Low temperature bonding of heterogeneous materials using Al2O3 as an intermediate layer

Direct wafer bonding is a key enabling technology for many current and emerging photonic devices. Most prior work on direct wafer bonding has, however, focused on the Si platform for fabrication of silicon-on-insulator (SOI) and micro-electromechanical systems (MEMS). As a result, a universal bonding solution for heterogeneous material systems has not yet been developed. This has been a roadblock in the realization of novel devices which need the integration of new semiconductor platforms such as III-V on Si, Ge on Sapphire, LiNbO3 on GaAs etc. The large thermal expansion coefficient mismatch in the hetero-material systems limits the annealing to low temperatures to avoid stressed films. This work explores the use of Al2O3 as an intermediate layer for bonding heterogeneous materials. The key to achieve a stronger bond is to maximize the hydroxyl group density of the bonding interfaces. The use of Al2O3 helps achieve that, since it has a high hydroxyl group density (around 18 OH/nm2 at RT) which is approximately 4 times that of a Si surface. This work optimizes the bonding process using Al2O3 by studying the contribution of Al2O3 deposition parameters. An optimized process is presented and applied to bond GaAs on Sapphire and InP on SiO2/Si.
Low temperature bonding of heterogeneous materials using Al₂O₃ as an intermediate layer
Integration of heterogeneous materials is crucial for many nanophotonic devices. The integration is often achieved by bonding using polymer adhesives or metals. A much better and cleaner option is direct wafer bonding, but the high annealing temperatures required make it a much less attractive option. Direct wafer bonding relies on a high density of hydroxyl groups on the surfaces, which may be difficult to achieve depending on the materials. Thus, it is a challenge to design a universal wafer bonding process. However, using an intermediate layer between the bonding surfaces reduces the dependence on the bonding materials, and thus, the bonding mechanism essentially remains the same. The authors present a systematic study on the use of Al₂O₃ as an intermediate layer for bonding of heterogeneous materials. The ability to achieve high hydroxyl group density and well-controlled films makes atomic layer deposited Al₂O₃ an excellent choice for the intermediate layer. The authors have optimized the bonding process to achieve a high interface energy of 1.7 J/m² for a low temperature annealing of 300 °C. The authors also demonstrate wafer bonding of InP to SiO₂ on Si and GaAs to sapphire using the Al₂O₃ interlayer. Published by the AVS.

General information
Publication status: Published
Organisations: Department of Photonics Engineering, Nanophotonic Devices, Diode Lasers and LED Systems, Department of Micro- and Nanotechnology, Silicon Microtechnology, Centre of Excellence for Silicon Photonics for Optical Communications
Contributors: Sahoo, H. K., Ottaviano, L., Zheng, Y., Hansen, O., Yvind, K.
Number of pages: 6
Publication date: 2018
Peer-reviewed: Yes

Publication information
Volume: 36
Issue number: 1
Article number: 011202
ISSN (Print): 1071-1023
Ratings:
BFI (2018): BFI-level 1
Web of Science (2018): Indexed yes
Original language: English
Keywords: Heterogeneous materials, Direct bonding, Al₂O₃, Low temperature, Silicon photonics, Laser
Electronic versions: LowTempBonding_Revision_Hitesh.pdf
DOIs: 10.1116/1.5005591
Source: PublicationPreSubmission
Source-ID: 140701811
Research output: Contribution to journal > Journal article – Annual report year: 2018 > Research > peer-review

Nano-engineered high-confinement AlGaAs waveguide devices for nonlinear photonics
The combination of nonlinear and integrated photonics enables applications in telecommunication, metrology, spectroscopy, and quantum information science. Pioneer works in silicon-on-insulator (SOI) has shown huge potentials of integrated nonlinear photonics. However, silicon suffers two-photon absorption (TPA) in the telecom wavelengths around 1550 nm, which hampers its practical applications. To get a superior nonlinear performance, an ideal integrated waveguide platform should combine a high material nonlinearity, low material absorption (linear and nonlinear), a strong light confinement, and a mature fabrication technology. Aluminum gallium arsenide (AlGaAs) was identified as a promising candidate for nonlinear applications since 1994. It offers a large transparency window, a high refractive index (n approximate to 3.3), a nonlinear index (n2) on the order of 10(-17) m²W(-1), and the ability to engineer the material bandgap to mitigate TPA. In spite of the high intrinsic nonlinearity, conventional deep-etched AlGaAs waveguides exhibit low effective nonlinearity due to the vertical low-index contrast. To take full advantage of the high intrinsic linear and nonlinear index of AlGaAs material, we reconstructed the conventional AlGaAs waveguide into a high index contrast layout that has been realized in the AlGaAs-on-insulator (AlGaAsOI) platform. We have demonstrated low loss waveguides with an ultra-high nonlinear coefficient and high Q microresonators in such a platform. Owing to the high confinement waveguide layout and state-of-the-art nanolithography techniques, the dispersion properties of the AlGaAsOI waveguide can be tailored efficiently and accurately by altering the waveguide shape or dimension, which enables various applications in signal processing and generation, which will be reviewed in this paper.

General information
Publication status: Published
Pulse carving using nanocavity-enhanced nonlinear effects in photonic crystal Fano structures

We experimentally demonstrate the use of a photonic crystal Fano resonance for carving-out short pulses from long-duration input pulses. This is achieved by exploiting an asymmetric Fano resonance combined with carrier-induced nonlinear effects in a photonic crystal membrane structure. The use of a nanocavity concentrates the input field to a very small volume leading to an efficient nonlinear resonance shift that carves a short pulse out of the input pulse. Here, we demonstrate shortening of ~500 ps and ~100 ps long pulses to ~30 ps and ~20 ps pulses, respectively. Furthermore, we demonstrate error-free low duty cycle return-to-zero signal generation at 2 Gbit/s with energy consumption down to ~1 pJ/bit and power penalty of ~2 dB. The device physics and limitations are analyzed using nonlinear coupled-mode theory.

Signal reshaping and noise suppression using photonic crystal Fano structures

We experimentally demonstrate the use of photonic crystal Fano resonances for reshaping optical data signals. We show that the combination of an asymmetric Fano resonance and carrier-induced nonlinear effects in a nanocavity can be used to realize a nonlinear power transfer function, which is a key functionality for optical signal regeneration, particularly for suppression of amplitude fluctuations of data signals. The experimental results are explained using simulations based on
coupled-mode theory and also compared to the case of using conventional Lorentzian-shaped resonances. Using indium
phosphide photonic crystal membrane structures, we demonstrate reshaping of 2 Gbit/s and 10 Gbit/s return-to-zero on-off
keying (RZ-OOK) data signals at telecom wavelengths around 1550 nm. Eye diagrams of the reshaped signals show that
amplitude noise fluctuations can be significantly suppressed. The reshaped signals are quantitatively analyzed using bit-
error ratio (BER) measurements, which show up to 2 dB receiver sensitivity improvement at a BER of 10−9 compared to a
degraded input noisy signal. Due to
efficient light-matter interaction in the high-quality factor and small mode-volume photonic crystal nanocavity, low energy
consumption, down to 104 fJ/bit and 41 fJ/bit for 2 Gbit/s and 10 Gbit/s, respectively, has been achieved. Device
perspectives and limitations are discussed.

General information
Publication status: Published
Organisations: Department of Photonics Engineering, Quantum and Laser Photonics, High-Speed Optical Communication
Centre of Excellence for Silicon Photonics for Optical Communications, Nanophotonic Devices
Pages: 19596-19605
Publication date: 2018
Peer-reviewed: Yes

Publication information
Journal: Optics Express
Volume: 26
Issue number: 15
ISSN (Print): 1094-4087
Ratings: BFI (2018): BFI-level 2
Web of Science (2018): Indexed yes
Original language: English
Electronic versions: oe_26_15_19596.pdf
DOIs: 10.1364/OE.26.019596
Source: PublicationPreSubmission
Source-ID: 151021367
Research output: Contribution to journal › Journal article – Annual report year: 2018 › Research › peer-review

Single-source chip-based frequency comb enabling extreme parallel data transmission
The Internet today transmits hundreds of terabits per second, consumes 9% of all electricity worldwide and grows by 20-
30% per year(1,2). To support capacity demand, massively parallel communication links are installed, not scaling
favourably concerning energy consumption. A single frequency comb source may substitute many parallel lasers and
improve system energy-efficiency(3,4). We present a frequency comb realized by a non-resonant aluminium-gallium-
aralase-on-insulator (AlGaAsOI) nanowaveguide with 66% pump-tocomb conversion efficiency, which is significantly
higher than state-of-the-art resonant comb sources. This enables unprecedented high data-rate transmission for chip-
based sources, demonstrated using a single-mode 30-core fibre. We show that our frequency comb can carry 661 Tbit s(-
1) of data, equivalent to more than the total Internet traffic today. The comb is obtained by seeding the AlGaAsOI chip with
10-GHz picosecond pulses at a low pump power (85 mW), and this scheme is robust to temperature changes, is energy
efficient and facilitates future integration with on-chip lasers or amplifiers(5,6).

General information
Publication status: Published
Organisations: Department of Photonics Engineering, High-Speed Optical Communication, Centre of Excellence for
Silicon Photonics for Optical Communications, Nanophotonic Devices, Fujikura Ltd., Technical University of Denmark
Contributors: Hu, H., Da Ros, F., Pu, M., Ye, F., Ingerslev, K., Porto da Silva, E., Nooruzzaman, M., Amma, Y., Sasaki, Y.
Mizuno, T., Miyamoto, Y., Ottaviano, L., Semenova, E., Guan, P., Zibar, D., Galili, M., Yvind, K., Morioka, T., Oxenløwe,
L. K.
Pages: 469-74
Publication date: 2018
Peer-reviewed: Yes

Publication information
Journal: Nature Photonics
Volume: 12
Issue number: 8
ISSN (Print): 1749-4885
Ratings:
Ultra-Efficient and Broadband Nonlinear AlGaAs-on-Insulator Chip for Low-Power Optical Signal Processing

Four-wave mixing (FWM) is a versatile optical nonlinear parametric process that enables a plethora of signal processing functionalities in optical communication. Realization of efficient and broadband all-optical signal processing with ultra-low energy consumption has been elusive for decades. Although tremendous efforts have been put into developing various material platforms, it has remained a challenge to obtain both high efficiency and broadband operation. Here, an aluminum gallium arsenide nonlinear chip with high FWM conversion efficiency per length per pump power and an ultra-broad bandwidth is presented. Combining an ultra-high material nonlinearity and strong effective nonlinear enhancement from a high-index-contrast waveguide layout, an ultra-high conversion efficiency of −4 dB is obtained in a 3-mm-long nanowaveguide. Taking advantage of high-order dispersion, a scheme is presented to realize an ultra-broad continuous conversion bandwidth covering 1280–2020 nm. A microresonator is also utilized to demonstrate a conversion efficiency enhancement gain of more than 50 dB with respect to a waveguide device, which significantly reduces the power consumption. Moreover, wavelength conversion of an optical serial data signal is performed at a bit rate beyond terabit-per-second, showing the capabilities of this III-V semiconductor material for broadband optical signal processing.

Wavelength tunable MEMS VCSELs for OCT imaging

MEMS VCSELs are one of the most promising swept source (SS) lasers for optical coherence tomography (OCT) and one of the best candidates for future integration with endoscopes, surgical probes and achieving an integrated OCT system. However, the current MEMS-based SS are processed on the III-V wafers, which are small, expensive and challenging to work with. Furthermore, the actuating part, i.e., the MEMS, is on the top of the structure which causes a strong dependence on packaging to decrease its sensitivity to the operating environment. This work addresses these design drawbacks and proposes a novel design framework. The proposed device uses a high contrast grating mirror on a Si MEMS stage as the bottom mirror, all of which is defined in an SOI wafer. The SOI wafer is then bonded to an InP III-V wafer with the desired active layers, thereby sealing the MEMS. Finally, the top mirror, a dielectric DBR (7 pairs of TiO2 - SiO2), is deposited on top. The new device is based on a silicon substrate with MEMS defined on a silicon membrane in an enclosed cavity. Thus the device is much more robust than the existing MEMS VCSELs. This design also enables
either a two-way actuation on the MEMS or a smaller optical cavity (pull-away design), i.e., wider FSR (Free Spectral Range) to increase the wavelength sweep. Fabrication of the proposed device is outlined and the results of device characterization are reported.

**General information**
Publication status: Published
Organisations: Department of Photonics Engineering, Nanophotonic Devices, Quantum and Laser Photonics, High-Speed Optical Communication, Experimental Surface and Nanomaterials Physics, Department of Micro- and Nanotechnology, Silicon Microtechnology, OCTLIGHT ApS
Contributors: Sahoo, H. K., Ansbæk, T., Ottaviano, L., Semenova, E., Hansen, O., Yvind, K.
Number of pages: 6
Publication date: 2018

**Host publication information**
Title of host publication: *Proceedings of SPIE*
Volume: 10552
Publisher: SPIE - International Society for Optical Engineering
Article number: 105520I
ISBN (Print): 9781510615892
(Keywords: MEMS, VCSEL, OCT, Wavelength tunable, Low threshold)
Electronic versions: 105520I.pdf
DOIs:
[10.1117/12.2289545](https://doi.org/10.1117/12.2289545)
Source: FindIt
Source-ID: 2398598570
Research output: Chapter in Book/Report/Conference proceeding – Article in proceedings – Annual report year: 2018 – Research – peer-review

**An ultra-efficient nonlinear planar integrated platform for optical signal processing and generation**
This paper will discuss the recently developed integrated platform: AlGaAs-on-insulator and its broad range of nonlinear applications. Recent demonstrations of broadband optical signal processing and efficient frequency comb generations in this platform will be reviewed.

**General information**
Publication status: Published
Organisations: Department of Photonics Engineering, Nanophotonic Devices, High-Speed Optical Communication, Fiber Optics, Devices and Non-linear Effects, Diode Lasers and LED Systems
Publication date: 2017

**Host publication information**
Title of host publication: *Proceedings of Asia Communications and Photonics Conference, ACPC 2017*
Volume: 2017
ISBN (Print): 9781557528209
(Keywords: Electronic, Optical and Magnetic Materials, Mechanics of Materials, Aluminum gallium arsenide, Gallium compounds, Nonlinear optics, Photonics, Signal processing, Frequency combs, Integrated platform, Nonlinear applications, Ultra-efficient, Optical signal processing)
DOIs:
[10.1364/ACPC.2017.S4J.6](https://doi.org/10.1364/ACPC.2017.S4J.6)
Source: FindIt
Source-ID: 2396990319
Research output: Chapter in Book/Report/Conference proceeding – Article in proceedings – Annual report year: 2018 – Research – peer-review

**Characterization and optimization of a high-efficiency AlGaAs-On-Insulator-based wavelength converter for 64- and 256-QAM signals**
In this paper, we demonstrate wavelength conversion of advanced modulation formats such as 10-Gbd 64-QAM and 256-QAM with high conversion efficiency over a 29-nm spectral window by using four-wave mixing in an AlGaAs-On-Insulator (AlGaAsOI) nano-waveguide. A thorough characterization of the wavelength converter is reported, including the optimization of the AlGaAsOI nano-waveguide in terms of conversion efficiency and associated bandwidth and the analysis of the impact of the converter pump quality and power as well as the signal input power. The optimized converter
enables generating idlers with optical signal-to-noise ratio (OSNR) above 30 dB over a 29-nm bandwidth leading to error-free conversion of 64-QAM and 256-QAM with OSNR penalty below 1.0 dB and 2.0 dB respectively. The generated idlers exhibit an OSNR margin to the chosen forward error correction thresholds of >3 dB and >7 dB for 64-QAM and 256-QAM, respectively, that can be used for transmission after conversion.

**General information**

Publication status: Published
Organisations: Department of Photonics Engineering, High-Speed Optical Communication, Centre of Excellence for Silicon Photonics for Optical Communications, Coding and Visual Communication, Nanophotonic Devices
Number of pages: 8
Pages: 3750-3757
Publication date: 2017
Peer-reviewed: Yes

**Publication information**

Journal: Journal of Lightwave Technology
Volume: 35
Issue number: 17
ISSN (Print): 0733-8724
Ratings:
  - BFI (2017): BFI-level 2
  - Scopus rating (2017): CiteScore 4.42 SJR 1.166 SNIP 1.791
  - Web of Science (2017): Impact factor 3.652
  - Web of Science (2017): Indexed yes
Original language: English
Keywords: Four-wave mixing, Integrated waveguides, Quadrature amplitude modulation, Coherent communications
Electronic versions:
  - DaRos_JLT2017_prePrint.pdf
DOIs:
  - 10.1109/JLT.2017.2722013

**Bibliographical note**

(c) 2017 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other users, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works for resale or redistribution to servers or lists, or reuse of any copyrighted components of this work in other works.
Source: PublicationPreSubmission
Source-ID: 133665129
Research output: Contribution to journal – Journal article – Annual report year: 2017 – Research – peer-review

**Fabrication and experimental demonstration of photonic crystal laser with buried heterostructure**

Development of ultra-small and efficient laser sources for photonic integrated circuits is one of the main cornerstones in achieving the requirements imposed for on-chip optical interconnects [1]. The InP photonic crystal (PhC) platform with selectively embedded gain medium [2] is a promising way of separating active light amplification regions from passive regions for light propagation without induced absorption losses and surface recombination. The main focus of this work is the fabrication and experimental demonstration of a buried heterostructure (BH) photonic crystal laser bonded to a silicon wafer, illustrating the effective single-platform active-passive material integration method.

**General information**

Publication status: Published
Organisations: Department of Photonics Engineering, Nanophotonic Devices, Quantum and Laser Photonics, DTU Danchip
Contributors: Sakanas, A., Yu, Y., Semenova, E., Ottaviano, L., Sahoo, H. K., Mørk, J., Yvind, K.
Number of pages: 1
Pages: 1-1
Publication date: 2017

**Host publication information**

Title of host publication: 2017 Conference on Lasers and Electro-Optics Europe & European Quantum Electronics Conference
Publisher: IEEE
ISBN (Print): 9781509067367
Keywords: Photonic crystals, Indium phosphide, III-V semiconductor materials, Cavity resonators, Fabrication, Quantum dot lasers
Lasers, switches and non-reciprocal elements based on photonic crystal Fano resonances
We discuss the realization of active photonic devices exploiting Fano resonances in photonic crystal membranes.

Optical Time Domain Demultiplexing using Fano Resonance in InP Photonic Crystals

Parity control of Fano resonances and its application for signal regeneration and pulse carving
Parity control of Fano resonances in a photonic crystal waveguide coupled to a nanocavity is implemented by controlling the position of a partially transmitting element (PTE) in the waveguide. We experimentally demonstrate regeneration and pulse carving of optical signals by exploiting nonlinearities in the nanocavity in combination with the asymmetrical Fano shape.

Photonic crystal Fano lasers and Fano switches
We show that Fano resonances can be realized in photonic crystal membrane structures by coupling line-defect waveguides and point-defect nanocavities. The Fano resonance can be exploited to realize optical switches with very small switching energy, as well as Fano lasers, that can generate short optical pulses.

Photonic crystal Fano resonances for realizing optical switches, lasers and non-reciprocal elements
We present our work on photonic crystal membrane devices exploiting Fano resonance between a line-defect waveguide and a side coupled nanocavity. Experimental demonstration of fast and compact all-optical switches for wavelength-conversion is reported. It is shown how the use of an asymmetric structure in combination with cavity-enhanced nonlinearity can be used to realize non-reciprocal transmission at ultra-low power and with large bandwidth. A novel type of laser structure, denoted a Fano laser, is discussed in which one of the mirrors is based on a Fano resonance. Finally, the design, fabrication and characterization of grating couplers for efficient light coupling in and out of the indium phosphide photonic crystal platform is discussed.
Towards Polarization-Independent Four-Wave Mixing in Dispersion Engineered AlGaAs-on-Insulator Nano-Waveguide

We demonstrate a polarization-independent continuous wave four-wave mixing conversion bandwidth of 70 nm (1530-1600 nm) in a dispersion engineered high-index contrast AlGaAs-on-insulator nano-waveguide. We obtain constant conversion efficiency over 175 nm for the TE mode.

General information
Publication status: Published
Organisations: Department of Photonics Engineering, Nanophotonic Devices, Centre of Excellence for Silicon Photonics for Optical Communications, DTU Danchip
Contributors: Pu, M., Ottaviano, L., Semenova, E., Yvind, K.
Number of pages: 3
Publication date: 2017

Host publication information
Title of host publication: Proceedings of 2017 European Conference on Optical Communication (ECOC)
Publisher: IEEE
ISBN (Print): 978-1-5386-5624-2
DOIs: 10.1109/ECOC.2017.8345909
Source: FindIt
Source-ID: 2432498652

Towards Ultra-High Q Microresonators in High-Index Contrast AlGaAs-On-Insulator

We demonstrate an AlGaAs-on-insulator microresonator with intrinsic Q as high as 690,000. We optimized the fabrication and investigated the impact of waveguide dimension on the Q in such a high-index contrast platform.

General information
Publication status: Published
Organisations: Department of Photonics Engineering, Nanophotonic Devices, Centre of Excellence for Silicon Photonics for Optical Communications, Fiber Optics, Devices and Non-linear Effects
Contributors: Pu, M., Kamel, A. N., Stassen, E., Ottaviano, L., Semenova, E., Yvind, K.
Number of pages: 2
Publication date: 2017

Host publication information
Title of host publication: CLEO: Science and Innovations 2017
Publisher: Optical Society of America OSA
Article number: SM1N.3
DOIs: 10.1364/CLEO_SI.2017.SM1N.3

Bibliographical note
From the session: High-Q Micro-cavities and Applications

An Ultra-Efficient Nonlinear Platform: AlGaAs-On-Insulator

The combination of nonlinear and integrated photonics enables applications including optical signal processing, multi-wavelength lasers, metrology, spectroscopy, and quantum information science. Silicon-on-insulator (SOI) has emerged as a promising platform [1, 2] due to its high material nonlinearity and its compatibility with the CMOS industry. However, silicon suffers two-photon absorption (TPA) in the telecommunication wavelength band around 1.55 µm, which hampers its applications. Different platforms have been proposed to avoid TPA in the telecom wavelength range such as Si3N4 and Hydex [3]. Though tremendous technological work in those platforms have greatly improved device performances, the relatively low intrinsic material nonlinearities of those materials limit device performances concerning efficiency. Therefore, an integrated nonlinear platform that combines a high material nonlinearity, a high-index contrast as SOI, and low linear
and nonlinear losses is highly desired. Aluminium gallium arsenide (AlGaAs) was early identified as a promising candidate and even nominated as “the silicon of nonlinear optical material” [4] when operated just below half its bandgap energy. It offers a nonlinear index (n2) on the order of 10−17 W/m2 and a high refractive index (n ≈3.3), a large transparency window (from near- to mid-infrared), and the ability to engineer the material bandgap to mitigate TPA [5]. In this presentation, we introduce AlGaAs-on-insulator (AlGaAsOI) platform which combines both strong nonlinear light-matter interaction induced by high-index contrast layout and the potential to fabricate complex designs similar to what is done in silicon-on-insulator photonics. We demonstrate low loss (~ 1.4 dB/cm) nanowaveguides with an ultra-high nonlinear coefficient (~660W−1m−1) and microring resonators with quality factors on the order of 105 [6]. The large effective nonlinearity of such platform enables efficient nonlinear processes such as high-speed optical signal processing [7], supercontinuum generation, and Kerr frequency comb generation [8]. Moreover, the required operation power for signal generation processes such as optical parametric oscillation in the AlGaAsOI platform is well within the range of standard on-chip light sources. In line with the fast-growing hybrid integration trend to combine different materials in multiple levels on a single CMOS compatible chip, the AlGaAsOI platform is very promising for realizing a compact fully-integrated multi-wavelength light source for high bandwidth optical interconnects.

**General information**

Publication status: Published

Organisations: Department of Photonics Engineering, Nanophotonic Devices, Centre of Excellence for Silicon Photonics for Optical Communications, High-Speed Optical Communication

Contributors: Pu, M., Ottaviano, L., Semenova, E., Hu, H., Oxenløwe, L. K., Yvind, K.

Number of pages: 1

Publication date: 2016

Peer-reviewed: Yes

Event: Abstract from Progress In Electromagnetics Research Symposium 2016, Shanghai, China.

Electronic versions:

2016_08_PIERS_An_Ultra_Efficient_Nonlinear_Platform_AlGaAsOI.pdf

DOIs:

10.1109/PIERS.2016.7735233

Source: PublicationPreSubmission

Source-ID: 127226577

Research output: Contribution to conference › Conference abstract for conference – Annual report year: 2016 › Research › peer-review

**Broadband and Efficient Dual-Pump Four-Wave Mixing in AlGaAs-On-Insulator Nano-Waveguide**

We characterize dual-pump four-wave-mixing in AlGaAs-on-insulator nano-waveguides and demonstrate an output conversion efficiency as high as −8.5 dB at 155-mW pump power. The idler optical signal-to-noise ratio is above 25 dB over a 26-nm bandwidth.

**General information**

Publication status: Published

Organisations: Department of Photonics Engineering, High-Speed Optical Communication, Centre of Excellence for Silicon Photonics for Optical Communications, Nanophotonic Devices

Contributors: Da Ros, F., Pu, M., Ottaviano, L., Hu, H., Semenova, E., Galili, M., Yvind, K., Oxenløwe, L. K.

Number of pages: 2

Publication date: 2016

**Host publication information**

Title of host publication: CLEO: Science and Innovations 2016

Place of publication: San Jose, California United States

Publisher: Optical Society of America OSA

Article number: SM1E.3


DOIs:

10.1364/CLEO_SI.2016.SM1E.3

Source: PublicationPreSubmission

Source-ID: 124337238

Research output: Chapter in Book/Report/Conference proceeding › Conference abstract in proceedings – Annual report year: 2016 › Research › peer-review

**Broadband and efficient dual-pump four-wave-mixing in AlGaAs-on-insulator nano-waveguides**

We characterize dual-pump four-wave-mixing in AlGaAs-on-insulator nano-waveguides and demonstrate an output conversion efficiency as high as ~8.5 dB at 155-mW pump power. The idler optical signal-to-noise ratio is above 25 dB over a 26-nm bandwidth.
Characterization of a Wavelength Converter for 256-QAM Signals Based on an AlGaAs-On-Insulator Nano-waveguide

High efficiency and broadband wavelength conversion in a 9-nm AlGaAs-On-Insulator waveguide is shown to provide high-quality (OSNR > 30 dB) idler generation over a 28-nm bandwidth enabling error-free conversion of 10-GBd 256-QAM with OSNR penalty below 2.5 dB.

Efficient frequency comb generation in AlGaAs-on-insulator

The combination of nonlinear and integrated photonics enables Kerr frequency comb generation in stable chip-based microresonators. Such a comb system will revolutionize applications, including multi-wavelength lasers, metrology, and spectroscopy. Aluminum gallium arsenide (AlGaAs) exhibits very high material nonlinearity and low nonlinear loss. However, difficulties in device processing and low device effective nonlinearity made Kerr frequency comb generation elusive. Here, we demonstrate AlGaAs-on-insulator as a nonlinear platform at telecom wavelengths with an ultra-high device nonlinearity. We show high-quality-factor (Q > 105) micro-resonators where optical parametric oscillations are achieved with milliwatt-level pump threshold powers, which paves the way for on-chip pumped comb generation.
Low-loss high-confinement waveguides and microring resonators in AlGaAs-on-insulator

AlGaAs is a promising material for integrated nonlinear photonics due to its intrinsic high nonlinearity. However, the challenging fabrication of deep etched AlGaAs devices makes it difficult to realize high-performance devices such as low-loss dispersion engineered waveguides and high quality microring resonators. Here, we report a process to make high-quality AlGaAs-on-insulator (AlGaAsOI) waveguides where high confinement waveguides can be realized. Using optimized patterning processes, we fabricated AlGaAsOI waveguides with propagation losses as low as 1 dB/cm and microring resonators with quality factors up to 350,000 at telecom wavelengths. Our demonstration opens new prospects for AlGaAs devices in integrated nonlinear photonics.

Nonlinear Optics in AlGaAs on Insulator

AlGaAs on insulator is a powerful nonlinear platform sporting a high effective nonlinearity and the possibility to fabricate complex designs. We will present low loss waveguides enabling efficient optical signal processing and Kerr comb generation.

General information
Optically pumped 1550nm wavelength tunable MEMS VCSEL
The paper presents the design and fabrication of an optically pumped 1550nm tunable MEMS VCSEL with an enclosed MEMS. The MEMS is defined in SOI and the active material, an InP wafer with quantum wells are bonded to the SOI and the last mirror is made from the deposition of dielectric materials. The design brings in flexibility to fabricate MEMS VCSELS over a wider range of wavelengths. The paper discusses results from the simulations and bonding results from fabrication. The device will push the boundaries for wavelength sweepspeed and bandwidth.

Phase-sensitive Four-wave Mixing in AlGaAs-on-Insulator Nano-waveguides
Phase-sensitive four-wave mixing is experimentally demonstrated in a 5-mm long AlGaAsOI nano-waveguide. More than 7 dB of phase-sensitive extinction ratio are reported without neither using active biasing nor polarization-assisted schemes. Measurements show a good match with numerical predictions.
Single-Source AlGaAs Frequency Comb Transmitter for 661 Tbit/s Data Transmission in a 30-core Fiber

We demonstrate an AlGaAs-on-insulator nano-waveguide-based frequency comb with high OSNR enabling a single-source to fully load a 9.6-km heterogeneous 30-core fibre with 661 Tbit/s data achieved by 30xcores, 80xWDM, 40 Gbaud, and PDM-16QAM

Supercontinuum Generation in AlGaAs-On-Insulator Nano-Waveguide at Telecom Wavelengths

We characterize pulse spectral broadening in an AlGaAs-on-insulator nano-waveguide at telecom wavelengths. We obtain a supercontinuum over 500 nm (30-dB bandwidth) with 410-fs pulses and self-phase modulation broadening covering the C-band with 1.1-ps pulses.
Surface Plasmons on Highly Doped InP
Silicon doped InP is grown by metal-organic vapor phase epitaxy (MOVPE) using optimized growth parameters to achieve high free carrier concentration. Reflectance of the grown sample in mid-IR range is measured using FTIR and the result is used to retrieve the parameters of the dielectric function. The derived dielectric function is used to simulate the excitation of surface plasmons by a diffraction grating made of the grown material. The grating structure is fabricated using standard nanofabrication techniques. Spectral features from the grating agree well with the simulations and show spp coupling at predicted angles of incidence and wavelengths.

Threshold Characteristics of Slow-Light Photonic Crystal Lasers
The threshold properties of photonic crystal quantum dot lasers operating in the slow-light regime are investigated experimentally and theoretically. Measurements show that, in contrast to conventional lasers, the threshold gain attains a minimum value for a specific cavity length. The experimental results are explained by an analytical theory for the laser threshold that takes into account the effects of slow light and random disorder due to unavoidable fabrication imperfections. Longer lasers are found to operate deeper into the slow-light region, leading to a trade-off between slow-light induced reduction of the mirror loss and slow-light enhancement of disorder-induced losses.
AlGaAs-On-Insulator Nanowire with 750 nm FWM Bandwidth, -9 dB CW Conversion Efficiency, and Ultrafast Operation Enabling Record Tbaud Wavelength Conversion

We present an AlGaAs-on-insulator platform for integrated nonlinear photonics. We demonstrate the highest reported conversion efficiency/length/pump-power, ultra-broadband fourwave mixing, and first-ever wavelength conversion of 1.28-Tbaud serial data signals in a 3-mm long dispersion-engineered AlGaAs nano-waveguide

AlGaAs-On-Insulator nonlinear photonics

We present an AlGaAs-on-insulator platform for integrated nonlinear photonics. We demonstrate the highest reported conversion efficiency and ultra-broadband fourwave mixing for an integrated platform around 1550nm
Highly Efficient Four-Wave Mixing in an AlGaAs-On-Insulator (AlGaAsOI) Nano-Waveguide
We propose an AlGaAs-on-insulator platform for nonlinear integrated photonics. We demonstrate highly efficient four-wave mixing in a 3-mm long AlGaAs-on-insulator nanowaveguide. A conversion efficiency of -21.1 dB is obtained with only a 45-mW pump.

General information
Publication status: Published
Organisations: Department of Photonics Engineering, Nanophotonic Devices
Contributors: Pu, M., Ottaviano, L., Semenova, E., Yvind, K.
Number of pages: 2
Publication date: 2015

Host publication information
Title of host publication: Proceedings of 2015 Conference on Lasers and Electro-Optics (CLEO)
Publisher: IEEE
DOIs:
10.1364/cleo_si.2015.stu1i.3
Source: PublicationPreSubmission
Source-ID: 108590191
Research output: Chapter in Book/Report/Conference proceeding > Article in proceedings – Annual report year: 2015 > Research > peer-review

Highly Sensitive Photonic Crystal Cavity Laser Noise Measurements using Bayesian Filtering
We measure for the first time the frequency noise spectrum of a photonic crystal cavity laser with less than 20 nW of fiber-coupled output power using a coherent receiver and Bayesian filtering.

General information
Publication status: Published
Organisations: Department of Photonics Engineering, High-Speed Optical Communication, Quantum and Laser Photonics, Nanophotonic Devices, Metro-Access and Short Range Systems, Helmut-Schmidt-University
Number of pages: 3
Publication date: 2015

Host publication information
Title of host publication: Proceedings of 2015 Optical Fiber Communications Conference and Exhibition
Publisher: IEEE
Article number: W2A.28
ISBN (Electronic): 978-1-55752-937-4
DOIs:
10.1364/OFCC.2015.W2A.28
Source: PublicationPreSubmission
Source-ID: 110721203
Research output: Chapter in Book/Report/Conference proceeding > Article in proceedings – Annual report year: 2015 > Research > peer-review

Slow-light effects in photonic crystal membrane lasers
In this paper, we present a systematic investigation of photonic crystal cavity laser operating in the slow-light regime. The dependence of lasing threshold on the effect of slow-light will be particularly highlighted.

General information
Publication status: Published
Organisations: Department of Photonics Engineering, Quantum and Laser Photonics, Nanophotonic Devices, Department of Micro- and Nanotechnology
Contributors: Xue, W., Yu, Y., Ottaviano, L., Semenova, E., Yvind, K., Mørk, J.
Number of pages: 3
Pages: 1-3
Publication date: 2015

Host publication information
Title of host publication: 2015 Opto-Electronics and Communications Conference (OECC)
Publisher: IEEE
ISBN (Print): 9781467379441
Keywords: Communication, Networking and Broadcast Technologies, Fields, Waves and Electromagnetics, Photonics and Electrooptics, Cavity resonators, Epitaxial growth, Integrated optics, Optical losses, Optical pumping, Photonics, Solids
Thermal analysis of line-defect photonic crystal lasers
We report a systematic study of thermal effects in photonic crystal membrane lasers based on line-defect cavities. Two material platforms, InGaAsP and InP, are investigated experimentally and numerically. Lasers with quantum dot layers embedded in an InP membrane exhibit lasing at room temperature under CW optical pumping, whereas InGaAsP membranes only lase under pulsed conditions. By varying the duty cycle of the pump beam, we quantify the heating induced by optical pumping in the two material platforms and compare their thermal properties. Full 3D finite element simulations show the spatial temperature profile and are in good agreement with the experimental results concerning the thermal tolerance of the two platforms.

We present a record-low threshold power of 7 mW at ~1.55 µm for on-chip optical parametric oscillation using a high quality factor micro-ring-resonator in a new nonlinear photonics platform: AlGaAs-on-insulator
Tailored design of WDM filters in BCB embedded PhC membranes

We propose a design strategy for wavelength division multiplexing (WDM) filters in BCB embedded photonic crystal membranes. Due to the weaker vertical confinement determined by the material embedding the whole structure, accurate tailoring of the resonant cavity and of both bus and drop waveguides is necessary, in order to guarantee the required performance of the filter for WDM applications.

General information
Publication status: Published
Organisations: Department of Photonics Engineering, Nanophotonic Devices, University of Ferrara, Thales
Contributors: Malaguti, S., Bellanca, G., Ottaviano, L., Yvind, K., Combrié, S., Rossi, A. D., Trillo, S.
Pages: 329-342
Publication date: 2013
Peer-reviewed: Yes

Publication Information
Journal: Optical and Quantum Electronics
Volume: 45
Issue number: 4
ISSN (Print): 0306-8919
Ratings:
BFI (2013): BFI-level 1
Scopus rating (2013): CiteScore 1.29 SJR 0.58 SNIP 0.881
Web of Science (2013): Impact factor 1.078
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
Original language: English
Keywords: Photonic crystals, Photonic crystal cavities, Photonic crystal filters
DOIs:
10.1007/s11082-012-9646-0
Source: dtu
Source-ID: n::oai:DTIC-ART:springer/383343022::29862

High-speed photodetectors in a photonic crystal platform

We demonstrate a fast photodetector (f3dB > 40GHz) integrated into a high-index contrast photonic crystal platform. Device design, fabrication and characterization are presented.

General information
Publication status: Published
Organisations: Department of Photonics Engineering, Nanophotonic Devices, Nanophotonics, Universite europeenne de Bretagne, University of Ferrara
Number of pages: 2
Publication date: 2012

Host publication information
Title of host publication: CLEO Technical Digest
Publisher: Optical Society of America
Electronic versions:
BEB6Fd01.pdf
High-speed photodetectors in a photonic crystal platform.pdf

Bibliographical note
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. Systematic or multiple reproduction or distribution to multiple locations via electronic or other means is prohibited and is subject to penalties under law.
Source: dtu
Strip detector for nanoscale resolution

General information
Publication status: Published
Organisations: Metal Structures in Four Dimensions, Materials Research Division, Risø National Laboratory for Sustainable Energy, Department of Photonics Engineering, Nanophotonic Devices
Contributors: Olsen, U. L., Schmidt, S., Poulsen, H. F., Yvind, K., Ottaviano, L.
Publication date: 2009

Event information
Event: Detektor Workshop
Location: Risø (DK), 27 Feb.
Keywords: Materials characterization and modelling, Materials research
Electronic versions:
Detector_presentation.pdf
Source: orbit
Source-ID: 254907
Research output: Non-textual form Sound/Visual production (digital) – Annual report year: 2009 Research

Projects:

Fabrication and characterization of novel nanophotonic structures with electrical control
Marchevsky, A., PhD Student, Department of Photonics Engineering
Yvind, K., Main Supervisor
Mørk, J., Supervisor
Ottaviano, L., Supervisor
Samfinansierede - Virksomhed
01/10/2016 → 30/09/2019
Award relations: Fabrication and characterization of novel nanophotonic structures with electrical control
Project: PhD

Ultrahigh-speed Si-integrated on-chip laser
Tandukar, S., PhD Student, Department of Photonics Engineering
Chung, I., Main Supervisor
Ottaviano, L., Supervisor
Frandsen, L. H., Examiner
Almuneau, G., Examiner
Hammar, M., Examiner
Samfinansieret - Andet
15/11/2015 → 14/01/2019
Award relations: Ultrahigh-speed Si-integrated on-chip laser
Project: PhD

Ultrahigh-speed hybrid III-C-on-Si lasers
Topic, V., PhD Student, Department of Photonics Engineering
Chung, I., Main Supervisor
Ottaviano, L., Supervisor
Yvind, K., Examiner
Birkedal, D., Examiner
Bakir, B. B., Examiner
Samfinansieret - Andet
15/03/2015 → 14/02/2019
Award relations: Ultrahigh-speed hybrid III-C-on-Si lasers
Project: PhD

Photonic crystal Fano structures
Bekele, D. A., PhD Student, Department of Photonics Engineering
This project is dedicated to the research of quantum dot (QD) epitaxial growth on both indium phosphate (InP) and silicon (Si) based platforms with the aim of creating superior gain material emitting in the 1.5-1.6 μm wavelength range. The majority of the proposed research is quite fundamental but will have noticeable impact to device applications for our everyday life in the near future. Diverse areas like telecommunication, optical coherence tomography including medical applications, sensing, computer and network clock-distribution, THz generation, and metrology can benefit from the materials investigated.

The projected research covers two directions. The first is the development of QDs which possess desired electronic and optical properties in the InP based material system, i.e. tailoring the energy level structure and wave functions in the dots. Manipulating the shape, chemical composition and surroundings of the nanostructures is the key to achieving the set goals. In the frame of the project I will implement two different approaches to design and grow high optical quality arrays of QDs. Those approaches are self-assembled quantum dot growth and selective area growth using block copolymer lithography. The second direction of the research is the deployment of the highly efficient QD gain material to a silicon platform. The development of epitaxial growth technology of III-V materials on Si combines the benefits of high optical quality III-V QD gain material with low cost silicon photonics, which is a key platform to push towards increased integration, higher speed and lower energy consumption.

COPERNICUS: Compact Otdm/wdm oPtical rEceiveRs based on photoNic crystal Integrated
COPERNICUS aims to develop compact demultiplexing receivers for 100 Gb/s optical time division multiplexed (OTDM) and wavelength division multiplexed (WDM) signals, based on photonic crystal technology. There is a pressing need for these devices for ultra-high bandwidth data links in server farms, optical storage networks and on-board internet/entertainment systems, where demand is driving the data bandwidth and technology integration level rapidly upwards. Next generation telecom systems will also benefit from these devices for OTDM and optical packet switching. Their high-speed and bandwidth, together with their ultra-low power consumption and extreme compactness, also make them a very promising technology for seamless cross-chip and off-chip data links for CMOS electronics. This approach has all the hallmarks of a highly disruptive technology with the potential to place Europe at the forefront of photonics. COPERNICUS targets advances in the physics, technology, modelling, and integration of photonic crystal devices. Key devices include high-speed all-optical gates, low-crosstalk wavelength drop filters, and high-speed integrated photodetectors. These devices rely on very strong light-matter interactions arising from the large, ultrafast nonlinear optical response of III-V semiconductors and the strong resonant field enhancement in photonic crystals. This is ideal for filters and all optical gates, enabling a dramatic reduction in size and switching energy. Their switching energy*delay product is two orders of magnitude smaller than that of competing technologies. Modelling will consider carrier plasma (spectral and spatial) contributions to the nonlinear optical response and develop a robust optical, thermal and electronic design tool for photonic crystal devices. New levels of photonic crystal integration will be pursued to combine these devices and achieve complex all-optical functions attractive to both medium- and long-term markets.

Prevotat, O., Contact Person, Thales
Wynne-Jones, M., Project Participant, University of Nottingham
Traimond, G., Contact Person, Centre National de la Recherche Scientifique
Bujan, G., Contact Person, Centre National de la Recherche Scientifique
Nielsen, C., Contact Person, Department of Photonics Engineering, Nanophotonic Devices
Activities:

**Tunable MEMS VCSEL on silicon substrate**

*Period: 12 Apr 2018 → 13 Apr 2018*

Hitesh Kumar Sahoo (Speaker)
Thor Ansbæk (Speaker)
Luisa Ottaviano (Speaker)
Elizaveta Semenova (Speaker)
Fedor I. Zubov (Guest lecturer)
Ole Hansen (Speaker)
Kresten Yvind (Speaker)

Centre of Excellence for Silicon Photonics for Optical Communications

Quantum and Laser Photonics

High-Speed Optical Communication

Nanophotonic Devices

Department of Photonics Engineering

Degree of recognition: International

**Related event**

**11th European VCSEL Day 2018**

*12/04/2018 → 13/04/2018*

Ulm, Germany

Activity: Talks and presentations › Conference presentations

**Ultrahigh-speed hybrid VCSEL for short-distance optical interconnects**

*Period: 28 Aug 2017 → 1 Sep 2017*

Vladimir Topic (Speaker)
Gyeong Cheol Park (Other)
Sushil Tandukar (Other)
Luisa Ottaviano (Other)
Il-Sug Chung (Other)

Department of Photonics Engineering

**Description**

Poster presentation

Degree of recognition: International
Related event

VI International School and Conference on Photonics
28/08/2017 → 01/09/2017
Belgrade, Serbia

Activity: Talks and presentations › Conference presentations