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.
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
Web of Science (2014): Indexed yes
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
BFI (2012): BFI-level 2
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
ISI indexed (2011): ISI indexed yes
Web of Science (2011): Indexed yes
BFI (2010): BFI-level 2
Scopus rating (2010): SJR 2.906 SNIP 2.428
Web of Science (2010): Impact factor 3.753
Web of Science (2010): Indexed yes
BFI (2009): BFI-level 2
Scopus rating (2009): SJR 3.039 SNIP 2.679
Web of Science (2009): Indexed yes
BFI (2008): BFI-level 2
Scopus rating (2008): SJR 3.204 SNIP 2.423
Web of Science (2008): Indexed yes
Scopus rating (2007): SJR 3.284 SNIP 2.11
Web of Science (2007): Indexed yes
Web of Science (2006): Indexed yes
Scopus rating (2005): SJR 3.313 SNIP 2.336
Web of Science (2005): Indexed yes
Scopus rating (2004): SJR 2.819 SNIP 2.472
Web of Science (2004): Indexed yes
Scopus rating (2003): SJR 2.669 SNIP 2.217
Web of Science (2003): Indexed yes
Scopus rating (2002): SJR 1.745 SNIP 1.748
Web of Science (2002): Indexed yes
Scopus rating (2001): SJR 1.496 SNIP 1.42
Web of Science (2001): Indexed yes
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Web of Science (2000): Indexed yes
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nd_quality_factors_in_p.pdf
DOIs:
10.1364/OE.26.011366
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.

General information
State: Published
Organisations: Department of Photonics Engineering, Quantum and Laser Photonics, Nanophotonic Devices, Electromagnetic Systems, Department of Electrical Engineering, Solid Mechanics, Department of Mechanical Engineering, Metamaterials, Zuse Institute Berlin, St. Petersburg National Research University of Information Technologies, Mechanics and Optics (ITMO)
Number of pages: 6
Publication date: 2018

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Source: PublicationPreSubmission
Source-ID: 147054258
Research output: Research - peer-review › Article in proceedings – Annual report year: 2018

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 in photonic 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
State: Published
Organisations: Department of Photonics Engineering, Quantum and Laser Photonics, Nanophotonic Devices, Department of Electrical Engineering, Electromagnetic Systems, Department of Mechanical Engineering, Solid Mechanics, Metamaterials, St. Petersburg National Research University of Information Technologies, Mechanics and Optics (ITMO), Zuse Institute Berlin
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Publication date: 2018

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Electronic versions:
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Source: PublicationPreSubmission
Source-ID: 147054413
Research output: Research - peer-review › Article in proceedings – Annual report year: 2018
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 COMPUTING Q FACTORS IN 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.
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 integral 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.
Peer-reviewed: Yes

Publication information
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BFI (2019): BFI-level 1
Web of Science (2019): Indexed yes
BFI (2018): BFI-level 1
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Scopus rating (2017): CiteScore 1.76
Web of Science (2017): Impact factor 1.566
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 2
Scopus rating (2016): CiteScore 1.54
Web of Science (2016): Impact factor 1.621
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 2
Scopus rating (2015): CiteScore 1.61
Web of Science (2015): Impact factor 1.457
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 2
Scopus rating (2014): CiteScore 1.72
Web of Science (2014): Impact factor 1.558
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 2
Scopus rating (2013): CiteScore 1.66
Web of Science (2013): Impact factor 1.448
ISI indexed (2013): ISI indexed no
BFI (2012): BFI-level 2
Scopus rating (2012): CiteScore 1.65
Web of Science (2012): Impact factor 1.665
ISI indexed (2012): ISI indexed no
Web of Science (2012): Indexed yes
BFI (2011): BFI-level 2
Scopus rating (2011): CiteScore 1.82
Web of Science (2011): Impact factor 1.562
ISI indexed (2011): ISI indexed no
Web of Science (2011): Indexed yes
BFI (2010): BFI-level 2
Web of Science (2010): Impact factor 1.936
Web of Science (2010): Indexed yes
BFI (2009): BFI-level 2
Web of Science (2009): Indexed yes
BFI (2008): BFI-level 2
Web of Science (2008): Indexed yes
Web of Science (2000): Indexed yes
Original language: English
Keywords: Fourier modal method, Computational electromagnetic methods, Micro-optics, Waveguides, Mathematical methods in physics, Numerical approximation and analysis
Electronic versions:
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Modelling open nanophotonic structures using the Fourier modal method in infinite domains

A modal approach to light emission and propagation in coupled cavity waveguide systems

Comparison of four computational methods for computing Q factors and resonance wavelengths in photonic crystal membrane cavities
Open-geometry Fourier modal method: modeling nanophotonic structures in infinite domains
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.

General information
State: Published
Organisations: Department of Photonics Engineering, Quantum and Laser Photonics
Contributors: Häyrynen, T., de Lasson, J. R., Gregersen, N.
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Journal: Journal of the Optical Society of America A
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ISSN (Print): 0740-3232
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Web of Science (2019): Indexed yes
BFI (2018): BFI-level 1
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BFI (2017): BFI-level 2
Scopus rating (2017): CiteScore 1.76
Web of Science (2017): Impact factor 1.566
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 2
Scopus rating (2016): CiteScore 1.54
Web of Science (2016): Impact factor 1.621
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 2
Scopus rating (2015): CiteScore 1.61
Web of Science (2015): Impact factor 1.457
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 2
Scopus rating (2014): CiteScore 1.72
Web of Science (2014): Impact factor 1.558
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 2
Scopus rating (2013): CiteScore 1.66
Web of Science (2013): Impact factor 1.448
ISI indexed (2013): ISI indexed no
BFI (2012): BFI-level 2
Scopus rating (2012): CiteScore 1.65
Web of Science (2012): Impact factor 1.665
ISI indexed (2012): ISI indexed no
Web of Science (2012): Indexed yes
BFI (2011): BFI-level 2
Scopus rating (2011): CiteScore 1.82
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.

General information
State: Published
Organisations: Department of Photonics Engineering, Quantum and Laser Photonics, Swiss Federal Institute of Technology Lausanne
Number of pages: 2
Publication date: 2016

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.

General information
State: Published
Organisations: Department of Photonics Engineering, Quantum and Laser Photonics
Contributors: Østerkryger, A. D., de Lasson, J. R., Heuck, M., Yu, Y., Mørk, J., Gregersen, N.
Pages: 2065-2068
Publication date: 2016
Peer-reviewed: Yes
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.

General information
State: Published
Organisations: Department of Photonics Engineering, Quantum and Laser Photonics
Contributors: Gregersen, N., de Lasson, J. R., Mørk, J.
Number of pages: 2
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Peer-reviewed: Yes
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, Quantum and Laser Photonics, 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

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.

General information
State: Published
Organisations: Department of Photonics Engineering, Quantum and Laser Photonics
Contributors: Østerkryger, A. D., de Lasson, J. R., Yu, Y., Mørk, J., Gregersen, N.
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Source-ID: 111442577
Research output: Research - peer-review » Poster – Annual report year: 2015

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, $\beta$, 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.

**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.
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.

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Contributors: de Lasson, J. R., Kristensen, P. T., Mørk, J., Gregersen, N.
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DOI:
doi:10.1117/12.2051885
Research output: Research - peer-review › Article in proceedings – Annual report year: 2014

**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.

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Contributors: de Lasson, J. R., Kristensen, P. T., Mørk, J., Gregersen, N.
Number of pages: 3
Publication date: 2014

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Title of host publication: Proceedings of META 2014
Source: PublicationPreSubmission
Source-ID: 98594714
Research output: Research - peer-review › Article in proceedings – Annual report year: 2014

**Calculation, normalization and perturbation of quasinormal modes in coupled cavity-waveguide systems**
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.

**General information**
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Contributors: Kristensen, P. T., de Lasson, J. R., Gregersen, N.
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Web of Science (2019): Indexed yes
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
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
Web of Science (2011): Impact factor 3.399
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
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.
Scaling of the Surface Plasmon Resonance in Gold and Silver Dimers Probed by EELS

The dependence of surface plasmon coupling on the distance between two nanoparticles (dimer) is the basis of nanometrology tools such as plasmon rulers. Application of these nanometric rulers requires an accurate description of the scaling of the surface plasmon resonance (SPR) wavelength with distance. Here, we have applied electron energy-loss spectroscopy (EELS) and scanning transmission electron microscopy (STEM) imaging to investigate the relationship between the SPR wavelength of gold and silver nanosphere dimers (radius R) and interparticle distance (d) in the range 0.1R < d < R. The choice of EELS enables probing the SPRs of individual dimers, whose dimensions and separation distances are measured in-situ with subnanometer resolution using STEM. We find that the decaying exponential description of the fractional SPR wavelength shift with (d/2R) holds valid only over a limited range of d. Instead, within the range 0.1R < d < R the fractional SPR wavelength shift is found to be related to (2R/d)^n, with n ~ 0.9 determined for both gold and silver dimers. Despite this common power dependence, consistently larger SPR wavelength shifts are registered for silver for a given change in d, implying silver dimers to be more sensitive plasmon rulers than their gold counterparts.
Calibrating Au and Ag plasmonic rulers with EELS

General information
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Organisations: Center for Electron Nanoscopy, Department of Photonics Engineering, Quantum and Laser Photonics, Department of Physics, Biophysics and Fluids
Contributors: Kadkhodazadeh, S., de Lasson, J. R., Kneipp, H., Wagner, J. B., Kneipp, K.
Number of pages: 1
Publication date: 2013
Peer-reviewed: Yes
Event: Poster session presented at Electron Microscopy and Analysis Group Conference, York, United Kingdom.
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Poster1_sk.pdf
Research output: Research - peer-review » Poster – Annual report year: 2013

Probing plasmon resonance’s dependence on gap size in silver dimers by EELS

General information
State: Published
Organisations: Center for Electron Nanoscopy, Department of Photonics Engineering, Quantum and Laser Photonics, Structured Electromagnetic Materials, Department of Physics, Biophysics and Fluids
Contributors: Kadkhodazadeh, S., de Lasson, J. R., Raza, S., Kristensen, P. T., Mørk, J., Wagner, J. B., Kneipp, K.
Number of pages: 1
Publication date: 2013
Peer-reviewed: Yes
Event: Poster session presented at Scandem 2013 - Annual Meeting of the Nordic Microscopy Society, Copenhagen, Denmark.
Electronic versions:
Poster1_2_sk.pdf
Research output: Research - peer-review » Poster – Annual report year: 2013

Probing plasmon resonance’s dependence on gap size in silver dimers by EELS

General information
State: Published
Organisations: Center for Electron Nanoscopy, Department of Photonics Engineering, Quantum and Laser Photonics, Structured Electromagnetic Materials, Department of Physics, Biophysics and Fluids
Contributors: Kadkhodazadeh, S., de Lasson, J. R., Raza, S., Kristensen, P. T., Mørk, J., Wagner, J. B., Kneipp, K.
Number of pages: 1
Publication date: 2013
Three-dimensional integral equation approach to light scattering, extinction cross sections, local density of states, and quasi-normal modes

We present a numerical formalism for solving the Lippmann–Schwinger equation for the electric field in three dimensions. The formalism may be applied to scatterers of different shapes and embedded in different background media, and we develop it in detail for the specific case of spherical scatterers in a homogeneous background medium. In addition, we show how several physically important quantities may readily be calculated with the formalism. These quantities include the extinction cross section, the total Green’s tensor, the projected local density of states, and the Purcell factor as well as the quasi-normal modes of leaky resonators with the associated resonance frequencies and quality factors. We demonstrate the calculations for the well-known plasmonic dimer consisting of two silver nanoparticles and thus illustrate the versatility of the formalism for use in modeling of advanced nanophotonic devices.

General information
State: Published
Organisations: Department of Photonics Engineering, Quantum and Laser Photonics
Contributors: de Lasson, J. R., Mørk, J., Kristensen, P. T.
Pages: 1996-2007
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Peer-reviewed: Yes

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Web of Science (2019): Indexed yes
BFI (2018): BFI-level 1
Web of Science (2018): Indexed yes
BFI (2017): BFI-level 1
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Web of Science (2017): Impact factor 2.048
Web of Science (2017): Indexed yes
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Web of Science (2016): Impact factor 1.843
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BFI (2015): BFI-level 1
Scopus rating (2015): CiteScore 1.78 SJR 0.963 SNIP 0.923
Web of Science (2015): Impact factor 1.731
BFI (2014): BFI-level 1
Scopus rating (2014): CiteScore 2.09 SJR 1.167 SNIP 1.137
Web of Science (2014): Impact factor 1.97
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 1
Scopus rating (2013): CiteScore 2.33 SJR 1.348 SNIP 1.286
Web of Science (2013): Impact factor 1.806
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 1
Scopus rating (2012): CiteScore 2.2 SJR 1.522 SNIP 1.28
Electromagnetic Scattering in Micro- and Nanostructured Materials.

The research fields of optical microstructures and plasmonic nanostructures are particularly active these years, and interesting applications in, e.g., quantum information technology in the former and novel types of solar cells in the latter, drive the investigations. Central in both fields is the interaction of light with matter, in the forms of semiconductors and metals in the two cases, and fundamental understanding of the interactions is important to optimize technological designs.
To address this, we in the present thesis develop a formalism for determining the electric field in a homogeneous three-dimensional space with spherical inhomogeneities embedded. The formalism accounts fully for the multiple reflections the field undergoes in such structures, and likewise the vectorial nature of the field is treated rigorously. The formalism is based on the Lippmann-Schwinger equation and the electromagnetic Green’s tensor and uses an expansion of the field on spherical wavefunctions. Addition theorems for these are extensively used, and all parts of the formalism are expressed analytically. With the formalism, we show that the simpler approach of modeling the spherical scatterers as polarizable dipoles, which is often alluded to in the literature, breaks down in the limit of closely spaced scattering objects. The study of metallic nanoparticles is particularly intriguing when these are in close proximity, due to the coupling of their near-fields, and the breakdown of the simpler approach reveals a need for the present formalism. Additionally, we study dimers and chains of metallic nanoparticles and analyze their spectra, when exposed to fields of different polarizations. The spectral response is highly dependent on the polarization, and we demonstrate for the dimer, under polarization along the dimer axis, a $d^{-1/2}$-dependence of the relative shift of the resonance wavelength, $d$ being the distance between the particles. This dependence on $d$ is softer than reported earlier, and thus constitutes the foundation for a more systematic study. The correlation of distance and spectral properties may have applications within biosensing and imaging on the nanoscale. For the chain, we demonstrate a next-nearest neighbor interaction between the nanoparticles through the study of its spectral properties. Finally, we present a calculation of the Green’s tensor for the dimer, illustrating that the formalism may likewise be used for modeling optical microstructures, e.g. three dimensional photonic crystals.

**General information**
- State: Published
- Organisations: Department of Photonics Engineering, Quantum and Laser Photonics
- Contributors: de Lasson, J. R., Mørk, J., Kristensen, P. T.
- Number of pages: 130
- Publication date: 2012

**Publication information**
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- Original language: English
- Electronic versions: Jakobrdl_MScThesis_July2012.pdf
- Research output: Research - peer-review - Report – Annual report year: 2012

**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 non-equidistant discretization are employed, and while both converge, only the non-equidistant 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.

**General information**
- State: Published
- Organisations: Department of Photonics Engineering, Structured Electromagnetic Materials, Quantum and Laser Photonics
- Contributors: de Lasson, J. R., Christensen, T., Mørk, J., Gregersen, N.
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- Peer-reviewed: Yes

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  - Scopus rating (2017): CiteScore 1.76
  - Web of Science (2017): Impact factor 1.566
  - Web of Science (2017): Indexed yes
  - Scopus rating (2016): CiteScore 1.54
  - Web of Science (2016): Impact factor 1.621
Multiple-scattering formalism beyond the quasistatic approximation: Analyzing resonances in plasmonic chains

We present a multiple-scattering formalism for simulating scattering of electromagnetic waves on spherical inhomogeneities in 3D. The formalism is based on the Lippmann-Schwinger equation and the electromagnetic Green's tensor and applies an expansion of the electric field on spherical wavefunctions. As an example, we analyze localized surface plasmons in chains of Ag spheres, and show how the resonances of such systems depend sensitively on the polarization of the incoming field, the spacing between the particles and the number of particles in the chain.

Bibliographical note
This paper was published in JOSA A 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/josaa/abstract.cfm?uri=josaa-29-7-1237. Systematic or multiple reproduction or distribution to multiple locations via electronic or other means is prohibited and is subject to penalties under law.

Research output: Research - peer-review › Journal article – Annual report year: 2012
Projects:

**Advanced simulation tools for nanophotonic devices**
de Lasson, J. R., PhD Student, Department of Photonics Engineering
Gregersen, N., Main Supervisor, Department of Photonics Engineering
Kristensen, P. T., Supervisor, Department of Photonics Engineering
Mørk, J., Supervisor, Department of Photonics Engineering
Laurynenka, A., Examiner, Department of Photonics Engineering
Søndergaard, 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

Activities:

**Nye forskere og Ph.D.-Studerende**
Period: Nov 2015
Jakob Rosenkrantz de Lasson (Invited speaker)
Department of Photonics Engineering
Quantum and Laser Photonics

**Related event**

**Nye forskere og Ph.D.-Studerende**
03/11/2015 → 04/11/2015
Nyborg, Denmark
Activity: Talks and presentations › Conference presentations

**Nanofotonik og fotoniske krystaller – Tryllekunster med lys**
Period: Apr 2015
Jakob Rosenkrantz de Lasson (Invited speaker)
Department of Photonics Engineering
Quantum and Laser Photonics

**Related event**

**Forskningens Døgn: Bestil en forsker**
23/04/2015 → 25/04/2015
Denmark
Activity: Talks and presentations › Conference presentations

2015 Progress In Electromagnetics Research Symposium
Period: 2015
Jakob Rosenkrantz de Lasson (Speaker)
Department of Photonics Engineering
Quantum and Laser Photonics
Related event

2015 Progress In Electromagnetics Research Symposium
06/07/2015 → 09/07/2015
Prag, Czech Republic
Activity: Talks and presentations › Conference presentations

META’14
Period: May 2014
Jakob Rosenkrantz de Lasson (Speaker)
Department of Photonics Engineering
Quantum and Laser Photonics

Related event

META’14: 5th International Conference on Metamaterials, Photonic Crystals and Plasmonics
20/05/2014 → 23/05/2014
Singapore, Singapore
Activity: Talks and presentations › Conference presentations

Nanofotonik og fotoniske krystaller – Tryllekunst med lys
Period: Apr 2014
Jakob Rosenkrantz de Lasson (Invited speaker)
Department of Photonics Engineering
Quantum and Laser Photonics

Related event

Bestil en Forsker - Forskningens Døgn
24/04/2014 → 26/04/2014
Denmark
Activity: Talks and presentations › Conference presentations

SPIE Photonics Europe Conference 2014
Period: Apr 2014
Jakob Rosenkrantz de Lasson (Speaker)
Department of Photonics Engineering
Quantum and Laser Photonics

Related event

SPIE Photonics Europe Conference 2014
14/04/2014 → 17/04/2014
Brussels, Belgium
Activity: Talks and presentations › Conference presentations

Les Houches Summer School
Period: Aug 2013 → …
Jakob Rosenkrantz de Lasson (Participant)
Department of Photonics Engineering
Quantum and Laser Photonics

Related event

Les Houches Summer School: Quantum Optics and Nanophotonics
05/08/2013 → 30/08/2013
Les Houches, France
International Physics Olympiad
Period: Jul 2013
Jakob Rosenkrantz de Lasson (External examiner)
Department of Photonics Engineering
Quantum and Laser Photonics

Description
Exam marker
Activity: Examinations and supervision › External examination

5th International Workshop on Theoretical and Computational Nano-Photonics
Period: Oct 2012
Jakob Rosenkrantz de Lasson (Speaker)
Department of Photonics Engineering
Quantum and Laser Photonics

Related event
5th International Workshop on Theoretical and Computational Nano-Photonics: TaCoNa-Photonics 2012
24/10/2012 → 26/10/2012
Bad Honnef, Germany
Activity: Talks and presentations › Conference presentations