All-Si photodetector for telecommunication wavelength based on subwavelength grating structure and critical coupling

We propose an efficient planar all-Si internal photoemission photodetector operating at the telecommunication wavelength of 1550 nm and numerically investigate its optical and electrical properties. The proposed polarization-sensitive detector is composed of an appropriately engineered subwavelength grating structure topped with a silicide layer of nanometers thickness as an absorbing material. It is shown that a nearly-perfect light absorption is possible for the thin silicide layer by its integration to the grating resonator. The absorption is shown to be maximized when the critical coupling condition is satisfied. Simulations show that the external quantum efficiency of the proposed photodetector with a 2-nm-thick PtSi absorbing layer at the center wavelength of 1550 nm can reach up to ~60%.

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Organisations: Department of Photonics Engineering, Nanophotonics Theory and Signal Processing, Technical University of Denmark, Tarbiat Modares University
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Compact dielectric cavities based on frozen bound states in the continuum

Dielectric microcavities are used widely today for confining the light to its wavelength scale, which is important for fundamental physics studies of light-matter interactions such as cavity quantum electrodynamics (QED) and cavity polaritons, as well as various applications including ultrafast lasers and single-photon light sources [1]. They have been implemented in various platforms such as microrings, microdisks, micropillars, photonic crystals (PhCs), etc. Usually, it is desirable to reduce the mode volume while keeping the quality-factor (Q-factor) as high as possible for an optical cavity to enhance the light-matter interaction. Recently, a particular type of optical mode with an infinite Q-factor has been reported in a PhC slab, which is referred to as bound state in the continuum (BIC) [2]. A BIC is a special solution of a wave equation, which is discrete and bounded while it lies inside a continuum of unbounded states [2].

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Control of exceptional points in photonic crystal slabs

Various ways of controlling the extent of the ring of exceptional points in photonic crystal slabs are investigated. The extent of the ring in photonic crystal slabs is found to vary with the thickness of the slab. This enables recovery of Dirac cones in open, non-Hermitian systems, such as a photonic crystal slab. In this case, all three bands exhibit a bound state in the continuum in close proximity of the $\Gamma$ point. These results may lead to new designs of small photonic-crystal-based lasers exhibiting high-quality factors.

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Organisations: Department of Electrical Engineering, Electromagnetic Systems, Department of Photonics Engineering, Nanophotonics Theory and Signal Processing
Authors: Kaminski, P. M. (Intern), Taghizadeh, A. (Intern), Breinbjerg, O. (Intern), Mørk, J. (Intern), Arslanagic, S. (Intern)
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Dynamical dispersion engineering in coupled vertical cavities employing a high-contrast grating

Photon's effective mass is an important parameter of an optical cavity mode, which determines the strength of light-matter interaction. Here, we propose a novel method for controlling the photon's effective mass by using coupled photonic cavities and designing the angular dependence of the coupling strength. This can be implemented by employing a high-contrast grating (HCG) as the coupling reflector in a system of two coupled vertical cavities, and engineering both the HCG reflection phase and amplitude response. Several examples of HCG-based coupled cavities with novel features are discussed, including a case capable of dynamically controlling the photon’s effective mass to a large extent while keeping the resonance frequency same. We believe that full-control and dynamical-tuning of the photon’s effective mass may enable new possibilities for cavity quantum electrodynamics studies or conventional/polariton laser applications. For instance, one can dynamically control the condensate formation in polariton lasers by modifying the polariton mass.

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Scopus rating (2015): SJR 2.057 SNIP 1.684 CiteScore 5.3
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ISI indexed (2013): ISI indexed yes
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Electronic versions:
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Efficient quality-eactor estimation of a vertical cavity employing a high-contrast grating

Hybrid vertical cavity lasers employing high-contrast grating reflectors are attractive for Si-integrated light source applications. Here, a method for reducing a three-dimensional (3D) optical simulation of this laser structure to lower-
dimensional simulations is suggested, which allows for very fast and approximate analysis of the quality-factor of the 3D cavity. This approach enables us to efficiently optimize the laser cavity design without performing cumbersome 3D simulations.

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**Hybrid Si-on-chip Lasers with Nano Structures**

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Organisations: Department of Photonics Engineering, Nanophotonics Theory and Signal Processing, Nanophotonic Devices, Centre of Excellence for Silicon Photonics for Optical Communications
Authors: Chung, I. (Intern), Park, G. C. (Intern), Taghizadeh, A. (Intern), Mørk, J. (Intern), Learkthanakhachon, S. (Intern), Semenova, E. (Intern)
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**Quasi bound states in the continuum with few unit cells of photonic crystal slab**

Bound states in the continuum (BICs) in photonic crystal slabs represent the resonances with an infinite quality (Q)-factor, occurring above the light line for an infinitely periodic structure. We show that a set of BICs can turn into quasi-BICs with a very high Q-factor even for two or three unit cell structures. They are explained by a viewpoint of BICs originating from the tight-binding of individual resonances of each unit cell as in semiconductors. Combined with a reciprocal-space matching technique, the microcavities based on quasi-BICs can achieve a Q-factor as high as defect-based PhC microcavities.

These results may enable the experimental studies of BICs in a compact platform as well as realizing high-Q mirrorless microcavities.

**General information**
Vertical cavity laser
The present invention provides a vertical cavity laser comprising a grating layer comprising an in-plane grating, the grating layer having a first side and having a second side opposite the first side and comprising a contiguous core grating region having a grating structure, wherein an index of refraction of high-index sections of the grating structure is at least 2.5, and wherein an index of refraction of low-index sections of the grating structure is less than 2, the core grating region defining a projection in a direction normal to the grating layer; a cap layer having a first side and having a second side opposite the first side, the first side of the cap layer abutting the second side of the grating layer, and an index of refraction of the cap layer within the projection of the core grating region onto the cap layer is at least 2.5, and within the projection of the core grating region, the second side of the cap layer is abutted by a first low-index layer and/or by air, an index of refraction of the first low-index layer or air being less than 2, and within the projection of the core grating region, the first side of the grating layer is abutted by a second low-index layer and/or by air, an index of refraction of the second low-index layer or air being less than 2; and a thickness of the cap layer and a thickness of the grating layer, and a pitch and a duty cycle of the grating structure are selected to obtain a resonance having a free-space resonance wavelength in the interval 300 nm to 3 microns, the cap layer comprises an active region configured to generate or absorb photons at the free-space resonance wavelength by stimulated emission or absorption when a sufficient forward or reverse bias voltage is applied across the active region, a thickness of the first low-index layer is less than 45 % or more than 55 % of the free-space resonance wavelength divided by a highest index of refraction of the first low-index layer within the core grating region, and a thickness of the cap layer is less than 5 microns.

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Hybrid grating reflectors: Origin of ultrabroad stopband
Hybrid grating (HG) reflectors with a high-refractive-index cap layer added onto a high contrast grating (HCG) provide a high reflectance close to 100% over a broader wavelength range than HCGs. The combination of a cap layer and a grating layer brings a strong Fabry-Perot (FP) resonance as well as a weak guided mode (GM) resonance. Most of the reflected
power results from the FP resonance, while the GM resonance plays a key role in achieving a reflectance close to 100% as well as broadening the stopband. An HG sample with 7 InGaAlAs quantum wells included in the cap layer has been fabricated by directly wafer-bonding a III-V cap layer onto a Si grating layer. Its reflection property has been characterized. This heterogeneously integrated HG reflector may allow for a hybrid III-V on Si laser to be thermally efficient, which has promising prospects for silicon photonics light sources and high-speed operation.

**General information**

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Scopus rating (2015): SJR 1.085 SNIP 0.983 CiteScore 2.47  
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Scopus rating (2014): SJR 1.799 SNIP 1.462 CiteScore 3.25  
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Scopus rating (2013): SJR 2.149 SNIP 1.652 CiteScore 3.77  
ISI indexed (2013): ISI indexed yes  
Web of Science (2013): Indexed yes  
BFI (2012): BFI-level 2  
Scopus rating (2012): SJR 2.554 SNIP 1.754 CiteScore 3.76  
ISI indexed (2012): ISI indexed yes  
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Scopus rating (2011): SJR 2.805 SNIP 1.94 CiteScore 4.04  
ISI indexed (2011): ISI indexed yes  
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Scopus rating (2010): SJR 2.926 SNIP 1.789  
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BFI (2009): BFI-level 2  
Scopus rating (2009): SJR 2.857 SNIP 1.848  
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Web of Science (2008): Indexed yes  
Scopus rating (2007): SJR 3.039 SNIP 1.913  
Web of Science (2007): Indexed yes
Hybrid III-V on Si grating as a broadband reflector and a high-Q resonator

Hybrid grating (HG) with a high-refractive-index cap layer added onto a high contrast grating (HCG), can provide a high reflectance close 100% over a broader wavelength range than HCGs, or work as an ultrahigh quality (Q) factor resonator. The reflection and resonance properties of HGs have been investigated and the mechanisms leading to these properties are discussed. A HG reflector sample integrating a III-V cap layer with InGaAlAs quantum wells onto a Si grating has been fabricated and its reflection property has been characterized. The HG-based lasers have a promising prospect for silicon photonics light source or high-speed laser applications.

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Hybrid III-V/SOI resonant cavity enhanced photodetector

A hybrid III–V/SOI resonant-cavity-enhanced photodetector (RCE-PD) structure comprising a high-contrast grating (HCG) reflector, a hybrid grating (HG) reflector, and an air cavity between them, has been proposed and investigated. In the proposed structure, a light absorbing material is integrated as part of the HG reflector, enabling a very compact vertical cavity. Numerical investigations show that a quantum efficiency close to 100% and a detection linewidth of about 1 nm can be achieved, which are desirable for wavelength division multiplexing applications. Based on these results, a hybrid RCE-PD sample has been fabricated by heterogeneously integrating an InP-based material onto a silicon-on-insulator
wafer and has been characterized, which shows a clear enhancement in photo-current at the designed wavelength. This indicates that the HG reflector provides a field enhancement sufficient for RCE-PD operation. In addition, a capability of feasibly selecting the detection wavelength during fabrication as well as a possibility of realizing silicon-integrated bidirectional transceivers are discussed.

**General information**

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Organisations: Department of Photonics Engineering, Nanophotonics Theory and Signal Processing, Metro-Access and Short Range Systems, Nanophotonic Devices, Centre of Excellence for Silicon Photonics for Optical Communications
Authors: Learkhanakhachon, S. (Intern), Taghizadeh, A. (Intern), Park, G. C. (Intern), Yvind, K. (Intern), Chung, I. (Intern)
Pages: 16512-16519
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Scopus rating (2016): CiteScore 3.48 SJR 1.487 SNIP 1.589
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BFI (2014): BFI-level 2
Scopus rating (2014): SJR 2.349 SNIP 2.166 CiteScore 4.18
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 2
Scopus rating (2013): SJR 2.358 SNIP 2.226 CiteScore 4.38
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 2
Scopus rating (2012): SJR 2.587 SNIP 2.145 CiteScore 3.85
ISI indexed (2012): ISI indexed yes
Web of Science (2012): Indexed yes
BFI (2011): BFI-level 2
Scopus rating (2011): SJR 2.579 SNIP 2.606 CiteScore 4.04
ISI indexed (2011): ISI indexed yes
Web of Science (2011): Indexed yes
BFI (2010): BFI-level 2
Scopus rating (2010): SJR 2.943 SNIP 2.466
Web of Science (2010): Indexed yes
BFI (2009): BFI-level 2
Scopus rating (2009): SJR 3.092 SNIP 2.669
Web of Science (2009): Indexed yes
BFI (2008): BFI-level 2
Scopus rating (2008): SJR 3.195 SNIP 2.393
Web of Science (2008): Indexed yes
Scopus rating (2007): SJR 3.27 SNIP 2.032
Web of Science (2007): Indexed yes
Scopus rating (2006): SJR 3.233 SNIP 2.326
Hybrid III-V/SOI Resonant Cavity Photodetector
A hybrid III-V/SOI resonant cavity photo detector has been demonstrated, which comprises an InP grating reflector and a Si grating reflector. It can selectively detect an incident light with 1.54-μm wavelength and TM polarization.

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Organisations: Department of Photonics Engineering, Nanophotonics Theory and Signal Processing, Nanophotonic Devices, Centre of Excellence for Silicon Photonics for Optical Communications
Authors: Learkthanakhachon, S. (Intern), Taghizadeh, A. (Intern), Park, G. C. (Intern), Yvind, K. (Intern), Chung, I. (Intern)
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Numerical Investigation of Vertical Cavity Lasers With High-Contrast Gratings Using the Fourier Modal Method
We explore the use of a modal expansion technique, Fourier modal method (FMM), for investigating the optical properties of vertical cavities employing high-contrast gratings (HCGs). Three techniques for determining the resonance frequency and quality factor (Q-factor) of a cavity mode are compared, and the computational uncertainties in the resonance frequency and Q-factor calculations are analyzed. Moreover, a method for reducing a three-dimensional (3D) simulation to lower-dimensional simulations is suggested, which allows for very fast and approximate analysis of a 3D structure. By using the implemented FMM, the scattering losses of several HCG-based vertical cavities with inplane heterostructures which have promising prospects for fundamental physics studies and on-chip laser applications, are investigated. This type of parametric study of 3D structures would be numerically very demanding using spatial discretization techniques.

General information
State: Published
Theoretical Investigation of Subwavelength Gratings and Vertical Cavity Lasers Employing Grating Structures

This thesis deals with theoretical investigations of a newly proposed grating structure, referred to as hybrid grating (HG) as well as vertical cavity lasers based on the grating reflectors. The HG consists of a near-subwavelength grating layer and an unpatterned high-refractive-index cap layer. Though both sides of the grating layer are not surrounded by low refractive-index materials as in high-index-contrast gratings (HCGs), the HG can provide a near-unity reflectivity over a broader wavelength range than HCGs, or work as a resonator with a quality (Q) factor as high as 109. The physics behind these reflector and resonator properties are studied thoroughly. A HG structure comprising a III-V cap layer with a gain material and a Si grating layer enables the realization of a compact vertical cavity laser integrated on Si platform, which has a superior thermal property and fabrication feasibility than the HCG-based ones. Furthermore, the concept of cavity dispersion in vertical cavities is introduced and its importance in the modal properties is numerically investigated. The dispersion curvature of a cavity mode is interpreted as the effective photon mass of the cavity mode. In a vertical cavity based on a HCG or HG reflector, this effective photon mass can be engineered by changing the grating parameters, which is not the case in a vertical cavity based on distributed Bragg reflectors (DBRs). This engineering capability enables us to form various photonic heterostructures in lateral directions, which is analogous to electronic quantum wells in conduction or valence bands. Several interesting configurations of heterostructures have been investigated and their potential in fundamental physics study and applications are discussed. For numerical and theoretical studies, a three-dimensional (3D) optical simulator has been implemented, based on the Fourier modal method (FMM). A method to simplify 3D simulations to lower dimensional simulations is suggested, which enables us to perform fast simulations before doing a thorough 3D simulation. Moreover, three different techniques for determining the resonance frequency and Q-factor of a cavity mode are compared. Based on that, the quasi-normal mode approach with real frequency has been chosen due to its numerical efficiency. In this comparison, the associated computational uncertainty for the resonance frequency and Q-factor is investigated, which shows that the uncertainty in the Q-factor can be several orders of magnitude larger than the uncertainty in the resonance frequency. Next, the HG is shown to possess a near-unity reflectivity in a broad wavelength range, which can be broader than the HCG, since the cap layer introduces more guided mode resonances (GMRs) in the reflectivity spectrum. The fabrication tolerance of the HG is investigated numerically, which shows that the broadband near-unity reflectivity characteristic is prone to common fabrication errors. An experimental demonstration of the HG reflector confirms its broadband reflection characteristics. Furthermore, the physics study of HG as high Q-factor resonator illustrates that the resonance mechanism is similar to the resonances appearing in HCG resonators, and it is quite different from the conventional GMR filters. The effect of fabrication errors and finite size of the structure is investigated to understand the feasibility of fabricating the proposed resonator. Finally, the significance of the cavity dispersion in vertical cavity structure is illustrated. An analytic expression is derived for the dispersion, which shows that the cavity dispersion has contributions from both top and bottom mirrors through their reflectivity phase response as well as the nominal cavity through its thickness. For conventional DBRs, the mirror contribution in dispersion curvature is always positive and negligible, compared to the nominal cavity contribution. However, the HCG or HG contributions can be a specific positive or negative value in different transverse directions, significantly modifying the entire dispersion curvature. The influences of the photon effective mass on the mode confinement, mode spacing and transverse modes are investigated. Particularly, it is shown that the anisotropic dispersion curvature in in-plane heterostructure is responsible for the phenomenon of mode grouping, which is also confirmed by experimental results. Furthermore, in Si-integrated photonics, a laser source that can output light into a Si waveguide is essential, and it is shown that in HGG-based vertical cavity laser the light can be coupled to an in-plane output waveguide. The design rules for achieving a high out-coupling efficiency into the in-plane waveguide are discussed and the in-plane out-coupling efficiency as high as 68% is achieved in design. Based on this platform, a system of two laterally coupled cavities is proposed and investigated, which exhibits the breaking of parity-time (PT) symmetry in vertical cavity structures. Compared to other types of platform for studying this phenomenon such as ring/disk resonators and photonic crystal cavities, the HCG/HG-based vertical cavities appear to be more feasible for realizing an electrically pumped device, which may pave the way for finding device applications for PT-symmetry breaking.
Toward 100 GHz direct modulation rate of antenna coupled nanoLED
We show that > 100 GHz direct modulation rate while maintaining a quantum efficiency higher than 25% is possible by using an optical antenna to enhance the spontaneous emission rate of an electrically injected III-V nanoLED.

Ultrabroadband Hybrid III-V/SOI Grating Reflector for On-chip Lasers
We report on a new type of III-V/SOI grating reflector with a broad stopband of 350 nm. This reflector has promising prospects for applications in high-speed III-V/SOI vertical cavity lasers with an improved heat dissipation capability.
VCSL structure
The invention relates to a VCSEL structure based on a novel grating reflector. The grating reflector comprises a grating layer with a contiguous core grating region having a grating structure, wherein an index of refraction of high-index sections of the grating structure is at least 2.5, and wherein an index of refraction of low-index sections of the grating structure is less than 2. The core grating region defines a projection in a direction normal to the grating layer. The grating reflector further comprises a cap layer abutting the grating layer, and an index of refraction of the cap layer within the projection of the core grating region onto the cap layer is at least 2.5, and within the projection of the core grating region, the cap layer is abutted by a first solid dielectric low-index layer, an index of refraction of the first low-index layer or air being less than 2; and within the projection of the core grating region, the grating layer is also abutted by a second low-index layer and/or by air, an index of refraction of the second low-index layer or air being less than 2. The VCSEL structure furthermore comprises a first reflector and an active region for providing a cavity and amplification.

Effect of In-plane Mirror Dispersion on Vertical Cavities Based on High-Contrast Grating Mirrors
We report how the in-plane dispersion of a high-index-contrast grating reflector influences the transverse mode properties such as shorter wavelengths for lower-order transverse modes and different transverse-mode wavelength spacings for modes with the same size.

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Hybrid III-V-on-Si Laser with Ultra-low Energy Consumption

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Authors: Taghizadeh, A. (Intern), Mørk, J. (Intern), Chung, I. (Intern)
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Main Research Area: Technical/natural sciences
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Relations
Activities:
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Hybrid vertical-cavity laser with lateral emission into a silicon waveguide

We experimentally demonstrate an optically-pumped III-V/Si vertical-cavity laser with lateral emission into a silicon waveguide. This on-chip hybrid laser comprises a distributed Bragg reflector, a III-V active layer, and a high-contrast grating reflector, which simultaneously funnels light into the waveguide integrated with the laser. This laser has the advantages of long-wavelength vertical-cavity surface-emitting lasers, such as low threshold and high side-mode suppression ratio, while allowing integration with silicon photonic circuits, and is fabricated using CMOS compatible processes. It has the potential for ultrahigh-speed operation beyond 100 Gbit/s and features a novel mechanism for transverse mode control.

General information
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Publication information
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Ultracompact resonator with high quality-factor based on a hybrid grating structure

We numerically investigate the properties of a hybrid grating structure acting as a resonator with ultrahigh quality factor. This reveals that the physical mechanism responsible for the resonance is quite different from the conventional guided mode resonance (GMR). The hybrid grating consists of a subwavelength grating layer and an un-patterned high-refractive-index cap layer, being surrounded by low index materials. Since the cap layer may include a gain region, an ultracompact laser can be realized based on the hybrid grating resonator, featuring many advantages over high-contrast-grating resonator lasers. The effect of fabrication errors and finite size of the structure is investigated to understand the feasibility of fabricating the proposed resonator.

General information
State: Published
Organisations: Department of Photonics Engineering, Nanophotonics Theory and Signal Processing
We show that the in-plane heterostructures realized in vertical cavities with high contrast grating (HCG) reflector enables exotic configurations of heterostructure and photonic wells. In photonic crystal heterostructures forming a photonic well, the property of a confined mode is determined by the well width and barrier height. We show that in vertical-cavity in-plane heterostructures, anisotropic dispersion curvatures plays a key role as well, leading to exotic effects such as a photonic well with conduction band like well and a valence band like barrier. We investigate three examples to discuss the rich potential of this heterostructure as a platform for various physics studies and propose a system of two laterally coupled cavities which shows the breaking of parity-time symmetry as an example.
Comparison of Different Numerical Methods for Quality Factor Calculation of Nano and Micro Photonic Cavities

Four different numerical methods for calculating the quality factor and resonance wavelength of a nano or micro photonic cavity are compared. Good agreement was found for a wide range of quality factors. Advantages and limitations of the different methods are discussed.

General information
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Organisations: Department of Photonics Engineering, Nanophotonics Theory and Signal Processing
Authors: Taghizadeh, A. (Intern), Mørk, J. (Intern), Chung, I. (Intern)
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Publication date: 2014

Host publication information
We suggest a new type of grating reflector denoted hybrid grating (HG) which shows large reflectivity in a broad wavelength range and has a structure suitable for realizing a vertical cavity laser with ultra-small modal volume. The properties of the grating reflector are investigated numerically and explained. The HG consists of an un-patterned III-V layer and a Si grating. The III-V layer has a thickness comparable to the grating layer, introduces more guided mode resonances and significantly increases the bandwidth of the reflector compared to the well-known high-index-contrast grating (HCG). By using an active III-V layer, a laser can be realized where the gain region is integrated into the mirror itself.
Effect of External Optical Feedback for Nano-laser Structures

We theoretically investigated the effect of optical feedback on a photonic crystal nanolaser, comparing with conventional in-plane and vertical-cavity lasers.

**General information**

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Organisations: Department of Photonics Engineering, Nanophotonics Theory and Signal Processing
Authors: Taghizadeh, A. (Intern), Mørk, J. (Intern), Chung, I. (Intern)
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**Host publication information**

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Hybrid III-V-on-Si laser with ultralow energy consumption
Department of Photonics Engineering
Period: 01/02/2013 → 04/05/2016
Number of participants: 6
Phd Student:
Taghizadeh, Alireza (Intern)
Supervisor:
Mark, Jesper (Intern)
Main Supervisor:
Chung, Il-Sug (Intern)
Examiner:
Lavrinenko, Andrei (Intern)
Hammar, Mattias (Ekstern)
Morthier, Geert Josef Ivo (Ekstern)

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Project: PhD

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Period: 22 Jan 2015 → 23 Jan 2015
Alireza Taghizadeh (Participant)
Department of Photonics Engineering
Nanophotonics Theory and Signal Processing

Description
Poster presentation
Documents:
IYL 2015

Related event

Danish Opening Ceremony of the International Year of Light
22/01/2015 → 23/01/2015
Lyngby, Denmark
Activity: Attending an event › Participating in or organising workshops, courses, seminars etc.

8th International Congress on Advanced Electromagnetic Materials in Microwaves and Optics
Alireza Taghizadeh (Organizer)
Department of Photonics Engineering
Nanophotonics Theory and Signal Processing

Related event

8th International Congress on Advanced Electromagnetic Materials in Microwaves and Optics
25/08/2014 → 30/08/2014
Kgs. Lyngby, Denmark
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