, Department of Electrical Engineering
Gregersen, N., Supervisor, Department of Photonics Engineering
Samfinansieret - Andet
01/03/2018 → 28/02/2021
Award relations: Nano-Photonic Circuits for Optical Communication (provisional)
Project: PhD

**Light-matter interaction and laser dynamics in nanophotonic structures**
Rasmussen, T. S., PhD Student, Department of Photonics Engineering
Mørk, J., Main Supervisor, Department of Photonics Engineering
Gregersen, N., Supervisor, Department of Photonics Engineering
Yu, Y., Supervisor, Department of Photonics Engineering
Grundforskningsfonden
15/08/2017 → 14/08/2020
Award relations: Light-matter interaction and laser dynamics in nanophotonic structures
Project: PhD

**An open quantum systems approach to few photon scattering in photonic devices**
Joanesarson, K. B., PhD Student, Department of Photonics Engineering
Mørk, J., Main Supervisor, Department of Photonics Engineering
Gregersen, N., Supervisor, Department of Photonics Engineering
Iles-Smith, J., Supervisor, Department of Photonics Engineering
Grundforskningsfonden
01/02/2017 → 31/01/2020
Award relations: An open quantum systems approach to few photon scattering in photonic devices
Project: PhD

**Nonlinear Signal Processing in Optical Quantum Information Systems**
Christensen, J. B., PhD Student, Department of Photonics Engineering
Rottwitt, K., Main Supervisor, Department of Photonics Engineering
Gregersen, N., Supervisor, Department of Photonics Engineering
Oxenløwe, L. K., Supervisor, Department of Photonics Engineering
Karlsson, L. M. I., Examiner
Polit, A., Examiner
Samfinansierede - Virksomhed
15/10/2015 → 14/10/2018
Award relations: Nonlinear Signal Processing in Optical Quantum Information Systems
Project: PhD

**Single-photon quantum information technology**
Taherkhani, M., PhD Student, Department of Photonics Engineering
Gregersen, N., Main Supervisor, Department of Photonics Engineering
Mørk, J., Supervisor, Department of Photonics Engineering
Jauho, A., Examiner, Center for Nanostructured Graphene
Marquardt, O., Examiner
Zinner, N. T., Examiner
McCutcheen, D., Supervisor, Department of Photonics Engineering
Marquardt, O., Examiner
Zinner, N. T., Examiner
Forskningsrådsfinansiering
15/05/2015 → 05/09/2018
Award relations: Single-photon quantum information technology
Project: PhD
**Single photon sources for quantum information applications**
Østerkryger, A. D., PhD Student, Department of Photonics Engineering
Gregersen, N., Main Supervisor, Department of Photonics Engineering
Mørk, J., Supervisor, Department of Photonics Engineering
Lavrinenko, A., Examiner, Department of Photonics Engineering
Burger, S., Examiner
Kristensen, P. T., Examiner, Department of Photonics Engineering
Samfinansieret - Andet
15/03/2015 → 05/09/2018
Award relations: Single photon sources for quantum information applications
Project: PhD

**Optical Methods for Characterization of Surface or Interface Structures on a Nanometer Scale**
Gregersen, N., PhD Student, Department of Photonics Engineering
Mørk, J., Main Supervisor, Department of Photonics Engineering
Garnæs, J., Supervisor, Department of Micro- and Nanotechnology
Hanson, S. G., Supervisor, Department of Photonics Engineering
Tromborg, B., Supervisor, Department of Photonics Engineering
Laegsgaard, J., Examiner, Department of Photonics Engineering
Bienstman, P., Examiner
Vohnsen, B., Examiner
Offentlig finansiering
01/11/2003 → 30/03/2007
Award relations: Optical Methods for Characterization of Surface or Interface Structures on a Nanometer Scale
Project: PhD

**Modelling of semiconductor single-photon sources**
Chen, Y., PhD Student, Department of Photonics Engineering
Mørk, J., Main Supervisor, Department of Photonics Engineering
Gregersen, N., Supervisor, Department of Photonics Engineering
Lodahl, P., Supervisor, Department of Photonics Engineering
Nielsen, T. R., Supervisor, Department of Photonics Engineering
Mortensen, N. A., Examiner, Department of Micro- and Nanotechnology
Björk, G., Examiner
Sendegaard, T., Examiner, Department of Electromagnetic Systems
DTU-lønnet stipendie
01/09/2007 → 21/12/2010
Award relations: Modelling of semiconductor single-photon sources
Project: PhD

**Advanced simulation tools for nanophotonic devices**
de Lasson, J. R., PhD Student, Office for Research and Relations
Gregersen, N., Main Supervisor, Department of Photonics Engineering
Kristensen, P. T., Supervisor, Department of Photonics Engineering
Mørk, J., Supervisor, Department of Photonics Engineering
Lavrinenko, A., Examiner, Department of Photonics Engineering
Hughes, S., Examiner
Sendegaard, T., Examiner, Department of Electromagnetic Systems
Hughes, S., Examiner
Institut stipendie (DTU) Samf.
01/10/2012 → 20/01/2016
Award relations: Advanced simulation tools for nanophotonic devices
Project: PhD

**MEMS tunable nano-structured photodetector**
Learkthanakhachon, S., PhD Student, Department of Photonics Engineering
Chung, I., Main Supervisor, Department of Photonics Engineering
Taful Monroy, I., Supervisor, Department of Photonics Engineering
Yvind, K., Supervisor, Department of Photonics Engineering
Gregersen, N., Examiner, Department of Photonics Engineering
Birkedal, D., Examiner, Department of Micro- and Nanotechnology
Larsson, A. G., Examiner
Larsson, A. G., Examiner
Institut stipendie (DTU) Samf.
15/09/2011 → 18/06/2015
Award relations: MEMS tunable nano-structured photodetector
Project: PhD

**Modeling of Coupled Nano-Cavity Lasers**
Skovgård, T. S., PhD Student, Department of Photonics Engineering
Mark, J., Main Supervisor, Department of Photonics Engineering
Gregersen, N., Supervisor, Department of Photonics Engineering
Abram, I., Examiner
Willatzen, M., Examiner, Department of Photonics Engineering
Institut stipendie (DTU) Samf.
01/10/2008 → 19/04/2012
Award relations: Modeling of Coupled Nano-Cavity Lasers
Project: PhD

**Coherent Dynamics of Quantum Dots in Photonic Crystals**
Madsen, K. H., PhD Student, Department of Photonics Engineering
Mark, J., Main Supervisor, Department of Photonics Engineering
Lodahl, P., Supervisor, Risø National Laboratory for Sustainable Energy
Gregersen, N., Examiner, Department of Photonics Engineering
Atatüre, M., Examiner
Julsøgaard, B., Examiner, Department of Photonics Engineering
Institut stipendie (DTU)
15/03/2010 → 30/09/2013
Award relations: Coherent Dynamics of Quantum Dots in Photonic Crystals
Project: PhD

**Quantum Information Networks**
Leandro, L., PhD Student, Department of Photonics Engineering
Akopian, N., Main Supervisor, Department of Photonics Engineering
Gregersen, N., Supervisor, Department of Photonics Engineering
Institut stipendie (DTU)
15/12/2015 → 14/06/2019
Award relations: Quantum Information Networks
Project: PhD

**GOSPEL: Governing the speed of light**
The GOSPEL project aims at developing new, highly effective technologies for enabling slow and fast light propagation as a tunable feature in photonic devices. In fact, controlling the speed of light offers a solution to a necessary, and often missing, functionality in broadband ICT systems: a time-delay/phase-shift line. The proposed research will address three slow and fast light device platforms: linear and nonlinear semiconductor photonic crystal waveguides with position controlled embedded quantum dots, active semiconductor waveguides based on quantum dots and advanced, specifically engineered optical fibers. These technologies will be harnessed in microwave and millimeter wave applications, such as: true time delay antenna feed systems for radars and ultra wide band wireless communication; complex microwave filters; high spectral purity opto-electronic oscillators and electro optical sampling systems. This project gathers world leading experts in microwave photonics and semiconductor and fiber technologies, under a unified vision of the role that slow and fast light can play in advanced microwave applications. The project tackles several key challenges of the 7th Framework Work programme in the ICT domain and represents a significant step towards the removal of a major roadblock, i.e. the lack of practical, tunable, broadband, low distortion time-delay/phase-shift lines for microwave signals. This elemental component, besides enabling several applications, can ease the convergence of photonics and electronics and can attribute new functions to photonic devices. The proposed fundamental research will produce new results in multi-disciplinary topics like semiconductor physics, quantum dots, photonic crystal design and fiber technology and it will also represent a significant advancement across many sectors of ICT.
Mark, J., Project Manager, Department of Photonics Engineering
Gregersen, N., Project Participant, Department of Photonics Engineering
Yvind, K., Project Participant, Department of Photonics Engineering
Kristensen, P. T., Project Participant, Department of Photonics Engineering
Hansen, P. L., Project Participant, Department of Photonics Engineering
Semenoova, E., Project Participant, Department of Photonics Engineering
Xue, W., Project Participant, Department of Photonics Engineering
Pu, M., Project Participant, Department of Photonics Engineering
Larsson, D., Project Participant, Department of Photonics Engineering

A high-efficiency nanowire single-photon source
The project aims at engineering a nanowire-based single photon source (SPS) with efficiency approaching 100 % and takes place in close collaboration with the fabrication and characterization activities of an external partner. A recently discovered screening effect in high-index-contrast low-diameter nanowires will be exploited, an effect promising improved tolerance towards the fabrication-induced geometry imperfections currently limiting the efficiency of existing micropillar SPSs. The new nanowire physics will be analyzed, the established know-how will be used to suggest specific SPS structures for fabrication and several design-fabrication-characterization iterations will be performed.

Gregersen, N., Project Manager, Department of Photonics Engineering, Nanophotonics Theory and Signal Processing
Mørk, J., Project Participant, Department of Photonics Engineering, Nanophotonics Theory and Signal Processing
Lodahl, P., Project Participant, Department of Photonics Engineering, Quantum Photonics
Gerard, J. M., Contact Person, CEA

Project ID: 70647
Forskningsrådene - Andre: DKK925,374.00
01/06/2010 → 31/05/2011
Collaborators: CEA
Award relations: A high-efficiency nanowire single-photon source
Project: Research

Nanowire Single Photon Source
A single-photon source (SPS) is a light-emitting diode (LED) with the particular capability of emitting single photons on demand. The photon is the smallest possible light energy, and whereas lasers and traditional LEDs always emit a large number of photons no matter how short an electrical voltage pulse is applied, the SPS takes advantage of the so-called quantum dot technology to limit the number of emitted photons per trigger to one. Our invention is an electrically driven SPS design implementing nanowire technology which allows for a record-high photon extraction efficiency. The efficiency describes how many photons per trigger reach the target and should be as close to 100 % as possible. Obtaining such a high efficiency is generally a challenge since various loss mechanisms, in particular the light absorption in the metal contacts that are necessary for electrical pumping, result in reduced efficiency. Our SPS design solves this problem by implementing a unique nanowire-based design in which the influence of the various loss mechanisms is minimized and an efficiency approaching 100 % can be obtained. The design is general and can be adapted to different material systems and emission wavelengths.

Reeh, L., Project Participant, Department of Photonics Engineering
Gregersen, N., Project Manager, Department of Photonics Engineering

Project ID: 70573
Forskningsprojekter - Andre ministerier og styrelser: DKK750,000.00
01/06/2010 → 30/11/2011
Award relations: Nanowire Single Photon Source
Project: Research

CEMOST: Center for Micro Optical Structures
Functional micro optical structures are key components of telecommunication systems and find increased application as advanced sensors. The centre addresses the development of measurement techniques and measurement facilities, which can support the research and development taking place in industry by bringing together three technological service institutes, one university institute and 6 industrial companies.

Garnaes, J., Project Manager, Dansk Fundamental Metrology A/S
Tromborg, B., Project Participant, Department of Photonics Engineering
Gregersen, N., Project Participant, Department of Photonics Engineering

Project ID: 70242
Forskningsprojekter - Andre ministerier og styrelser: DKK1,369,000.00
01/01/2003 → 31/12/2006
Award relations: Center for Micro Optical Structures
Project: Research
Activities:

Matheon-Workshop: "8th Annual Meeting Photonic Devices"
Period: 17 Feb 2015 → 18 Feb 2015
Niels Gregersen (Participant)
Department of Photonics Engineering
Nanophotonics Theory and Signal Processing

Description
Invited presentation: Single-photon source engineering using a modal method

Related external organisation

The International Workshop on Theoretical and computational Nanophotonics (TaCoNa-Photonics 2010); 3
Period: 3 Nov 2010 → 5 Nov 2010
Niels Gregersen (Speaker)
Department of Photonics Engineering
Nanophotonics Theory and Signal Processing

Description
An electrically-pumped single-photon source design with a predicted efficiency of 89% is proposed. The design is based on a quantum dot embedded in a photonic nanowire with tailored ends and optimized contact electrodes. Unlike cavity-based approaches, the photonic nanowire features broadband spontaneous emission control and an improved tolerance towards fabrication imperfections. The various building blocks of the design are analyzed using an elements-splitting approach.
Place: Bad Honnef, Germany

Related external organisation

Unknown external organisation
Activity: Talks and presentations › Conference presentations

Journées de la Matière Condensée
Niels Gregersen (Participant)
Department of Photonics Engineering
Nanophotonics Theory and Signal Processing

Related event

Journées de la Matière Condensée
23/08/2010 → 27/08/2010
Troyes, France
Activity: Attending an event › Participating in or organising a conference

10th International Workshop on Nonlinear Optics and Excitation Kinetics in Semiconductors
Niels Gregersen (Participant)
Department of Photonics Engineering
Nanophotonics Theory and Signal Processing

Description
We will review recent studies performed on InAs quantum dots embedded in GaAs photonic wires, which highlight the strong interest of the photonic wire geometry for quantum optics experiments and quantum optoelectronic devices.

Related event

**10th International Workshop on Nonlinear Optics and Excitation Kinetics in Semiconductors**
16/08/2010 → 19/08/2010
Paderborn, Germany
Activity: Attending an event › Participating in or organising a conference

**International Conference on Superlattices, Nanostructures and Nanodevices**
Period: 18 Jul 2010 → 23 Jul 2010
Niels Gregersen (Participant)
Department of Photonics Engineering
Nanophotonics Theory and Signal Processing

Related event

**International Conference on Superlattices, Nanostructures and Nanodevices 2010**
18/07/2010 → 23/07/2010
Beijing, China
Activity: Attending an event › Participating in or organising a conference

**6th International Conference on Quantum Dots 2010**
Period: 26 Apr 2010 → 30 Apr 2010
Niels Gregersen (Participant)
Department of Photonics Engineering
Nanophotonics Theory and Signal Processing

Related event

**6th International Conference on Quantum Dots 2010**
26/04/2010 → 30/04/2010
Nottingham, United Kingdom
Activity: Attending an event › Participating in or organising a conference

**17th International Workshop on Optical Waveguide Theory and Numerical Modelling**
Niels Gregersen (Speaker)
Department of Photonics Engineering
Nanophotonics Theory and Signal Processing

Description
An improved perfectly matched layer in the eigenmode expansion technique--------- When employing the eigenmode expansion technique (EET), parasitic reflections at the boundary of the computational domain can be suppressed by introducing a perfectly matched layer (PML). However, the traditional PML suffers from an artificial field divergence limiting its usefulness. We propose a remedy.

Related event

**17th International Workshop on Optical Waveguide Theory and Numerical Modelling**
13/05/2008 → 14/05/2008
Eindhoven, Netherlands
Activity: Talks and presentations › Conference presentations