INSTITUT foton

Highlights 2020

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INSA INSTITUT NATIONAL DES SCIENCES APPLIQUÉES RENNES

SPM Physique Chimie Mécanique

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IMT Atlantique Bretagne-Pays de la Loire École Mines-Télécom

ENSSAT LANNION

FOREWORD

This document is a digest of **scientific highlights selected** among the results obtained during year **2020** by the teams and platforms(*) of Institut FOTON (CNRS UMR 6082). By browsing these pages the reader will get a flavor of the on-going research topics in our laboratory, that are organized around six axes:

Axis I: Devices and functionalities for optical communications

Axis II: Microwave, millimeter-wave, and THz optics

Axis III: Innovative materials for photonics

Axis IV: Instrumentation, optical sensors and coherent imaging

Axis V: Advanced concepts for photovoltaics

Axis VI: Physics and metrology of lasers

Each highlight corresponds to an article published in an international peer-reviewed journal. The reader will find **additional information through that reference**, or by **contacting** the mentioned **laboratory member**.

Please visit also the laboratory **website** : http://foton.cnrs.fr/

(*)The Institut FOTON is composed of three research teams:

- ***DOP** team (Univ. Rennes 1 / CNRS), Rennes Beaulieu – Head: F. Bondu*
- ***OHM** team (INSA / CNRS), Rennes INSA - Head: C. Cornet*
- ***SP** team (Univ. Rennes 1 / CNRS), Lannion ENSSAT – Head: M. Thual*

and three platforms:

- ***CCLO** (Univ. Rennes 1 / CNRS), Lannion ENSSAT – Head: M. Guendouz*
- ***PERSYST** (Univ. Rennes 1 / CNRS), Lannion ENSSAT – Head: M. Gay*
- ***NANORENNES** (INSA / Univ. Rennes 1 / CNRS), Rennes INSA – Head: C. Paranthoën*

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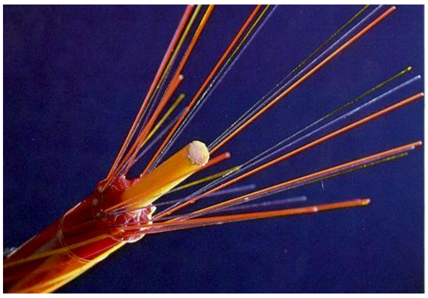


HIGHLIGHTS

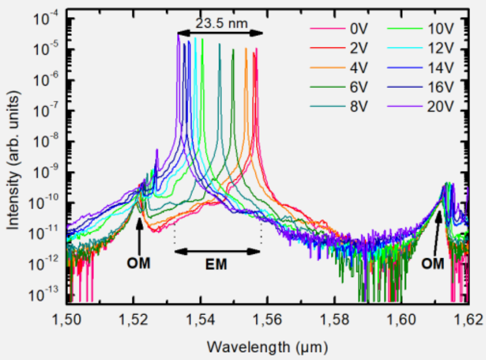
INP BASED VCSEL INTEGRATING LIQUID CRYSTAL MICRO-CELLS

OHM / DOP

Miniaturized tunable photonic devices can be of great interest for applications in wavelength division multiplexing systems or metrology applications. For a widespread deployment, such systems have to be compact, dynamically reconfigurable in wavelength, and with a low power consumption. To achieve such devices, many studies have been conducted in the past by using the MEMS technologies. However, MEMS solutions may have some drawbacks related to power consumption, high driving voltage or fragility of the MEMS structure.

As an alternative to this MEMS approach, the use of the well-known and mature liquid crystals (LC) material within a monolithic microcavity structure has been proposed. After successful demonstration of a tunable photodiode in 2018 and 2019 which was used as a micro-spectrometer in the telecom C-band (see more information), we present here a tunable InP based Vertical Cavity Surface Emitting Laser integrating the same LC micro-cell technology than the one used for the photodiode.

For such a device, laser emission in CW operation has been demonstrated for the first time with this LC based technology. This tunable VCSEL has been characterized under optical pumping with typical threshold of 6 mW, which is very similar to the one obtained with single frequency VCSELs realized without any LC micro-cells. This is an experimental evidence than optical losses introduced by the LC inserted in the VCSEL cavity are very low. Output power in the mW range is also demonstrated. As shown on the figure, without applying any voltage on the LC, VCSEL wavelength is centered at 1557 nm. The VCSEL output polarization state is almost fixed according to the LC alignment, corresponding to the extraordinary mode (EM) of the LC birefringent material. By increasing the applied voltage up to 20 V, this mode is bue-shifted down to 1534 nm to achieve a wavelength tuning higher than 23 nm. On these lasing spectra, ordinary modes (OM) can be also seen. Expected to be unchanged with voltage, the OM are all slightly red-shifted. For a better understanding of this behavior, thermo-optical simulations have been conducted. By taking into account the heating properties of the LC and the reduction in its birefringence with temperature, all these wavelength shifts have been completely reproduced. Finally, by using LC with a better thermal tolerance larger tuning ranges are expected. Further works including investigation of the dynamical behavior of wavelength tuning are under investigation. Indeed, typical response time of such LC being in the millisecond range, a frequency chirp of 4 THz/ms could be also reached for coherent Lidar applications.



Contact

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Reference

"CW Operation of a Tunable 1550-nm VCSEL Integrating Liquid-Crystal Microcells", B.Boisnard *et al.*, *IEEE Photonics Technol. Lett.* **32** 7 391-394 (apr 2020)

hal-02876673

« CW operation has been demonstrated for the first time with this LC based technology »

More Information

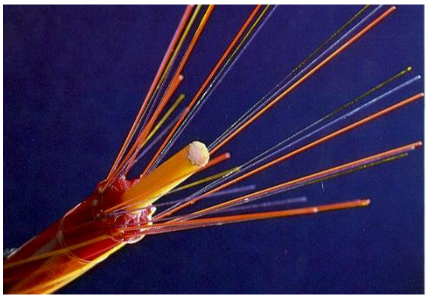
- hal.archives-ouvertes.fr/hal-01879162
- hal.archives-ouvertes.fr/hal-02290527

Collaborations

- Laboratoire d'Analyse et d'Architecture des Systèmes (France)
- Centre de Nanosciences et de Nanotechnologies (France)
- Institut Mines-Telecoms Atlantique (France)
- Institute of Electronics, Computer and Telecommunication Engineering (Italy)

ORIGIN OF OPTICAL LOSSES IN GAP/SI MICRODISK RESONATORS

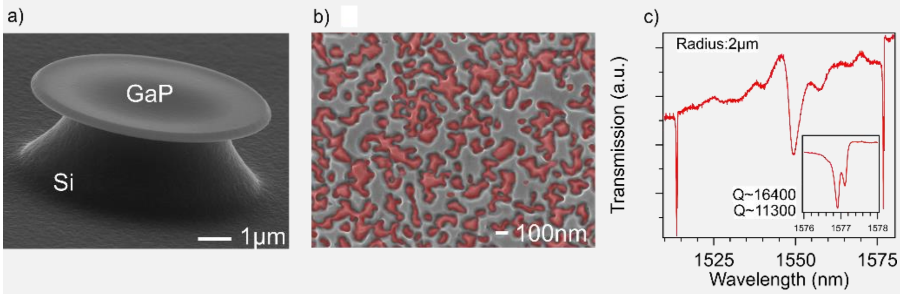
OHM / SP



Photonic components based on III-V semiconductors are at the heart of optical interconnect technologies. III-V alloys are indeed the materials of choice to realize light emitters for optical communications. Encouraged by the quest of cost reduction and miniaturization of the devices, first III-V lasers grown on silicon substrates, with state-of-the-art performances have recently been reported, demonstrating the potential of the platform for future generations of photonic integrated circuits.

But III-V materials are also well-known for their strong nonlinear properties, key ingredients of present and future information processing technologies. Gallium phosphide (GaP) couples this advantage to a large band gap and a lattice parameter well-suited for epitaxial growth on silicon. More than this, we already demonstrated that the random distribution of opposite crystal polarity domains, appearing in GaP when grown on silicon, can be a strong asset for the realization of broadband and reliable nonlinear functionalities. Still, the impact of these so-called antiphase domains (APDs) on the linear optical losses of the material needs to be assessed.

In the present work, high quality factor GaP microdisks (see Fig. a) have been fabricated from a GaP epilayer on silicon. Low roughness at the surface of the devices was achieved by use of chemical mechanical polishing. The APD distribution within was engineered to reach a configuration suited to efficient nonlinear wavelength conversion. In Fig.b, we used chemical etching to reveal APD walls at the surface of the GaP layer, allowing us to monitor the geometrical parameters of the APD distribution. We obtained a near-zero average polarity (same surface of grey and red domains in Fig.b) and typical domain size in the range of 100nm in agreement with our expectation.



The whispering gallery modes of the microdisks around 1550nm were investigated by transmission measurements through a dimpled tapered fiber evanescently coupled to the resonators. A statistical evaluation of the resonances Q factors depending on the disks size was carried out allowing us to identify the different origins of optical losses in the devices. The resonances Q factors, bounded below 20 000 as shown in Fig.c are both limited by the lateral roughness of the devices about 7nm RMS and volume losses induced by APD walls in the range of 10dB/cm for a density of domains wall of 8 000 per mm. With the refinement of our technological process, we expect an improvement of the device Q factors up to 45 000, which holds great promise for the demonstration of random nonlinear phenomena in these devices.

Contact

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Reference

"Loss assessment in random crystal polarity gallium phosphide microdisks grown on silicon", R.Saleem-Urothodi *et al.* *Opt. Lett.* **45** 16 4646-4649 (aug 2020)

hal-02926153

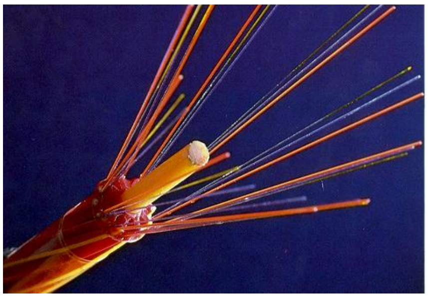
« This is the first assessment of the optical losses induced by antiphase domains in III-V/Si materials »

More Information

- hal.archives-ouvertes.fr/hal-01529567

Collaborations

- Institut d'Electronique et de Télécommunications de Rennes (France)



FREQUENCY CHIRP IN SILICON RING RESONATOR MODULATORS

SP

Silicon ring resonator modulators (RRMs) are promising devices for short-distance optical communication systems thanks to their compactness, energy efficiency and low cost. Their resonant nature enables highly-efficient intensity modulation. Short-distance systems based on direct-detection, such as the inter data center links that are the objects of significant interest at the present time, can reach transmission lengths exceeding 80 km over standard single-mode fibers that are dispersive at 1.5 µm. The frequency chirping properties of RRMs are therefore of paramount importance for such applications. However, they have been to date the object of only a few numerical studies and some preliminary experimental characterizations based on measurements of the instantaneous variations of the frequency in an interferometer or from measurements of the small-signal frequency responses of dispersive direct-detection channels.

In this work, we experimentally investigate the chirping properties of a silicon RRM by measuring the variations of the amplitude and phase of the electric field at its output in the time domain using a coherent detection technique. The measurements are made in the small-signal regime for different wavelength detuning values between the laser and the resonance (noted $\Delta\lambda$), and as a function of the modulation frequency. Fig. 1 (a) shows the time-dependent chirp α-parameter extracted from the measured phase and power waveforms, which is studied and compared to the results of an analytical model, where a good agreement is obtained. In order to circumvent difficulties associated with the divergent nature of the instantaneous chirp parameter $\alpha(t)$, the peak-to-peak chirp parameter α_c is used [1]. It is based on peak-to-peak values of the modulated power and phase waveforms. The full dependence of α_c on wavelength detuning and modulation frequency is then experimentally characterized leading to the maps shown in fig. 1 (b). The variations of the chirp parameter are mainly caused by the variations of intensity modulation amplitude, induced by the spectral response of the RRM. Thus, this comprehensive investigation brings a better understanding of silicon RRMs chirping properties in the dynamic regime in order to optimize them for high-speed communication applications.

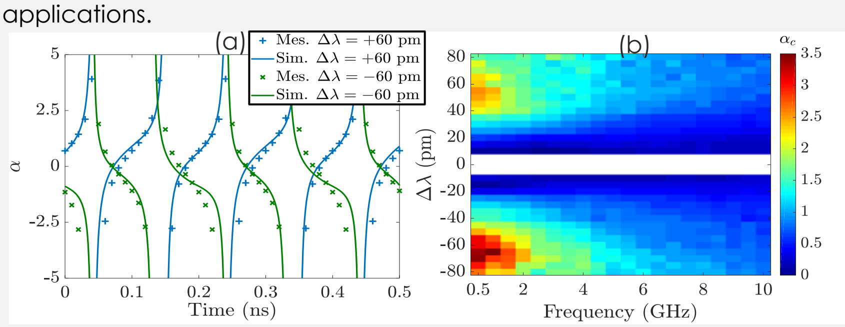


Fig. 1: (a) Measured and simulated α-parameter as a function of time for wavelength detuning values of +60 pm and -60 pm at a modulation frequency of 1 GHz. (b) Measured α_c-parameter as a function of the wavelength detuning and the modulation frequency.

Contact

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Reference

“Comprehensive frequency chirp characterization of silicon ring resonator modulators”, E.Weckenmann *et al.*, OSA Advanced Photonics Congress 2020 ITu1A.4 (jul 2020)

hal-02916195

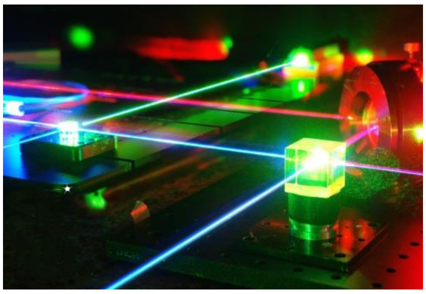
« The influence of the wavelength detuning as well as of the modulation frequency on the RRM time-dependent chirp parameter are shown for the first time »

More Information

- [1] doi.org/10.1109/jlt.2016.2586470

Collaborations

- Centre de Nanosciences et de Nanotechnologies (France)
- ST-Microelectronics (France)



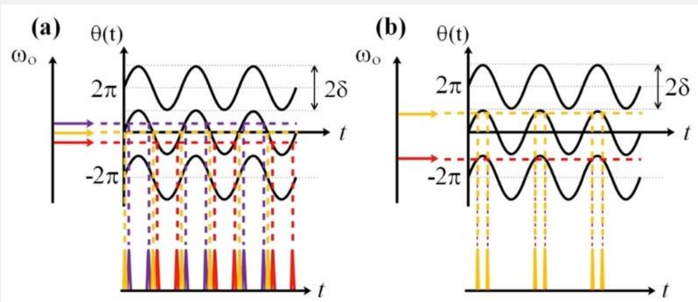
THEORETICAL ANALYSIS OF EO-BASED FREQUENCY-SHIFTING LOOPS

DOP

Frequency-shifted feedback loops (FSL) have attracted much attention recently because their peculiar time-frequency properties could lead to numerous applications, such as ultra-high repetition rate pulse generation, frequency-to-time mapping (FTM), microwave-photonic signal processing, etc. A FSL is a ring resonator seeded by a continuous-wave laser, it contains a modulator and an amplifier. Up to now the modulator in the FSL was usually an acousto-optic (AO) frequency-shifter.

While it features high frequency conversion efficiency in the sub-100 MHz range, AO has limited efficiency in the GHz range and offers limited tunability. Besides, a phase modulator (PM) or an amplitude modulator (AM) can also provide frequency-shifted sidebands at each round-trip, with a potentially much higher bandwidth. In addition, EO modulators are compact and easy to integrate with other fiber devices. We have derived analytical expressions to investigate the output characteristics of the EO-based FSLs. We emphasized in this analysis the cases of the integer and fractional Talbot conditions, and compared the EO-AM and EO-PM schemes to the AO scheme. We can draw some conclusions about the ability of either EO-AM or EO-PM schemes to provide frequency-to-time mapping (FTM), or to multiply the repetition rate through the fractional Talbot effect

When the integer Talbot condition is satisfied, the output signals show periodic pulses in any case, but the three modulation schemes have specific properties. On the one hand, amplitude modulation (EO-AM) FSL fails to provide FTM but features a double-pulse regime with an interval between the two pulses that can be continuously adjusted by changing the static phase retardance or the modulation depth. On the other hand, phase modulation (EO-PM) can yield FTM, with an interesting "mirror effect" due to the sine modulation function in one modulation period. Another specific feature of the EO-PM is the possibility of nonlinear FTM that may lead to chirped pulse generation.



The analysis drawn in this paper will trigger future experimental demonstrations. Indeed, the FTM effect under phase modulation condition needs to be explored, a perspective being the *real-time Fourier transform in an all-integrated system*. Besides, the present analysis predicts the possibility of observing repetition rate multiplication in the AM case, which needs further experimental efforts.

Contact

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Reference

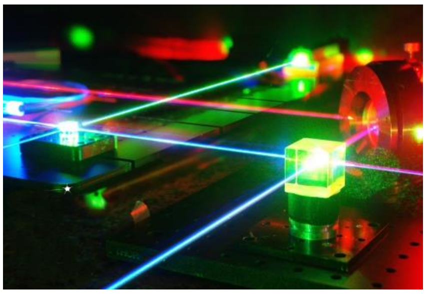
"Analysis of frequency-shifting loops in integer and fractional Talbot conditions: electro-optic *vs* acousto-optic modulation ", H. Yang *et al.*, *J. Opt. Soc. Am. B-Opt. Phys.* **37** 11 3162-3169 (oct 2020)

hal-03046194

« The perspective is the real-time Fourier transform by an all-integrated system »

Collaborations

- Beijing Institute of Technology (China)



HIGHLIGHTS

LOW THRESHOLD 1550-NM EMITTING QD OPTICALLY PUMPED VCSEL

OHM / DOP

Contact

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Reference

"Low threshold 1550 nm emitting QD optically pumped VCSEL", C. Paranthoen et al., IEEE Photonics Technology Letters, **33** 2 69-72 (dec 2020)

hal-03101472

« … first QD VCSEL demonstration at 1550 nm and up to six times threshold reduction … »

More Information

- [1] hal.archives-ouvertes.fr/hal-02338850

Collaborations

- Institut de Physique de Rennes (France)

1550 nm Vertical Cavity Surface Emitting Lasers (VCSELs) are widely used for a wide panel of applications, for long Haul transmission networks, fiber based sensors, and more recently for LIDAR. The association of VCSEL with quantum dots is attractive, because of its high potentials for low threshold, wide wavelength gain and high frequency modulation. The main challenge lies on the QDs themselves, as the VCSEL growth prerequisites to maximize the modal gain are much more restrictive than edge emitting lasers. In a previous paper, we have been already able to demonstrate the first 1550 nm QD VECSEL with state of the art performances [1]. This recent result has been achieved according to QD material improvements, which have been also considered in this work for the realization of a 1550 nm QD VCSEL.

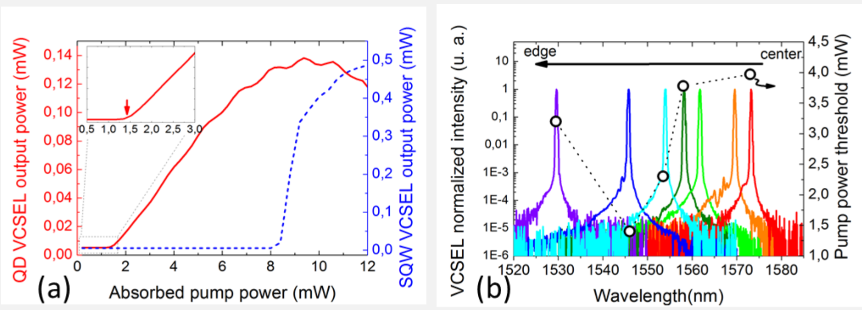
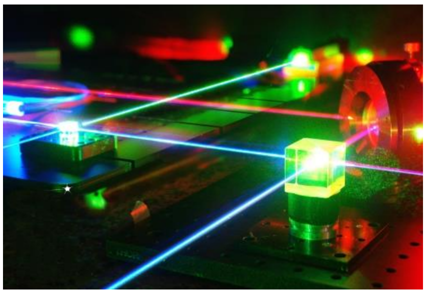


Fig.(a) : QD VCSEL (red line) and QW VCSEL (blue dotted line) output power as function of absorbed pump power (Inset is a magnification of the QD VCSEL characteristic at threshold) (b) QD VCSEL emission measured at threshold, for different location on the wafer (from the center up to the edge), and the corresponding pump power threshold (black circles).

The integration of QD layers within a VCSEL structure has enabled to achieve CW operation at room temperature in the C-band at 1550 nm, with a robust polarization. A 1.4 mW absorbed pump power threshold has been measured, which is up to 6 times smaller than any similar VCSEL structure integrating conventional quantum wells (Figure (a)). This result is the first demonstration of a 1550 nm QD VCSEL. VCSEL operation has been also obtained over 43 nm wavelength range (Figure (b)). Further work will be devoted to implement electrical injection and tunable potentialities based on these QDs VCSELs.

This work was conducted in the framework of the international IDYLIC ANR project, which objectives were to develop dual frequency lasers based on QD V(E)CSELs.

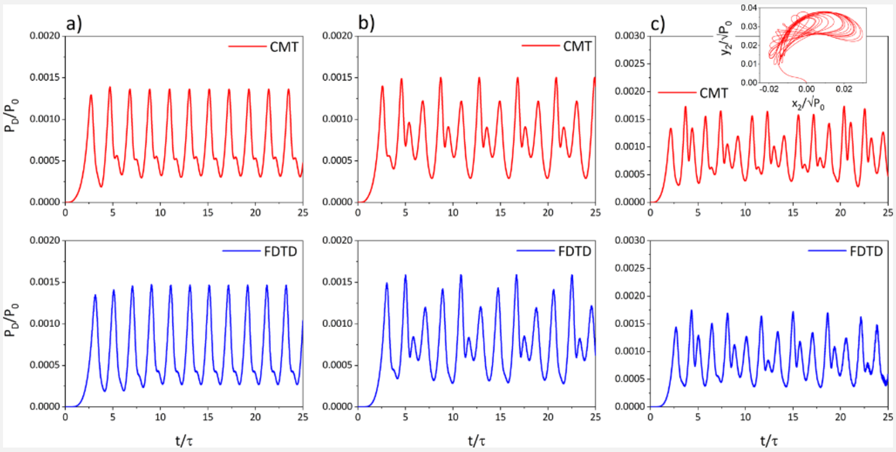


NONLINEAR COUPLED RESONATORS NUMERICAL MODELLING

SP

Nonlinear microring resonators are of great interest in modern photonics. They have applications in all-optical signal processing, all-optical switching, frequency conversion, quantum photonics, or frequency comb generation. Systems of coupled microring resonators offer additional degrees of freedom to optimize their optical properties such as the dispersion with applications in nonlinear optics. In particular, the coupling between resonators expands the dynamic of nonlinear optical microresonators, which leads to multistable chaotic or self-pulsing behaviors. The latter effect could be used to fully miniaturize frequency comb generators or all-optical microwave signal sources with frequency in the 10–40 GHz range.

Most of numerical studies of two coupled-microcavity systems have been carried out in the coupled-mode theory (CMT) framework. In this approach, the temporal evolutions of the amplitudes of the two modes are described by coupled ordinary differential equations. Another method consists of describing the propagation within each resonator using one dimensional spatiotemporal partial differential equations and by assuming a linear coupling between each resonator. There is no study of coupled nonlinear microrings based on direct integration of Maxwell's equations without simplifying assumptions on the system, such as linear and constant coupling, nondispersive materials, or single-mode operation. In this paper, we compare CMT and full-numerical finite-difference time-domain (FDTD) analyses of a two coupled microrings system made of a Kerr material.



By pumping the coupled resonators close to the bistability threshold, it is possible to observe a self-pulsing response [Fig. a) and b)] or even a quasi-periodic behavior [Fig. c)] as shown by the phase portrait given in the insert of Fig. c). In each case, there is a good agreement between the CMT and the FDTD simulations.

This study shows that the CMT is really useful to predict the nonlinear properties of coupled resonator structures and illustrates one more time the complementarity of the CMT and FDTD method in the design of nonlinear photonic devices.

Contact

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Reference

"Combining FDTD and coupled-mode theory for self-pulsing modeling in coupled nonlinear microring resonators", N. Jebali *et al.*, *J. Opt. Soc. Am. B - Opt. Phys.* **37** 9 2557-2563 (sep 2020)

hal-03080015

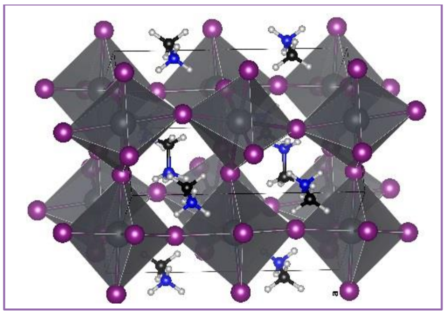
« We compare coupled mode theory and finite-difference time-domain (FDTD) analyses of a two coupled microrings system made of a Kerr material »

More Information

- hal.archives-ouvertes.fr/hal-01308025
- doi.org/10.1364/JOSAB.31.003081
- hal.archives-ouvertes.fr/hal-01939635

Collaborations

- Université de Genève (Switzerland)



ELECTRON–PHONON COUPLING IN 2D HOMOVALENT III–V SINGULARITIES

OHM

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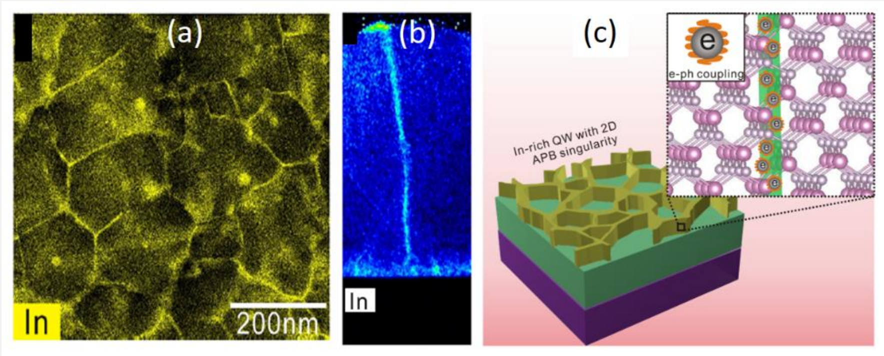
Reference

"Strong Electron–Phonon Interaction in 2D Vertical Homovalent III–V Singularities", L.Chen *et al.*, ACS Nano **14** 10 13127-13136 (sep 2020)

hal-03032030

The electron–phonon interaction has a strong impact on the electrical, optical, and thermal properties of solids. In particular, strong electron–phonon interactions were recently investigated for material and device development as well as for understanding of fundamental physical processes, such as phonon lasing, superconductivity, or colossal magnetoresistance. The strength of this interaction and the formation of a polaron, however, highly depends on the polarizability of the chemical bonds composing the material. Therefore, a strong electron–phonon interaction was preferentially studied in highly polar materials, such as alkali halides, oxides, or perovskites. On the other hand, group II–VI, III–V, or IV semiconductors have been widely used in photoelectric device applications due to their excellent optical and/or transport properties, but the electron–phonon interaction remains generally weak, as the chemical bonds are either covalent (group IV) or slightly polar (group III–V or II–VI).



« We demonstrate strong electron–phonon interactions in a 2D III–V singularity, which combines both phonon and charge carrier confinements »

In this work, we demonstrate strong electron–phonon interactions in a 2D III–V singularity, which combines both phonon and charge carrier confinements. The nanostructure is composed of a vertical atomically thin In-rich indium gallium phosphide ((In,Ga)P) antiphase boundary (APB) (fig. (a) and (b)), where the homovalent bonds drastically change the local polarity and charge distribution in the crystal, leading to efficient phonon confinement and localized hole wave functions. It is furthermore surrounded by a Ga-rich (In,Ga)P barrier, enabling the quantum confinement of carriers (fig(c)). We therefore demonstrated that the local change of chemical bond polarity at the atomic scale in a weakly polar III–V crystal, positioned at the heart of a quantum-confined vertical nanostructure enabled the simultaneous confinement of charge carriers and phonons at the vicinity of the 2D homovalent singularity. The unusual electron–phonon coupling strength measured in these buried and non-oxidized III–V vertical singularities provides many perspectives to understand the physics of the electron–phonon interaction in weakly polar semiconductors.

More Information

- hal.archives-ouvertes.fr/hal-01833206
- hal.archives-ouvertes.fr/hal-02878985

Collaborations

- Innovations for High Performance Microelectronics (Germany)
- Institut de Physique de Rennes (France)
- Leibniz Institute for Crystal Growth (Germany)

POROSITY CALIBRATION IN A 4-LAYER POROUS SILICON MICRO-RESONATOR

SP

Porous silicon (PSi) is a widely studied material that is used in many applications, particularly in the field of label free biosensors thanks to its large surface specific area and its biocompatibility. Due to the electrochemical anodization used process, the porosity and the thickness of the PSi layers are tunable, making it possible to manufacture many optical components and in particular, micro-resonator (MR) for bio-sensing applications. As optical losses in such a porous material are relevant, the final objective is to implement a hybrid structure by associating the PSi transducer MR with polymer waveguides that will ensure the transmission and recovery of the optical signal with lower optical losses. For this aim, the PSi MR will be butt-coupled to the polymer waveguides with the constraint that the refractive index of the PSi guiding layer corresponds to that of the polymer core waveguide. To further fabricate this hybrid structure, a 4-layer PSi structure will be needed since guiding and confinement PSi layers will be subjected to a photolithography process inducing a resin deposit and then a polymer deposit. Consequently, both the guiding and the confinement layers have to be protected by thin PSi barrier layers of low porosity to prevent from polymer or resin infiltration. The knowledge of the porosity and thus the refractive index of each PSi layer is then crucial to fabricate and characterize the integrated component. In this context, calibration of the porosity as well as the electrochemical anodization rate in a 4-layer PSi waveguide structure, including a guiding, a confinement and two technological barrier layers, have been studied and validated. The porosities (figure 1a) of the guiding and confinement PSi layers (including barrier layers: schemes B and C) are lower than if these layers had been manufactured separately (one layer only: scheme A). Taking into consideration the calibration results to obtain the target thicknesses and refractive indices of the guiding and the confinement PSi layers respectively (figure 1b), a 4-layer PSi structure (scheme C) is prepared with defined current densities of J_G = 85mA/cm² for the guiding layer and J_C = 110 mA/cm² for the confinement layer. The good fit of the experimental reflectance spectrum of the 4-layer PSi structure with a theoretical spectrum calculated from the SEM measurements and the targeted refractive indices certifies the validity of the porosity calibration taking into consideration the thin barrier layers.

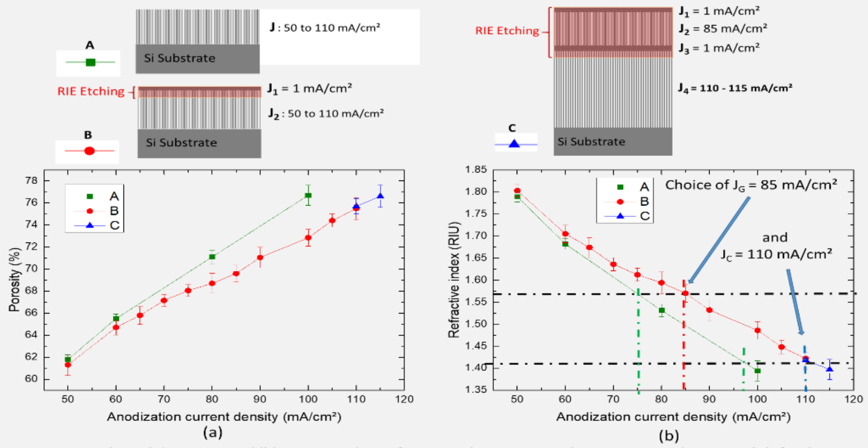
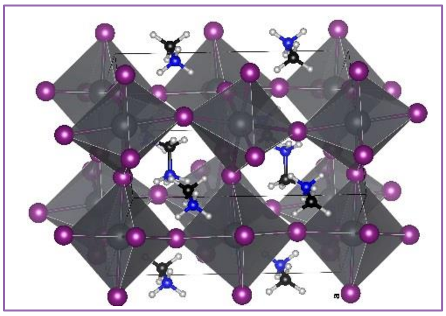


Figure 1 : *PSi layer (a) porosity and (b) corresponding refractive index versus anodization current density J : (A): for the case of one single layer; (B): for the case of the 2–layer structure with a barrier layer ; (C): for the case of the 4–layer structure.*



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Reference

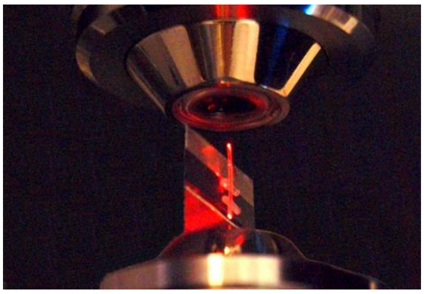
"Porosity calibration in a 4-layer porous silicon structure to fabricate a micro-resonator with well-defined refractive indices and dedicated to biosensing applications", F. Cassio, N. Lorrain, P. Pirastesh, L. Poffo, I. Hardy and M. Guendouz, *Opt. Mater.* **111** 110468 (dec 2020)

hal-03052881

« A calibration of porosity in a 4 layer porous silicon optical component is studied and validated... »

More Information

- Paul Azuelos PhD thesis (2018)
- Fabien Cassio thesis (2021)
- Thesis funded by Région Bretagne, Département des Côtes d'Armor & Lannion-Trégor Communauté



Contact

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Reference

"Orthogonality-breaking polarimetric sensing modalities for selective polarization imaging", F. Parnet *et al.*, *Opt. Lett.* **45** 6 1423-1426 (mar 2020)

hal-02879088

« An informative & selective endogenous polarization contrast in cells from a single scan of the sample »

More Information

- Funded by CNRS Mission for Interdisciplinarity
- arxiv.org/abs/2009.14490
- hal.archives-ouvertes.fr/hal-02879509

Collaborations

- Institut de Génétique et Développement de Rennes (France)
- Biologie Santé Innovation Technologie (France)

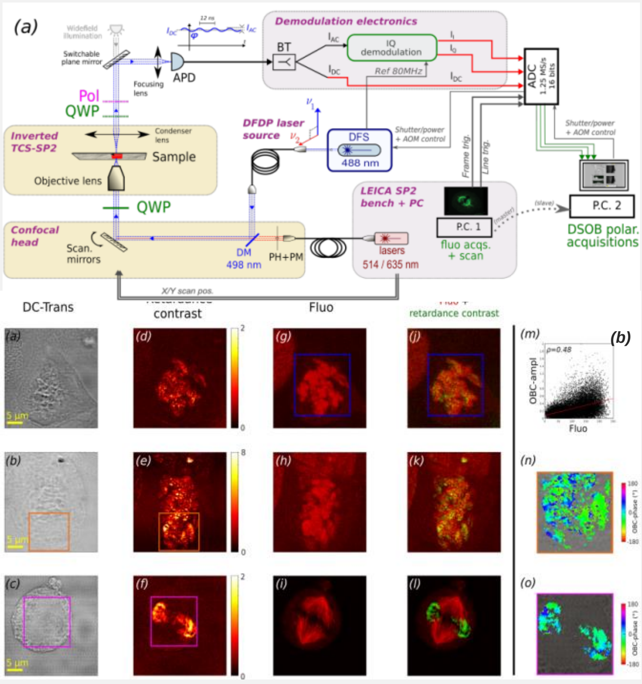
HIGHLIGHTS

Selective Polarization Imaging in Biological Cells

DOP

Polarimetric sensing/imaging by orthogonality breaking is a microwave-photonics-inspired optical remote sensing technique based on the use of a dual-frequency dual-polarization laser illumination of a sample, and on the detection and demodulation of backscattered/transmitted optically carried RF signals. This technique was previoulsy shown to be particularly suited for the characterization of dichroic samples in a direct and single-shot way. We recently expanded the scope of this approach to provide sensitivity on birefringent and/or purely depolarizing materials by introducing a polarization analysis step in front of the detection module. We experimentally validated the interest of these new « induced » orthogonality-breaking modalities in the context of infrared active imaging (see Reference).

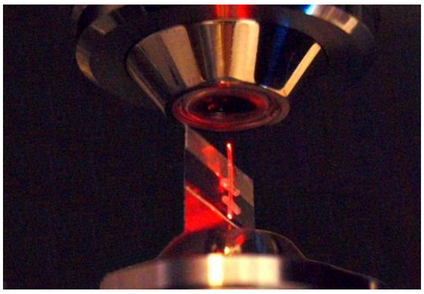
In collaboration with a biology team of the IGDR, we have achieved the transfer of this technology in the BIOSIT cell imaging facility (Rennes) in order to assess its potential for intra-cellular polarization imaging. The developed confocal microscope is now able to provide OB polarization contrast images while acquiring simultaneously fluorescence images on various biological samples.



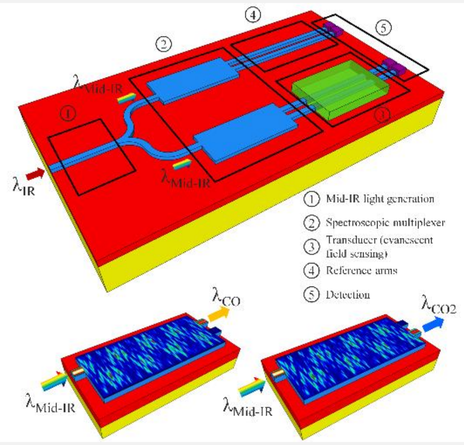
As a first result, the comparison of the images of various cell lines at different cell-cycle stages obtained by OB polarization microscopy and fluorescence confocal images showed that an endogenous polarimetric contrast related to birefringence properties of the sample arises on compacted chromosomes during cell division. The implementation of this technique could be improved to enable label-free real-time polarization imaging of mitotic chromosomes with further potential applications in histology and cancer diagnosis.

DESIGN OF A 1×2 MMI MULTIPLEXER FOR MID-IR CO/CO_2 SENSING

SP



Mid-Infrared (mid-IR) integrated sensing of liquids and gases has found applications as diverse as environmental monitoring and pollutant detection (smoke and greenhouse gases detection, emerging water pollutant identification), military and homeland security (detection of drugs and hazardous materials) but also industrial and healthcare (food processing industry, pharmaceutical and medical products identification). To improve detection capability of photonic integrated circuits in the mid-IR spectral domain, numerous works have targeted the miniaturization of optical spectrometers, either based on Fourier Transform spectrometers or relying on dispersive devices such as array waveguide gratings (AWG), planar concave gratings or multimode interferometers (MMI).



This paper reports the design of a 1 × 2 MMI multiplexer operating in the mid-IR spectral region based on chalcogenides waveguides to develop a multispecies gas sensor.

The proposed integrated platform is envisioned to be part of a generic mid-IR lab-on-a-chip sensing system (see top figure). It associates a broadband mid-IR light source based on Pr^{3+}-doped selenides with an integrated spectroscopic system made from the same materials. Under optical pumping at 1.55 µm, broadband mid-IR light overlapping CO and CO_2 absorption bands, around 4.23 µm and 4.6 µm respectively, is emitted from Pr^{3+} ions. The light generated will then be multiplexed in two different wavelength bands overlapping CO_2 and CO absorption using the 1 × 2 MMI. Light coming out of this spectroscopic element will propagate towards an evanescent field sensing unit. Eventually, light will reach the detection elements. Reference arms could also be implemented to enable auto-calibration of the sensor.

The MMI dimensions were assessed to enable a robust multiplexing of mid-IR broadband emission from Pr^{3+}-doped selenides to develop a dual-gas sensor allowing simultaneous detection of CO and CO_2 gases. In particular, the MMI multimode section dimensions were engineered to enlarge the operation bandwidth and to diplex mid-IR light on two spectral windows overlapping CO and CO_2 absorption bands, each of them coming through one of the two MMI output channels (see bottom figures). The design robustness was then evaluated over different parameters such as refractive index change or multimode section width and length variation. Finally, tapered input and output ports were introduced to further relax fabrication tolerances and to reduce device insertion optical losses.

These results pave the way to the development of on-chip mid-IR multigas sensing devices providing low-cost solution for on-field chemical analysis.

Contact

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Reference

"Design of a multimode interferometer-based mid-infrared multispecies gas sensor", L.Bodiou *et al.*, *IEEE Sens. J.* **20** 22 13426-13435 (nov 2020)

hal-02936794

« Integrated devices based on luminescent selenides thin films could enable low-cost mid-IR multigas sensing for on-field chemical analysis »

Collaborations

- University of Pardubice (Czech Republic)
- Institut des Sciences Chimiques de Rennes (France)

Contact

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Reference

"Semiconductor physics of organic–inorganic 2D halide perovskites", J.-C. Blancon *et al.*, *Nat. Nanotechnol.* **15** 12 969-985 (dec 2020)

hal-03041435

« Achieving technologically relevant performance and stability for optoelectronics, energy conversion, photonics, spintronics and quantum devices requires creating atomically precise materials with tailored homo- and hetero-interfaces »

More Information

- hal.archives-ouvertes.fr/hal-01343129
- hal.archives-ouvertes.fr/hal-01486953
- hal.archives-ouvertes.fr/hal-01982514

Collaborations

- Rice University Houston (USA)
- Department of Materials Science and Technology, University of Crete (Greece)
- Northwestern University, Evanston (USA)

HIGHLIGHTS

SEMICONDUCTOR PHYSICS OF ORGANIC–INORGANIC 2D HALIDE PEROVSKITES

OHM

Organic–inorganic two-dimensional halide perovskites (2DPKs) are organic and inorganic two-dimensional layers, which self-assemble in solution to form highly ordered periodic stacks. They exhibit a large compositional and structural phase space, which has led to novel and exciting physical properties. In this Review, we discuss the current understanding in the structure and physical properties of 2DPKs from the monolayers to assemblies, and present a comprehensive comparison with conventional semiconductors.

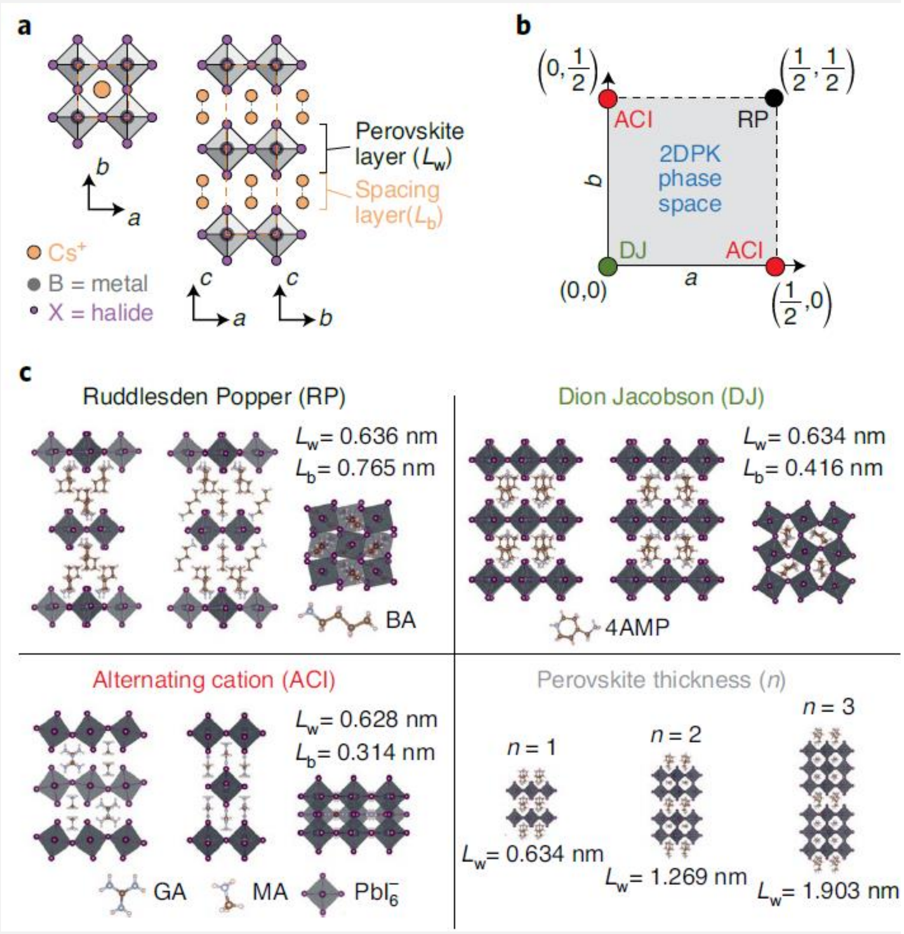
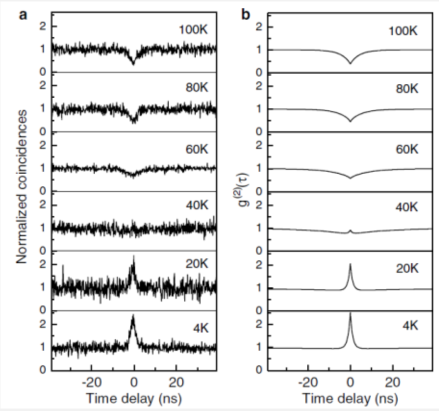


Illustration of 2DPKs structural and chemical phase space

DARK EXCITON IN PEROVSKITE PROMOTES PHOTON-PAIR EMISSION

OHM

Perovskite quantum dots (QDs) are promising nanostructures for optoelectronics, especially for the application to light emitting devices or single photon sources. CsPbX3 inorganic QDs or FAPbX3 hybrid QDs (X=I, Br, Cl and FA= formamidinium) are especially attractive. The authors of the present work have directly adressed in a previous paper on FAPbBr3 QDs (Tamarat et al, Nature materials 2019), the controversy on the nature of the exciton ground state, demonstrating that it corresponds to a singlet dark exciton state. The exceptional brillancies and high quantum yields of these nano-objects are attributed to the absence of one-phonon assisted classical relaxations from the exciton bright triplet to the exciton dark state, first revealed on FAPbI3 QDs in Fu et al Nature Comm. 2018. The present work confirms these results on inorganic CsPbI3 QDs and further evidences the cascade emission of correlated photon-pairs from the biexciton state. Photon bunching remains visible up to about 40K in CsPbI3 QDs, while it vanishes at about 10K in classical CdSe QDs. This effect is again attributed to the lack of efficiency of the dark exciton singlet as a diversion channel.



Tuning the photon statistics of single NCs with temperature and magnetic field. (a) Normalized photon coincidence histograms of a NC for various temperatures, in zero field. The photon bunching obtained at low temperatures turns to antibunching as thermal mixing between bright and dark exciton states operates. (b) Simulations of the PL autocorrelation function with a four-level model including exciton fine structure, biexciton and two-phonon relaxation process.

Contact

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Reference

"The dark exciton ground state promotes photon-pair emission in individual perovskite nanocrystals", P.Tamarat *et al.*, *Nat. Commun.* **11** 6001 (nov 2020)

hal-03015064

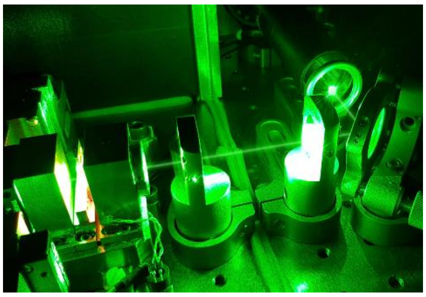
« The lowest-energy exciton state is a long-lived dark singlet state, which promotes the creation of biexcitons at low temperatures and thus correlated photon pairs »

More Information

- doi.org/10.1021/acs.nanolett.7b00064
- doi.org/10.1038/s41467-018-05876-0
- doi.org/10.1038/s41563-019-0364-x

Collaborations

- Laboratoire Photonique, Numérique et Nanosciences (France)
- Swiss Federal Laboratories for Materials Science and Technology (Switzerland)
- Swiss Federal Institute of Technology in Zürich (Switzerland)
- Institut d'Électronique de Microélectronique et de Nanotechnologie (France)
- Laboratoire Ondes et Matière d'Aquitaine (France)



HIGHLIGHTS

DELAYED FEEDBACK STABILIZES DUAL-FREQUENCY FIBER LASERS… OR NOT

DOP

Contact

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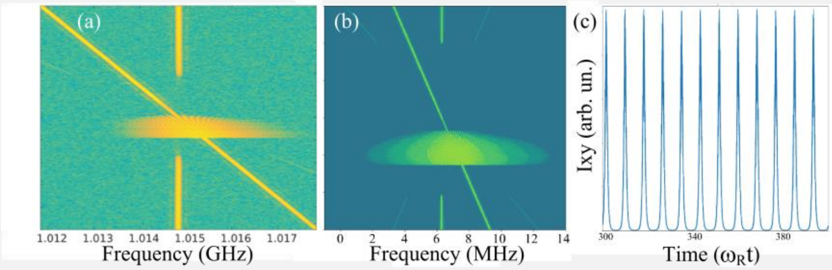
Reference

"Delay-induced instability in phase-locked dual-polarization distributed-feedback fiber lasers", M.Guionie *et al.*, *Phys. Rev. A* **100** 4 043843 (apr 2020)

hal-02565340

Distributed-feedback (DFB) fiber lasers are appealing sources for various applications, notably because they offer a combination of low linewidth and high power. When operating in a regime of simultaneous emission of two orthogonal eigenstates, such short-cavity lasers can be considered as microwave-optical sources, since the typical beat frequency between the two polarization modes is in the GHz range. In this context, the stabilization of the beat frequency is an important issue. We have studied experimentally and theoretically a dual-polarization fiber laser in presence of frequency-shifted feedback. In addition to the expected phase-locking effect typical of coupled oscillators, we have observed an original dynamical regime of self-pulsed operation inside the phase-locking region.



As regards microwave photonics applications, our feedback scheme provides a very efficient stabilization mechanism of the beat note. The locking range can reach 4 MHz at maximum gain in our set-up; it could be further enhanced with higher optical gain in the loop. The locking range is wide enough to compensate for environmental drifts, leading to robust beat note stabilization for days, with a phase noise as low as –90 dBc/Hz at 1 kHz offset frequency. The set-up is all-fibered and could be integrated in a compact system.

Our work also shows that the phase-locked state can be destabilized into a regular self-pulsing state, even with a modest delay. We have found that this instability area is characterized by the following features: (i) it appears when the reinjected optical frequency is lower than the other laser frequency only (denoting a non-zero value of the α-factor.), (ii) its width increases with the reinjection rate, (iii) it appears whatever the sweeping direction but with a slight hysteresis. This impacts of course the design of such loops for applications, where shorter loops would be preferable to avoid spurious self-pulsed states.

Finally our rate-equation model provides simulations consistent with all the experimental results, showing in particular the necessity to include the α-factor and the feedback loop time-delay. Extension to longer delays can be conveniently realized in our all-fibered laser platform, and easily implemented in the simulations for comparison. This model could also provide a basis for further study of other short-cavity dual-frequency lasers, such as DBR fiber lasers or VECSELs}.

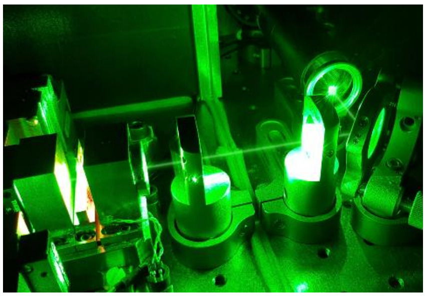
« A clear manifestation of the α-factor in fiber lasers »

Collaborations

- iXblue Photonics (France)

HYBRID INP-Si_3N_4/SiO_2 INTEGRATED OPTICAL COMB SOURCE

DOP



Frequency combs are key elements in numerous applications, such as metrology, clocking, ultrafast ranging or multiplexing in photonic communications. As broad combs can be generated by Kerr nonlinearity in micro-resonators, such sources now benefit from the maturity of silicon plateforms. Indeed, nonlinear effects occur at a low optical power in silicon nitride (Si_3N_4) because of its significant nonlinear index. Moreover, its ultra-low loss allows microring resonators with very high quality-factors Q.

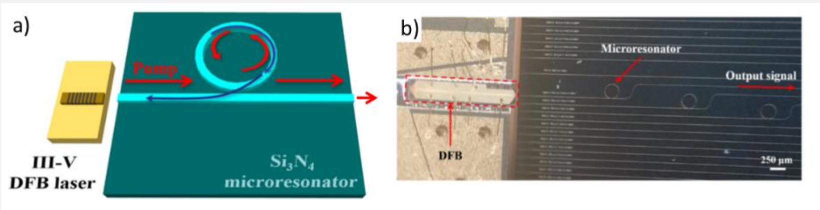


Fig.1 : a) Principle of the hybrid source. b) Picture of the butt-coupling.

In this work, we demonstrate an integrated Kerr frequency comb source based on the butt-coupling between a Si_3N_4/$Si0_2$ micro-resonator and a III-V semiconductor laser. The micro-resonators, provided by CEA-LETI, are made of low-loss tightly-confined Si_3N_4 waveguides. Such guides lead to Q larger than 5 10^6 and parametric oscillation threshold as low as 300 µW. The pump laser, made at III-V Lab, consists in a high-power InGaAsP/InP DFB laser that delivers a single-mode continuous beam of more than 200 mW. The DFB is butt-coupled to the passive component, as shown on Fig.1.

Backscattering from the micro-ring induces an optical feedback in the DFB laser, that leads to a self-locking mechanism of the pump frequency to a resonance. It thus circumvents external bulky stabilization methods, while reducing the pump intrinsic linewidth down to 1 kHz.

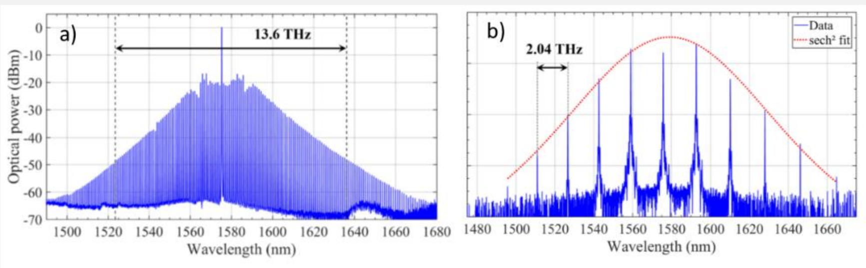


Fig. 2 : Optical spectrum of : a) a ISL-spaced frequency comb b) a 17-soliton crystal state. Global powers :10 mW.

Our compact (less than 1 cm^3) hybrid source then emits an optical comb centered at 1576 nm with a 30 dB bandwidth of 13.6 THz (Fig. 2a), and a repetition rate of 113.5 GHz. We also observe the generation of a 17-soliton crystal state, consisting in a stable comb with a 2.04 THz line spacing (Fig. 2b).

Contact

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Reference

"Microcomb Source Based on InP DFB / Si3N4 Microring Butt-Coupling", S. Boust *et al.*, *J. Lightwave Technol.* **38** (19) 5517-5525. (2020)

hal-02994120

« Butt-coupling yields self-locking to microrings resonances »

More Information

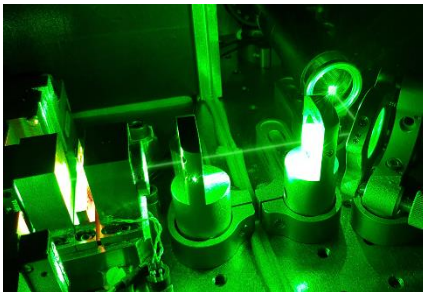
- hal.archives-ouvertes.fr/hal-03128968

Collaborations

- III-V Lab (France)
- Laboratoire d'Électronique et de Technologie de l'Information (France)
- Laboratoire des Technologies de la Microélectronique (France)

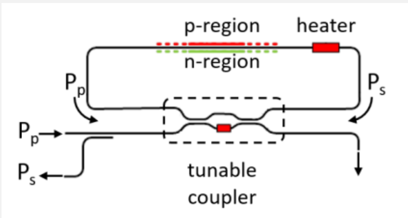
DESIGN OF A ROBUST MID-IR RAMAN LASER ON STANDARD SOI PLATFORM

SP



Leveraging from mature microelectronics industry technologies, Silicon On Insulator (SOI) has emerged, over the past two decades, as the preferred technology for photonic integration in the near-IR (1.3-1.6 µm), notably for telecom/datacom applications. Currently, Si photonics (SiPh) provides a thorough components library with high performance, reliable operation and high-volume manufacturing capabilities. However, the Si indirect band gap hampers light generation, especially in the mid-infrared (mid-IR). Thus, alternative approaches are required to integrate on-chip mid-IR light source on Si and exploit the large transparency of Si (1.1-8 µm wavelength).

Several routes have been proposed for light source integration on Si. These include coupling external III-V semiconductors lasers to SiPh chips through photonic wire bonding or on-chip III-V laser integration that can be achieved either through entirely monolithic (heteroepitaxy) or combined hybrid-monolithic (heterogeneous integration) approaches. Another option to implement on-chip lasers on SiPh relies on the use of luminescent cladding materials such as carbon nanotubes-incorporated organic films or rare earth-doped materials as gain medium. Finally, exploiting the nonlinear effects of SiPh is a promising option as it can provide an on-chip tunable laser source through nonlinear frequency generation or conversion (supercontinuum generation, optical parametric oscillators or Raman lasers). Stimulated Raman scattering (SRS) is among the nonlinear effects in SiPh that can be readily exploited in SiPh to provide gain since it does not require dispersion engineering.



This paper proposes a comprehensive modeling and design of a mid-IR Raman laser compatible with standard 220 nm SOI wafers. The developed SiPh 2.232 µm Raman laser model enabled the assessment of cavity length, free carrier lifetime, and propagation loss impact on threshold power and output power. Optimized values for the cavity length and coupling coefficients, while considering the design tolerance to fabrication errors, were reported. To mitigate fabrication variations, a thermally tunable directional coupler was engineered to provide adequate coupling coefficients at both pump and signal wavelengths.

These simulations enabled the design of a robust 2.232 µm Raman laser that would display, considering Si waveguides propagation loss of 0.6 dB/cm and free carriers removal, a threshold power of 16 mW and a slope efficiency of 62%. An output power of 33 mW could be obtained with a pump power of 100 mW at 2 µm. The proposed Raman laser on SOI offers a compact and low cost solution compatible with mass scale fabrication to achieve frequency conversion in the mid-IR. Considering that linear and nonlinear losses are significantly reduced at longer wavelengths, optimized Raman laser design with cascaded cavities can also be envisioned to access wavelengths further in the mid-IR.

Contact

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Reference

"Comprehensive Modeling and Design of Raman Lasers on SOI for Mid-Infrared Application", M.Ahmadi *et al.*, *J. Lightwave Technol.* **38** 15 4114-4123 (aug 2020)

hal-02878365

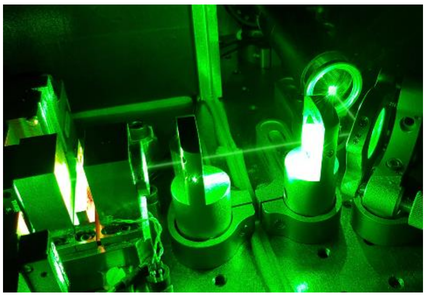
« Design of a robust mid-IR Raman laser on 220 nm SOI platform that mitigates fabrication variations »

Collaborations

- Centre d'Optique, Photonique et Laser (Québec)

CHALCOGENIDE-BASED ER^{3+}-DOPED VERTICAL CAVITY FOR NEAR INFRARED

SP



Chalcogenide glasses have gained great popularity, owing to their wide transparency range and high refractive index in the Near infrared and Mid-Infrared. The development of IR light sources and amplifiers is therefore an important part of this field: in particular, compact sources and integrated devices make for very interesting research topics. Light amplification and laser generation can be obtained through high-quality factor optical cavities fabricated with the use of interferential mirrors, which can be obtained by RF-sputtering. In addition to the nonlinear effects of chalcogenides to generate IR sources, rare earth-doped chalcogenides can also offer innovative solutions. Chalcogenide-based photonic crystals and optical cavities are therefore an extremely appealing set of devices, as they can be implemented as free-standing elements as well as integrated components in waveguides and fiber optics.

So, chalcogenide-oxide Bragg reflectors and a 1-D vertical cavity for operation at 1.55 µm were designed and fabricated via radio-frequency sputtering. The Bragg reflectors were made out of repeating layers of Al2O3 and As2Se3 (Fig. 1), and the cavity was obtained via a Ga5Ge20Sb10S65:Er3+ defect layer. The layers' properties were assessed via ellipsometry and SEM imaging. Transmission spectroscopy verifies the appearance of a well-defined stop-band centered around 1.5 µm with a very wide bandgap, and extremely low transmission (Fig. 2a), even with a relatively low layer count. The vertical optical cavity fabrication results in the appearance of a resonance within the band, at a wavelength corresponding to the 4I13/2⟶4I15/2 transition of erbium. The high transmittance at 808 and 980 nm allows for optical pumping, and thus light amplification and coherent light generation from the cavity (Fig 2b and Fig.3).

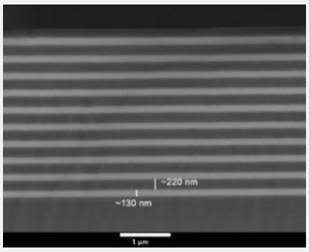


Fig. 1 SEM images of the multilayer BRs deposited on silicon substrates

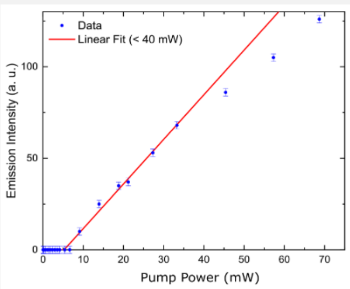


Fig. 3 Data and linear fit of the cavity emission at 1.5 µm as a function of pump power

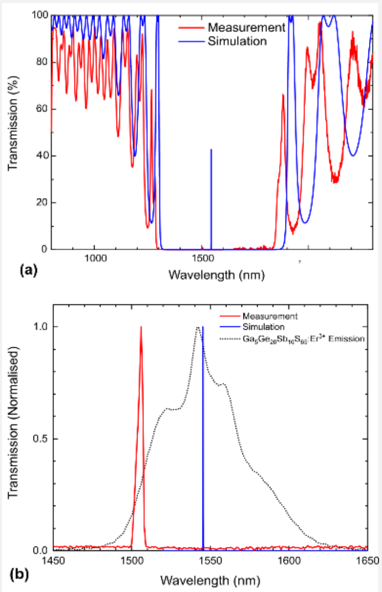


Fig. 2 Comparison between the transmission measurements on the vertical cavity and the simulated spectrum (a) and (b)

Contact

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Reference

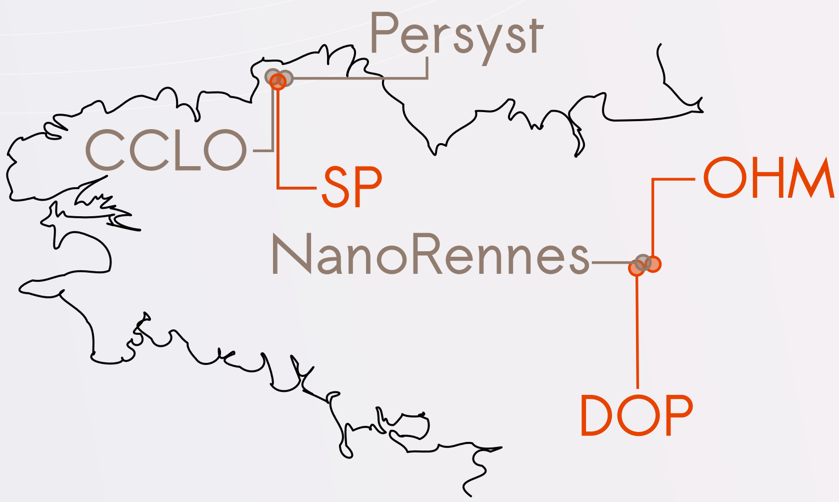
"Radio-frequency sputtering fabrication of chalcogenide-based Er^{3+}-doped vertical optical cavities for near-infrared operation", S.Normani *et al.*, *Opt. Mater. Express* **10** 10 2500-2512 (oct 2020)

hal-02996400

« Cavity emission at 1.55 µm from chalcogenide-based Er^{3+}doped vertical cavity »

Collaborations

- University of Pardubice (Czech Republic)
- Institut des Sciences Chimiques de Rennes (France)



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