INSTITUT foton

Highlights 2017

UNIVERSITÉ DE RENNES 1

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INSA INSTITUT NATIONAL DES SCIENCES APPLIQUÉES RENNES

SPM Physique Chimie Mécanique

IUT Lannion

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 **2017** 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 ENSSA – Head: M. Thual*

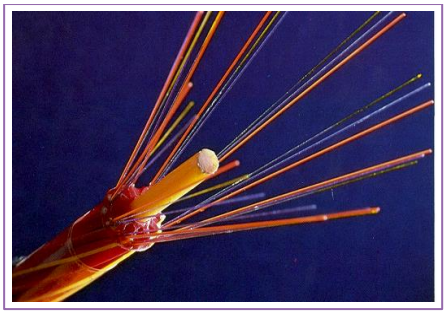
and three platforms:

*- **CCLO** (Univ. Rennes 1 / CNRS), Lannion ENSSAT – Head: M. Guendouz*

*- **PERSYST** (Univ. Rennes 1 / CNRS), Lannion ENSSAT – Head: C. Peucheret*

*- **NANORENNES** (INSA / Univ. Rennes 1 / CNRS), Rennes INSA – Head: C. Paranthoën*

CONTENTS



NONLINEAR OPTICS IN RANDOM-POLARITY III-V MICRODISKS ON SI

OHM / SP

Contact

yoan.leger@insa-rennes.fr

Reference

"Second harmonic generation in gallium phosphide microdisks on silicon: from strict 4^{-} to random quasi-phase matching", P.Guillemé *et al., Semicond. Sci. Technol.* **32** 065004 (jun 2017)

hal-01529567

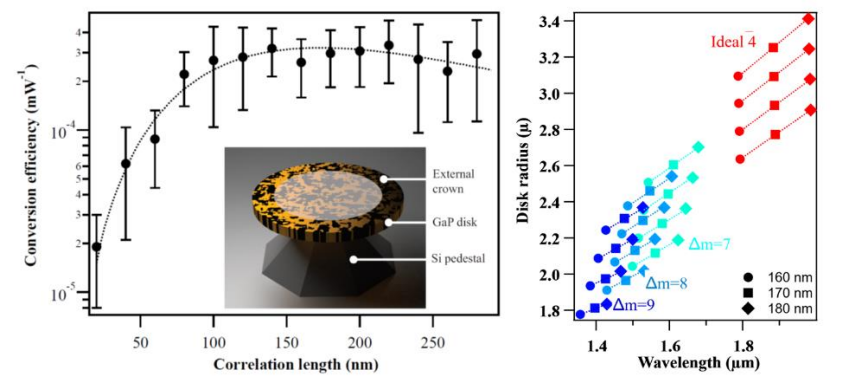
« The random crystal polarity of a III-V on Si photonic device relaxes the 2nd order phase matching condition »

Collaborations

- Centre d'Élaboration de Matériaux et d'Études Structurales (France)

The convergence of nonlinear optical devices and silicon photonics is a key milestone for the practical emergence of photonic integrated circuits. However, the miscellaneous geometries of integrated photonic devices are often not well suited to the strict selection rules of 2nd order nonlinear phenomena.

One of these rules is called phase matching and refers to the momentum conservation of photons during the nonlinear process. III-V semiconductors are well known for their high 2nd order nonlinear properties but the absence of birefringence in these crystals prevents to find strict phase matching conditions. In microdisk resonators, where the light is confined on the external crown of the disk (see left panel inset), one can in principle take advantage of the crystal symmetry: a quarter turn rotation is equivalent to the inversion of group III and group V atoms (so-called $\bar{4}$ symmetry). This crystal polarity inversion can be used to compensate the photons momentum mismatch, but the price to pay is to adjust the size of the disk at the nanometer scale, which is hardly achieved experimentally (on the right panel, only a few of ideal $\bar{4}$ configurations are found).

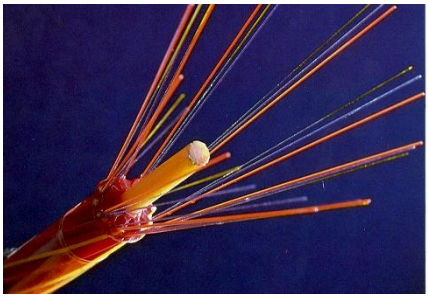


When III-V semiconductors are grown on silicon wafers, locally, the growth can start arbitrarily with III or five atoms, resulting in the formation of grains of opposite polarity (in orange and black on the left panel inset). These grains are called antiphase domains. We demonstrated that the random crystal polarity of a III-V on Si photonic device relaxes the 2nd order phase matching condition.

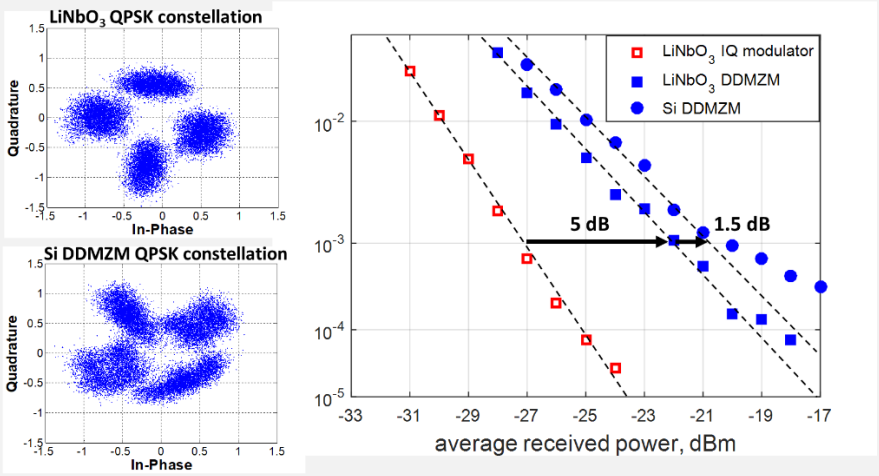
If antiphase domains are very small (below 50 nm in size) the random polarity distribution of a gallium phosphide (GaP) microdisk on Si tends to hinder the nonlinear conversion process (see left panel). On the contrary, high conversion efficiencies can be obtained when the size of the antiphase domains are tuned to 100-250 nm. Since the nonlinear process is no more limited by phase matching, much more microdisk geometries are then eligible for nonlinear optical conversion (the blue dots on the right panel reflects the density of eligible configurations). This works opens the road towards the development of advanced III-V on Si nonlinear photonic circuits.

ADVANCED SIGNAL GENERATION USING SILICON MODULATORS

SP



Silicon optical modulators are of high interest in the context of short-range optical fiber communication systems such as access and data center networks, where their reduced footprint and power consumption as well as their potentially low cost are highly attractive. In such systems, the use of the O-band (1260 nm – 1360 nm) is an interesting option in order to benefit from the low dispersion of standard single-mode fibers compared to the C-band (1530 nm – 1565 nm). The use of the free-carrier plasma dispersion effect through carrier depletion in lateral PN junctions results in an interesting trade-off between modulation efficiency, insertion loss and electro-optical bandwidth. However, this effect is somehow weaker in the O-band than in the C-band. The use of a single dual-drive Mach-Zehnder modulator (DD-MZM) to generate QPSK modulation has been proposed and demonstrated using LiNbO3 modulators. The scheme is well suited for lower-efficiency phase-shifters, since it only requires a peak-to-peak voltage of Vπ (half-wave voltage) to be applied to each phase-shifter, instead of 2Vπ in an IQ modulator. It also benefits from a simpler modulator structure, although at the expense of stronger requirements on the quality and control of amplitude of the driving signals.



We have reported the first use of a silicon dual-drive Mach-Zehnder modulator to generate a 20 Gbps QPSK signal in the O-band. The bit error rate (BER) performance for the $LiNbO_3$ DD-MZM presents 5 dB penalty at a BER of 10^{-3} with respect to the conventional IQ modulator, which is due to the presence of intensity ripples that are inherent to this modulation scheme. The silicon DD-MZM presents a remarkably low 1.5 dB extra penalty compared to its LiNbO3 counterpart, which is linked to its reduced electro-optical bandwidth of 15 GHz. The penalty compared to an IQ modulator could be further decreased thanks to pre-emphasis of the electrical drive voltages or with an optical pulse carve.

Contact

laurent.bramerie@enssat.fr

Reference

"20 Gbps QPSK Signal Generation Using a Silicon Dual-Drive Mach-Zehnder Modulator Operating in the O-Band", L.Bramerie *et al.*, *43rd European Conference on Optical Communication (ECOC 2017)*, Gothenburg, Sweden. Th.1.C.2 (sep 2017)

hal-01609722

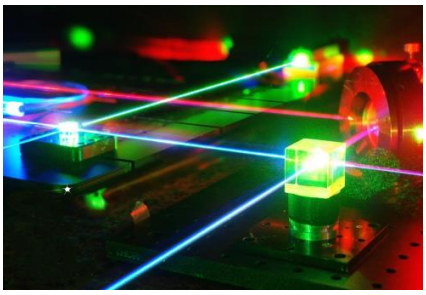
« The first use of a silicon dual-drive Mach-Zehnder modulator to generate a 20-Gbps QPSK signal in the O-band »

More Information

- doi.org/10.1109/JLT.2018.2851370

Collaborations

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



PHOTONIC SYNTHESIS OF LOW LINEWIDTH MILLIMETER WAVES

DOP

Contact

francois.bondu@univ-rennes1.fr

Reference

"Synthesis of a 30-Hz Linewidth Wave Tunable Over 500 GHz", A.Hallal *et al.*, *IEEE Trans. Microw. Theory Tech.* **65**(4) 1367-1371 (apr 2017)

hal-01427869

« Photonic synthesis of submillimeter waves would prove to be particularly useful for detecting the metabolism of microorganisms »

More Information

- hal.archives-ouvertes.fr/hal-01622232

Collaborations

- Institut de Physique de Rennes (France)

Millimeter and submillimeter waves find uses in molecular spectroscopy, communications with high throughput and radar systems. While some systems generating that kind of waves already exist, they are usually complex and expensive. The use of fiber optics components could help to build compact instruments that would simultaneously reach a wide frequency range (hundreds of gigahertz) and have a highly coherent output.

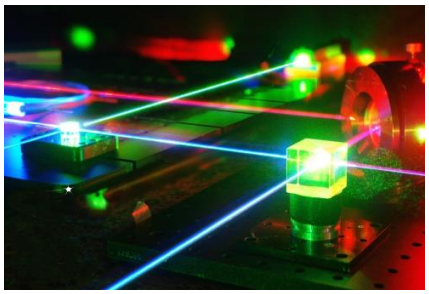
Photonic instrumentation has a strong advantage with respect to electrical instrumentation for the synthesis of millimeter or submillimeter waves. The electrical synthesis requires electrical components (amplifiers, frequency multipliers, and wave guides) adapted to each frequency band. Photonic instrumentation has much more ability to reach wide frequency ranges, but usually at the expense of a smaller stability of the waves. Instruments using that technique would allow applications that are now confined to laboratories to reach industrial markets.

We have built a first stage of such an instrument. When two lasers are superposed onto a fast detector, it generates a current at the frequency difference. We have used two commercial fibered lasers from the Irish Eblana company, designed for optical telecommunications. These lasers have a "linewidth" of about 100 kHz and could be tuned on approximately 500 GHz. We have locked the laser wavelengths on two different resonances of a commercial fibered optical resonator. Using that technique, the difference of the laser frequencies is a multiple of 1 GHz, that latter number being defined by the optical length of the resonator. We have put a particularly strong emphasis on the design and realization of the electronics. The result is a very robust and simple operation. We have measured the phase noise of a carrier at 92 GHz of -90 dBc/Hz at 100 kHz frequency offset, the same order of magnitude as the one of commercial instruments based on electrical synthesis, but with a much larger accessible range of carrier frequencies, over 500 GHz. We have shown here that we can reach simultaneously the two goals of stability and frequency range accessibility.

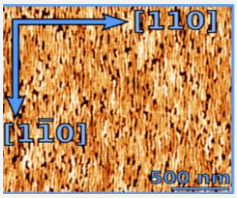
This kind of performance would allow the spectroscopy, with a compact instrument, at low pressure, of the rovibrational motion of volatile molecules that are the product of the metabolisms of microorganisms. Indeed, the metabolisms of a community of microorganisms provide a large diversity of complex molecules. Each molecule has a specific frequency for the line that gives a maximum absorption. Thus, to be sensitive to a wide variety of molecules requires operating the spectroscopy on a wide range of frequencies. This opens the possibility for a novel instrument in biology: the understanding of ecological equilibrium of microorganisms is a challenge for soils, health, and food processing.

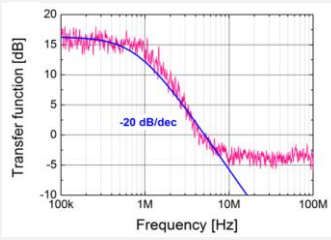
CLASS-A OPERATION OF QUANTUM DASH-BASED VECSEL ON INP

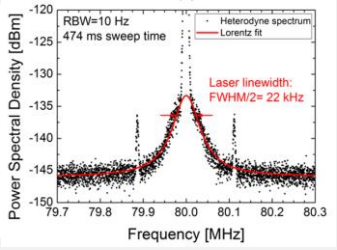
OHM / DOP



Vertical-External-Cavity Surface-Emitting Lasers (VECSELs) have emerged as original devices, capable to ensure high quality circular beams and narrow linewidth, with relatively high power levels, which are typical of solid-state lasers, together with the advantages of semiconductor lasers, such as wide spectral coverage through bandgap engineering. Thanks to their optical properties and versatility, VECSELs are envisaged in wide range of applications, and in particular in microwave photonics. In this latest case strict constraints are set on the spectral purity of the optical source as well as on the intensity noise that must be shot-noise limited over a wide frequency range. In this framework, quantum well based VECSELs have already been demonstrated to exhibit shot noise levels, provided that they are operated in the so-called Class-A regime where the relaxation oscillations vanish. This can be reached using high-finesse and sufficiently long laser cavities that ensure a photon lifetime much longer than the active medium carrier lifetime. In parallel, quantum dash-based active media have been extensively studied in the past. The advantages offered by the quantification of low-dimensional quantum systems in terms of lower threshold current, broader gain response and improved thermal and polarization stability with respect to quantum wells has been proved.







This work was intended to combine the advantages brought by Q-Dash active media and the low noise Class A operation of VECSEL architectures. An Optically-Pumped InAs A Quantum-Dash-based active medium on InP substrate has been grown and implemented in a Vertical-External-Cavity Surface-Emitting Laser (OP-QDH-VECSEL). This laser operates at room-temperature in the telecom L-band at 1.6 µm and provides a robust linear polarization independent of the pumping power. Up to 163 mW output power has been obtained in the multi-longitudinal mode regime. Moreover, single-frequency oscillation was achieved with an estimated linewidth of 22 kHz for a 49 mm cavity and a wavelength tunability ranging from 1609 nm to 1622 nm. In such conditions, the laser is shown to exhibits a Class-A behavior as initially targeted, with a cut-off frequency of 800 kHz. RIN levels of -135 dB/Hz at 100 kHz and below -158 dB/Hz (shot-noise limited) above 10 MHz are obtained for 2 mA of detected photocurrent. Further work will address possible dual-frequency operation of such OP-QDH-VECSEL.

This research was conducted in the framework of the ASTRID project Hypocamp. S. PES PhD Thesis was funded by the French Defence Agency (DGA) and Région Bretagne

Contacts

cyril.paranthoen@insa-rennes.fr
mehdi.alouini@univ-rennes1.fr

Reference

"Class-A operation of an optically-pumped 1.6 µm-emitting quantum dash-based vertical-external-cavity surface-emitting laser on InP", S.Pes et al., *Opt. Express* **25** 11760-11766 (may 2017)

hal-01533213

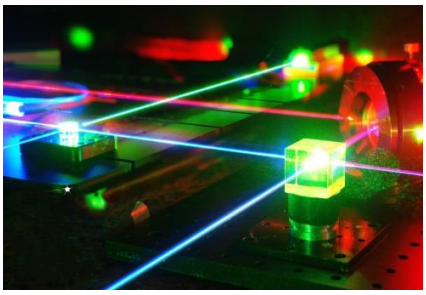
« Q-Dash active media ensuring robust polarization operation of Class A lasers »

More Information

- hal.archives-ouvertes.fr/hal-00717931
- doi.org/10.1364/OL.32.000650

Collaborations

- Centre de Nanosciences et de Nanotechnologies (France)



OPTICAL RF SOURCE USING DUAL WAVELENGTH WGM LASER

SP

Contact

patrice.feron@enssat.fr

Reference

"Theoretical and experimental analysis of rare earth whispering gallery mode laser relative intensity noise", J.-B.Ceppe *et al.*, *Opt. Express* **25** 32732 (dec 2017)

hal-01939586

« We developed a RIN model for class-B lasers including nonlinear coupling of population inversion and photon number fluctuations »

More Information

- SHYRO project website

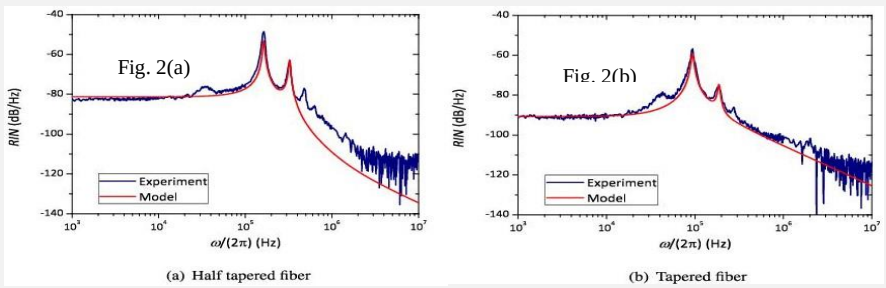
Collaborations

- Institut de Recherche de Chimie Paris (France)

IR CP Institut de Recherche de Chimie Paris

These works are dedicated to the study of whispering gallery mode laser dynamics in order to realize a micro-wave source using simultaneous oscillations in a unique whispering gallery mode micro-laser. We show here experimental results on the relative intensity noise (RIN) of a Whispering Gallery Mode Laser in ZBLALiP glass doped with Er3+ ions. The RIN spectrum gives informations about the dynamics inside the cavity, such as photon lifetime, effective pumping rate and noise sources. Moreover, we have shown that a single-mode emission comes with the presence of multiple harmonics of the relaxation frequency. The theoretical model taking account the non-linear coupling between photons and atoms allows us to determine the mode volume of the whispering gallery mode in laser regime, which is quite difficult to evaluate in this regime.

Abstract: The relative intensity noise (RIN) of a solid state whispering-gallery-mode class-B laser is studied both theoretically and experimentally under different pumping regimes. In particular, we show that harmonics of the spiking frequency are observed in the RIN spectrum. A rate equation model including Langevin forces and the nonlinear coupling between inverted ion and photon number fluctuations has been developed to reproduce the experimental results and to extract relevant physical parameters from the fitting of the RIN spectrum.



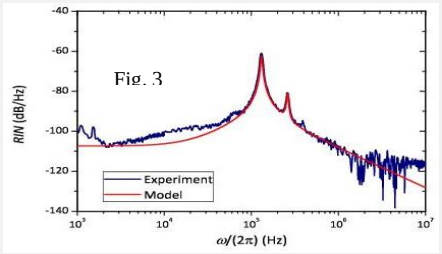


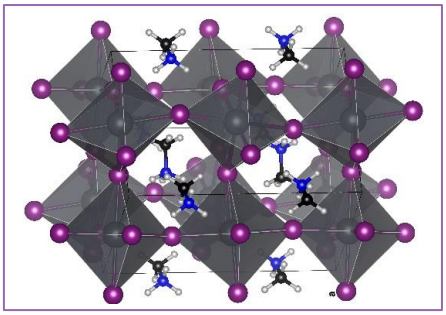
Fig. 2. RIN measurement for a broadband pumping.
a) Half tapered fiber configuration and
b) tapered fiber configuration.
Fig. 3. RIN measurement in the case of a narrow line-width pump laser and a tapered fiber configuration. The physical and fit parameters are given in Table

	Fig. 2(a)	Fig. 2(b)	Fig. 3
$2a$ (μm)	85	90	90
P_L (nW)	57.0	105	129
λ_0 (nm)	1563.6	1565.1	1565.7
r	9.5 ± 0.1	3.8 ± 0.1	6.5 ± 0.1
τ_{ph} (ns)	40 ± 4	$(1.0 \pm 0.1) \times 10^2$	47 ± 5
D_{NN} (s^{-1})	$(2.0 \pm 0.7) \times 10^{19}$	$(2.5 \pm 0.8) \times 10^{17}$	$(1.5 \pm 0.5) \times 10^{16}$
D_{FF} (s^{-1})	$(1.5 \pm 0.3) \times 10^{14}$	$(8.5 \pm 1.7) \times 10^{14}$	$(3.0 \pm 0.6) \times 10^{14}$
κ (s^{-1})	$(2.0 \pm 0.2) \times 10^{-2}$	$(2.0 \pm 0.2) \times 10^{-2}$	$(2.2 \pm 0.2) \times 10^{-2}$
Q_e	$(4.8 \pm 0.5) \times 10^7$	$(1.2 \pm 0.1) \times 10^8$	$(5.7 \pm 0.6) \times 10^7$
V_m (μm^3)	$(3.0 \pm 0.6) \times 10^3$	$(3.0 \pm 0.6) \times 10^3$	$(2.7 \pm 0.5) \times 10^3$

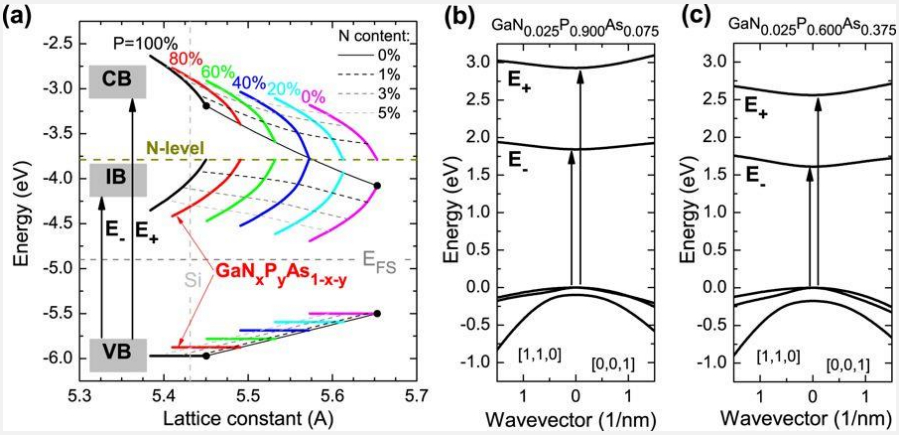
Physical and fit parameters for the WGM laser shown in the three previous figures. a: radius of the sphere, P_L : WGM laser power. We also give the deduced parameters Q_e and V_m. The mode volume is calculated in TE since the theoretical resonance wavelength values match well with experimental data in this polarization.

INTERMEDIATE BANDS IN P-RICH GaNPAs ALLOYS

OHM



The concept of intermediate band solar cells (IBSCs) has been originally proposed because IBSC with properly located bands could attain very high solar power conversion efficiencies. The elegant simplicity of the IBSC concept has motivated researchers to search for novel materials and materials structures with an intermediate band that would satisfy strict requirements regarding photon absorption and charge collection. In general, the intermediate band materials/structures can be divided into three main groups: nanostructures, such as quantum dots (QDs); semiconductor bulk materials containing a high density of deep-level impurities; and highly mismatched alloys (HMAs). An important example of intermediate band HMA is the GaNPAs alloy in which P to As ratio can be tuned at will to change the band gap and modify the respective offsets between the conduction band edge and the localized N level energy making this alloy one of the most promising materials for IBSC applications. The possibility of growing GaNPAs on Si substrates is a very important advantage of this alloy as it makes it feasible to co-integrate IBSC, multi-junctions solar cells or laser emitters with Si technology.



In this contribution, the electronic band structure of phosphorus-rich GaNPAs alloys is studied experimentally using optical absorption, photomodulated transmission, contactless electroreflectance, and photoluminescence. It is shown that incorporation of a few percent of N atoms has a drastic effect on the electronic structure of the alloys (fig (a)). The band anti-crossing interaction results in the formation of a narrow intermediate band with the minimum at the Γ point of the Brillouin zone resulting in a change of the nature of the fundamental band gap from indirect to direct (fig. (b) and (c)). The splitting of the conduction band by the BAC interaction is further confirmed by a direct observation of the optical transitions to the E+ band using contactless electroreflectance spectroscopy. This work opens the way to the development of high efficiency IBSCs.

Contact

charles.cornet@insa-rennes.fr

Reference

"Nitrogen-related intermediate band in P-rich $GaN_xP_yAs_{1-x-y}$ alloys", K.Zelazna *et al.*, *Sci Rep* **7** 15703 (nov 2017)

hal-01715130

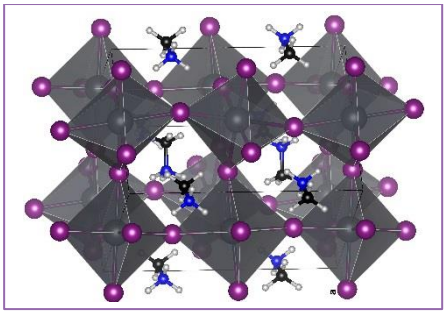
« The band anti-crossing interaction results in the formation of a narrow intermediate band in GaNPAs »

More Information

- doi.org/10.1103/PhysRevLett.78.5014
- doi.org/10.1002/adma.200902388
- doi.org/10.1063/1.4916561

Collaborations

- Wroclaw University of Science and Technology (Poland)
- Lawrence Berkeley National Laboratory (USA)



Contacts

loic.bodiou@univ-rennes1.fr
joel.charrier@univ-rennes1.fr

Reference

"Chalcogenides photonic integrated circuits for near- and mid-infrared applications", J.Lemaitre *et al.*, *European Conference on Integrated Optics (ECIO)*, Eindhoven (2017).

hal-02274871

« Exaltation of non-linear effects in photonic integrated micro-resonators based on chalcogenide »

More Information

- hal.archives-ouvertes.fr/hal-01146713
- Enguerran Delcourt PhD thesis (2017)

Collaborations

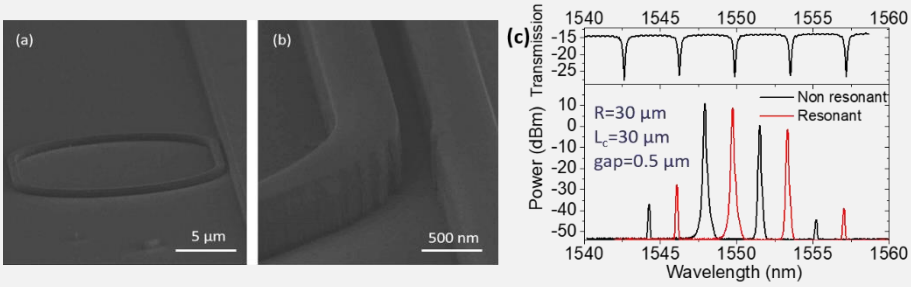
- Institut des Sciences Chimiques de Rennes (France)

STUDY OF NON-LINEAR EFFECT IN PHOTONIC INTEGRATED CIRCUITS

SP

Photonic integrated circuits are a key component of future telecommunication networks, which aim at greater bandwidth, network flexibility and low energy consumption. Nonlinear optics offers an all-optical alternative to optical-electrical-optical based solutions and may offer competitive advantages as data densities and rates continue to increase. Four-wave mixing (FWM) has the capacity of implementing a broad range of functionalities dedicated to optical signal processing. FWM can provide signal regeneration, wavelength channel conversion, and logic operations, all of which could be modulation-format transparent and compatible with coherent communications. The quest for all-optical components has naturally targeted materials with extremely large nonlinearity, including semiconductors (Si, III-V), chalcogenide glasses and polymers but also low-loss platforms (silicon dioxide and silicon nitride). A complementary strategy lies in the resonant enhancement of these nonlinear effects using high Q-factor integrated resonant cavities.

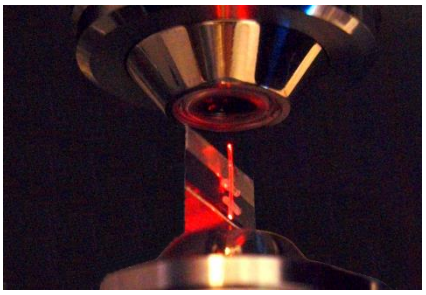
This work concerns the study and development of integrated nonlinear effects based on polymers incorporating nonlinear chromophores or chalcogenides materials. Technological processing of ridge waveguides based on a polymer matrix doped with non-linear molecules [hal-01146713] and chalcogenides glasses have first been developed. Straight chalcogenides waveguides initially allowed the observation of self-phase modulation with a maximum phase shift of 2.02 π for a peak power of 30.2 W but also four wave mixing.



To benefit from the resonant enhancement of nonlinear effects, micro-ring resonators waveguides based on selenides have also been designed, processed (Fig a and b) and optically characterized (Fig c). These chalcogenide-based micro-resonators enabled the demonstration of cascaded four wave mixing with a conversion efficiency of-26.3 dB for a pump power of 16.1 dBm [E. Delcourt PhD].

ACTIVE IR POLARIMETRIC IMAGING BY ORTHOGONALITY BREAKING SENSING

DOP



Contacts

julien.fade@univ-rennes1.fr
mehdi.alouini@univ-rennes1.fr

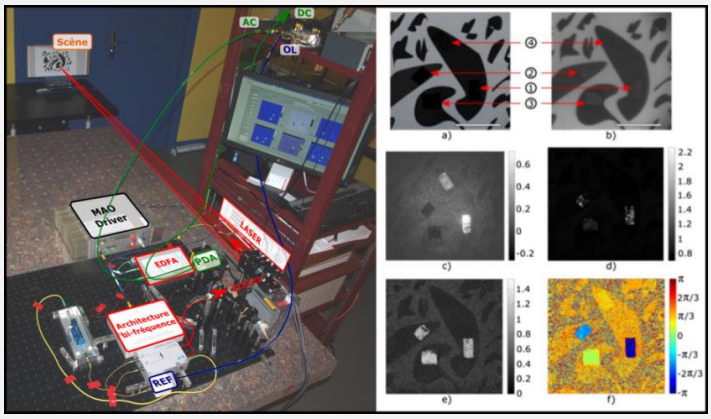
Reference

"Free-space active polarimetric imager operating at 1.55 µm by orthogonality breaking sensing", F.Parnet *et al.*, *Opt. Lett.* **42** 4723-4726 (feb 2017)

hal-01462047

Measuring the polarization properties of materials is a powerful sensing tool for numerous civil and military applications, ranging from biomedical diagnostic or non-destructive control, to active target detection/ recognition. In this domain therefore, constant effort is made to increase the sensitivity, robustness and versatility of imagers. Meanwhile, reduction of the complexity, cost and duration of such optical measurements is intensely sought after, by trying to exhibit the most discriminating polarimetric figures of contrast for a given application.

In this context, we have proposed and we studied over the last past years an active polarimetric imaging technique based on the original concept of "*orthogonality breaking*" *sensing*. This non-conventional technique relies on a specific dual-frequency dual-polarization laser source, whose first implementation at 1,55 µm using telecom components was reported in 2017 in an Optics Letters paper. This article addressed the design and optimization of an original free-space laser-scanning imaging architecture, and of the dedicated fast electronical demodulation circuit. We showed how this imager, from a single scan of the scene within a short acquisition time (~ 1s), can simultaneously record high resolution reflectance map and original polarization contrast images, providing direct and relevant information on the sample diattenuation (absorption anisotropy) magnitude and orientation. By comparing this technique with one of the state-of-the-art approaches involving sequential polarimetric image acquisitions (namely, the Orthogonal States Contrast (OSC)), we illustrated its potential benefits for target detection applications, in particular in the presence of air turbulence.



« Imaging polarization properties of remote objects with a microwave photonics inspired approach »

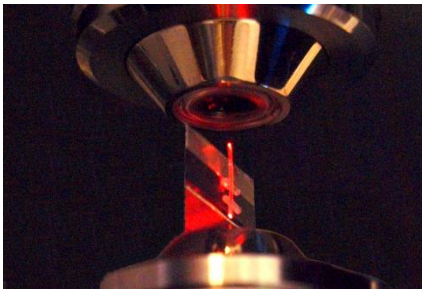
More Information

- doi.org/10.1364/OL.40.001270
- doi.org/10.1103/PhysRevLett.109.043901
- Funded by DGA, Région Bretagne, MI-CNRS

Collaborations

- Institut Fresnel (France)
- Institut de Génétique et Développement de Rennes / BIOlogie, Santé, Innovation Technologique (France)

This work is a part of F. Parnet's PhD work, funded by the french Defence Agency (DGA) and by Région Bretagne. N. Ortega-Quijano also largely contributed to this work as a post-doctoral fellow within the RADIO LIBRE project (ASTRID, DGA), conducted in collaboration with M. Roche from Institut Fresnel in Marseille (France). The technique is currently being developed within the cell imaging platform of Rennes (MRIc-BIOSIT) in collaboration with biologists from IGDR (Rennes) to assess the potential of the DSOB imaging approach for label-free & real-time cell microscopy.



GRAVITATIONAL WAVES FROM NEUTRON STARS

DOP

Contact

francois.bondu@univ-rennes1.fr

Reference

"GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral", B.P.Abbott *et al.*, *PRL* **119** 161101 (oct 2017)

hal-01645859

Laser interferometry has proven to be a very successful way to measure gravitational waves. The LIGO and Virgo instruments are kilometer-scale laser interferometers, with an extremely low noise level. Gravitational waves correspond to the gravitational force, in the scheme of the general relativity established by A. Einstein in 1915. In 2015 the first detection by the LIGO-Virgo collaboration has shown for the first time the final spirals before coalescence of two black holes. The event brought a whole lot of new findings in astronomy: existence of black holes with masses higher than 10 solar masses; proof a radius in the range of a hundred kilometers for heavy black holes; applicability of general relativity to this class of event, rather than classical gravitation established by I. Newton; possibility for heavy stars to form heavy black holes. Two signals were measured in 2015; after an improvement of the resolution of the instruments, height new signals were measured in 2017.

The signal of August 17th, 2017, was different from the others, with smaller amplitude but a detectable signal with duration as long as one minute. The analysis showed that this was the signal from much lighter bodies, about 1.4 solar mass, compatible with the expected mass of neutron stars. The signal was triggered by two interferometers in USA and one in Europe. With triangulation, the signal direction in the sky was reconstructed and given to the astronomers, who indeed observed transient signals at that position for days. Indeed, when the two neutron stars crash a whole lot of mass is expelled and is ignited. This has been detected at a variety of wavelengths by many astronomy observatories (Nature 551, p. 85, 2017). It is shown that in this event more gold is produced than the mass of the earth! The detection in various means allows determining the origin of the source, so simultaneously measuring its relative speed (environmental galaxy) and its distance (with gravitational waves). This provides a new measurement of the "Hubble constant", measuring the expansion in the universe as modeled within general relativity.

There are still unobserved phenomena due to the non sufficient resolution of the interferometers. When a new black hole forms, it is not completely spherical, it should relax, proving general relativity at very strong fields. Imploding stars forming supernovae may emit gravitational waves. Fast pulsars may emit gravitational waves. The observation of many neutron star coalescences would provide a measurement of universe expansion independent of observational astronomy. Finally, the scientific community would like to see signals that deviate from the predictions of general relativity, as hints to make general relativity and quantum mechanics compatible. To answer these questions, the Virgo and LIGO collaborations aim to improve the noise level of the instruments; the actual goal is to move from about one signal per month to a signal per day. Among the challenges to improve the resolution, the FOTON institute is at work to deal with the apparition of "parametric instabilities" at high laser power levels in front of the interferometers, where the laser light makes the mirrors to vibrate.

« Laser interferometry gives birth to multi-messenger astronomy »

More Information

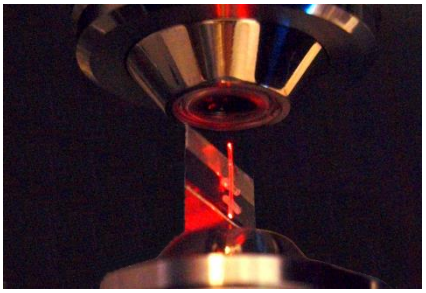
- doi.org/10.1038/nature24471

Collaborations

- Virgo Collaboration (EU)
- LIGO Collaboration (USA)

INTEGRATED VCSEL ON SILICON WITH AN EFFICIENT HEAT SPREADER

OHM



The development of power efficient vertical-cavity surface-emitting lasers (VCSELs) in the 1.55 µm range, with relatively high output power (>1mW) and enhanced thermal dissipation is still challenging but would represent a real breakthrough for the scientific community, with important perspectives in different areas of fundamental research and applied physics (Gas sensing and deformation detectors, microwaves, etc.). In this context, a novel bonding technique is presented in this work. It relies on the use of a BCB polymer bonding to virtually report any material on a Si host platform, through the use of Cu-filled vias acting as µ-heat sinks. This process is expected to reduce significantly the internal temperature of the device. We apply this process to realize 1.55 µm VCSEL and a lasing emission in continuous wave operation from room temperature up to 55°C has been demonstrated. A decrease of 30% of the overall device thermal impedance has been also estimated. The VCSEL fabricated with this process consists in two distinct parts which are depicted below (Fig. (a)). The first one is the host Si substrate, on which matrices of squares holes have been realized by anisotropic wet etching, with typical dimensions of 200x200 µm² and 700x700 µm² on both sides of the Si wafer. The second part is the VCSEL itself, designed to operate under optical pumping. It consists in 9 strained InGaAsP quantum wells, grown by gas source molecular beam epitaxy on InP(001), and then surrounded by two a-Si/SiN_x dielectric DBR. Prior to the deposition of the upper DBR, the VCSEL active region with its patterned bottom DBR is first bonded on Si with BCB, then a thick electroplated Cu layer is deposited inside each Si hole to achieve a robust mechanical link between each VCSEL and the Si substrate. This Cu layer is also used to promote the heat spreading from the device, thereby acting as a localized and efficient µ-heat sink.

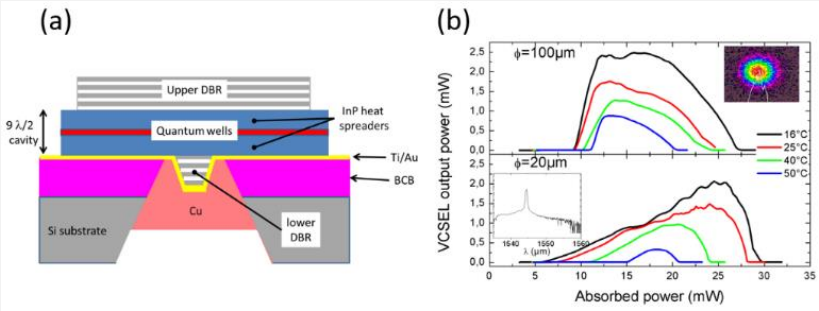


Fig. (b) shows the light output power as a function of the absorbed pump power measured at different device temperature and for two VCSELs integrating a bottom DBR diameter of 100 µm and 20 µm respectively, while the insets give a lasing spectrum and a typical optical mode emitted by the VCSEL. Those measurements have been also completed by wavelength drift analysis when pump power or temperature are changed. VCSEL with the smallest bottom DBR revealed operating temperatures lower than that of large diameter, demonstrating the advantage of using this fabrication process. This result open the way to the realization of potential advanced functionalities using the VCSEL as efficient optical sources on a Si platform to develop new types of sensors.

Contact

christophe.levallois@insa-rennes.fr

Reference

"Enhancement of VCSEL Performances Using Localized Copper Bonding Through Silicon Vias", F.Taleb *et al.*, *IEEE Photonics Technol. Lett.* **29**(13) 1105-1108 (jul 2017)

hal-01582538

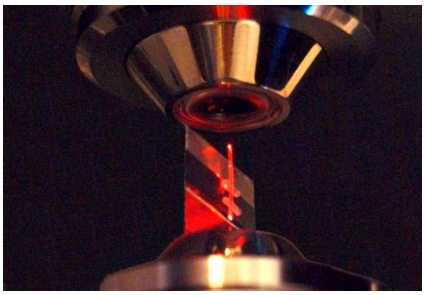
« This process is expected to reduce significantly the internal temperature of the device »

More Information

- hal.archives-ouvertes.fr/hal-01328020

Collaborations

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



INTEGRATED OPTICAL TRANSDUCER FOR MID-IR APPLICATIONS

SP

Contact

loic.bodiou@univ-rennes1.fr
joel.charrier@univ-rennes1.fr

Reference

"Theoretical study of an evanescent optical integrated sensor for multipurpose detection of gases and liquids in the mid-infrared", A.Gutierrez-Arroyo *et al.*, *Sens. Actuator B-Chem.* **242** 842–848 (apr 2017)

hal-01500404

« Proof of Concept of integrated optical platform based on chalcogenide for Mid-IR sensing »

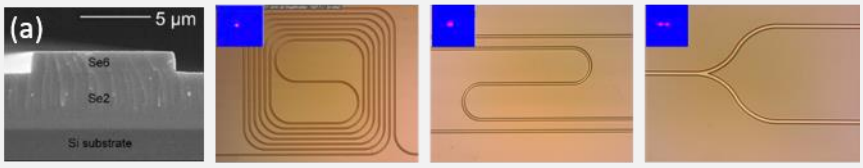
More Information

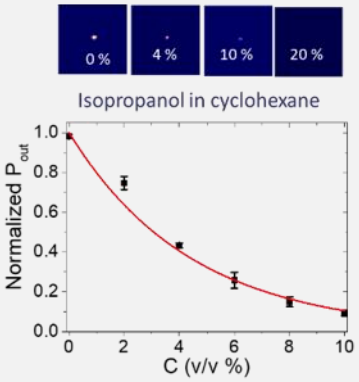
- tel.archives-ouvertes.fr/tel-01686222
- hal.archives-ouvertes.fr/hal-01398053

Collaborations

- Institut des Sciences Chimiques de Rennes (France)

The mid-infrared is a spectral range (2-20 µm) of great scientific and technological interest. Indeed, the strong vibrational absorption bands of numerous molecules overlap this wavelength range. Thus, the mid-infrared has become in the last years a suitable solution for chemical sensing applications in gas or liquid phase. Furthermore, on-chip sensors provide several advantages over other kinds of sensors, such as high integration of elements in a compact device and low fabrication cost by an easy-going to mass production. They could allow quantitative, sensitive and selective detection for health, defense and environmental applications. This study presents the design, fabrication and optical characterization at 7.7 µm of a spectroscopic optical integrated sensor based on chalcogenide glasses [tel-01686222]. Ge-Sb-Se multilayered structures were deposited by RF magnetron sputtering. Using i-line photolithography and fluorine-based reactive ion etching (RIE-ICP), ridge waveguides were processed as straight waveguide, Y-junction, spiral and S-shape waveguides (Fig (a)).



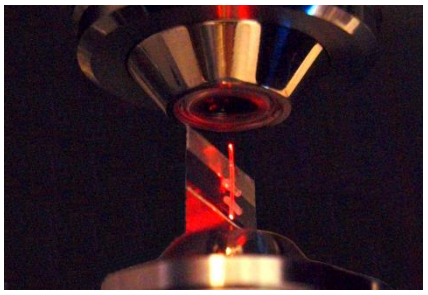


Single-mode optical propagation at 7.7 µm was observed by optical near-field imaging and optical propagation losses of 2.5 dB/cm were measured [hal-01398053]. Finally, chemical substances in liquid phase (isopropanol and acetic acid, both dissolved in cyclohexane) were detected at 7.7 µm by evanescent field. Limits of detection of 2 %v/v and 0.2 %v/v are demonstrated, respectively, for isopropanol and acetic acid (Fig (b)). Furthermore, simulations were performed to assess the potential of the optical integrated sensor to achieve limits of detection lower than environmental and health standards for air and water pollutants.

These results represent a first promising step towards the development of mid-infrared applications at the Foton Institute.

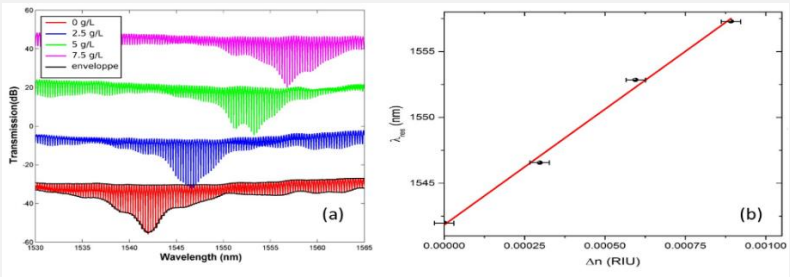
HIGH SENSITIVITY INTEGRATED OPTICAL POLYMER BIOSENSOR

SP



The increasing demand for ultra-sensitive and compact sensors for rapid and specific detection of various biochemical analytes has induced a large development of integrated optical waveguide-based label free sensors. Several configurations of integrated optical sensors using bulk materials have been demonstrated with the objective of increasing the sensitivity as well as reducing the limit of detection as in, for example, Mach-Zehnder (MZ) interferometers, micro-resonators (MR)… To further increase the sensitivity of such an integrated optical sensor, Vernier effect configurations based on cascaded MRs or using both MZ and MR, are now widely recognized in integrated optics applications for the detection of various substances with enhanced sensitivities, by a factor, up to several hundred times that of a single MR, which can then reduce the sensor limit of detection or ease the detection of low concentration analytes using simplified experimental setups.

In this context, a new optical transducer based on the Vernier effect has been developed for glucose concentration detection. The transducer is based on one MR embedded on each arm of a MZ interferometer and has been fabricated with polymer materials using standard photolithography process.



The characterization of the optical sensor is performed with glucose solutions of 2.5, 5 and 7.5 g/l with an accuracy of 0.25 g/l and the reference transmission spectra is registered with deionized water. The experimental spectra are shown, in Fig.(a), near the peak of the envelope in the range 1530-1565 nm. The sensitivity can be calculated from the slope of the linear fit of the minimum position of the fitted Lorentzian peaks (Fig.(b)). The experimental sensitivity obtained here is 17558 nm/RIU (Refractive index Unit) with a standard error on the slope of less than 5%.

This work demonstrates the ability to develop a highly sensitive and low cost polymer optical transducer for biological detection with several interferometers. The sensitivity of the transducer developed in this work is more than 250 times higher than that of a single SU8/PMATRIFE polymer MR with similar fabrication process which demonstrates the advantage of Vernier effect sensor over to a single MR in achieving high sensitivity. The obtained experimental transducer sensitivity of 17558 nm/RIU in the RIU range of [1.1×10^{-6} - 3.1×10^{-3}] is greatly increased compared with 5866 nm/RIU and 6317 nm/RIU sensitivities obtained with other Vernier effect transducers based on cascaded MRs using SOI or SiN materials. The advantage of the use of polymers in this work is their low cost and the ease standard technological process compared with e-beam technology.

Contacts

nathalie.lorrain@univ-rennes1.fr
mohammed.guendouz@univ-rennes1.fr
monique.thual@univ-rennes1.fr

Reference

"High sensitivity optical biosensor based on polymer materials and using the Vernier effect", P.Azuelos *et al.*, *Opt. Express* **25** 30799-30806 (nov 2017)

hal-01891943

« The obtained experimental transducer sensitivity is greatly increased »

More Information

- Paul Azuelos PhD thesis (2018)
- Pauline Girault PhD thesis (2016)
- Funded by Région Bretagne & Lannion-Trégor Communauté

Collaborations

- Institut Mines-Telecoms Atlantique (France)

CUTTING EDGES FOR EXCITON ON HYBRID PEROVSKITES

OHM

Contact

laurent.pedesseau@insa-rennes.fr

Reference

"Extremely efficient internal exciton dissociation through edge states in layered 2D perovskites", J.-C. Blancon *et al.*, *Science* **355**(6331) 1288-1292 (mar 2017).

hal-01486953

« 2D perovskites: sharp edges and excitons »

More Information

- phys.org/news/2017-03-perovskite-edges-tuned-optoelectronic.html

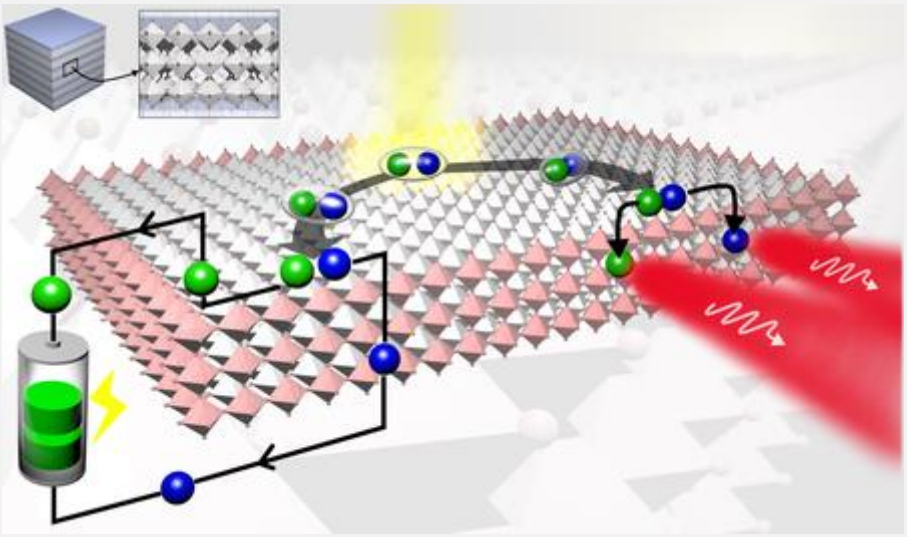
Collaborations

- Los Alamos National Laboratory (USA)
- Northwestern University (USA)
- Rice University (USA)
- Institut des Sciences Chimiques de Rennes (France)
- Brookhaven National Laboratory (USA)

Understanding and controlling the transport of electrical charges and energy flow in low-dimensional semiconductors, such as quantum wells, have led to the development of high-performance optoelectronic devices.

The quantum confinement in these wells usually leads to photo-generated charges : electron-hole pairs or "excitons", strongly linked by Coulomb interactions. The joint efforts of the teams of Los Alamos, Northwestern, Brookhaven and Rennes have shown that this phenomenon is much richer in the thin films of lamellar hybrid perovskites.

In these materials, alternating layers of organic molecules (in this case butylammonium) are separated by an organic-inorganic hybrid layer in which the cavities left by the PbI 6 octahedra are filled with methylammonium cations.



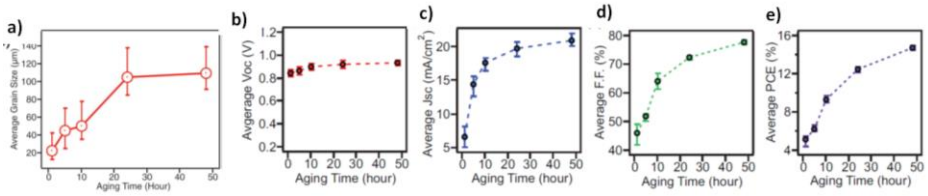
© J.-C. Blancon/LANL

When the thickness of this hybrid layer is at least 3 octahedrons, the Franco-American consortium has demonstrated the emergence of edge states that allow the spontaneous conversion of electron-hole pairs into free charge carriers. This phenomenon has major implications for the performance of perovskite layered devices as demonstrated in the case of solar cells and light-emitting diodes.

IMPROVEMENT OF PEROVSKITE SOLAR CELLS PERFORMANCE

OHM

The rapidly improving certified photovoltaic (PV) cell power conversion efficiency (PCE), which now exceeds 22% has made hybrid perovskite-based materials the rising star among solution processed thin-film PV technologies, which placed them into the center stage of the thin-film PV research community. The near exponential rise in photovoltaic performance is attributed to perovskites remarkable properties such as strong optical absorption giving rise to highly mobile free charge carriers that can migrate up to few microns. Moreover, perovskite family is extremely tunable system that can incorporate a broad variety of organic cations or anions into perovskite structure that provides chemical synthetic means to control the optical absorption and improve photo- and environmental stability by passivation of the interfaces. One of the key challenges in the field of hybrid perovskites today is the dependence of the optoelectronic properties of hybrid perovskites thin films predominantly on the processing conditions. Subtle changes in preparation of the precursors or processing conditions, can lead to a substantial variation in the physical properties of the thin films and, as a result, in the observed experimental data.



We report a strong correlation between solution aging time and thin-film crystallinity in hybrid $MAPbI_3$ perovskite material system. Indeed, progressive aging of the precursor promotes efficient formation of larger seeds after the fast nucleation of a large density of small seeds. The hot-casting method then leads to the growth of large grains in uniform thin-films (fig. a) with excellent crystallinity validated using scanning microscopy and X-ray diffraction. Moreover, the structural characterization reveals that the ratio of $MAPbI_3$/$MAPBCl_3$ is enhanced upon aging and AFM studies on the as cast solution elucidate the key role of nucleation within the precursor solution with progressive aging. Once the precursor solutions aged for more than 24 h, the crystallinity and grain-like features of perovskite are dramatically improved. We also show that the high-quality films cast from aged solution is ideal for thin-film photovoltaic device fabrication (fig b, c, d, e) with reduced shunt current and good charge transport. In summary, we have demonstrated that precursor aging represents an essential discovery for not only researchers working on perovskite materials but in general when precursors are converted to thin films by nucleation and crystal growth during the film formation that can lead to high performance and reliable optoelectronic devices.

Contact

jacky.even@insa-rennes.fr

Reference

"Effect of Precursor Solution Aging on the Crystallinity and Photovoltaic Performance of Perovskite Solar Cells", H.Tsai *et al.*, *Adv. Energy Mater.* **7**(11) 1602159 (jun 2017).

hal-01450074

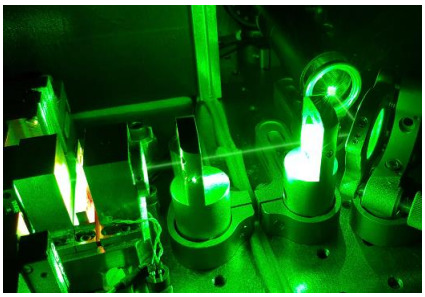
« The aging time of the precursor solution is a very important parameter that controls the crystalline quality of the thin films and in turn the overall performance of any optoelectronic device »

More Information

- www.nrel.gov/pv/assets/pdfs/pv-efficiency-chart.20190103.pdf
- doi.org/10.1002/pip.2788
- hal.archives-ouvertes.fr/hal-01343129

Collaborations

- Los Alamos National Laboratory (USA)
- Rice University (USA)



INJECTION BASED MEASUREMENT OF α-FACTOR IN SOLID-STATE LASERS

DOP

Contact

aurelien.thorette@univ-rennes1.fr

Reference

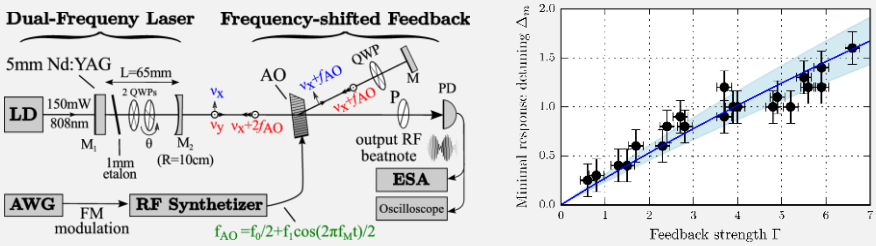
"Linewidth enhancement factor measurement based on FM-modulated optical injection: application to rare-earth-doped active medium", A.Thorette, M.Romanelli, M.Vallet, *Opt. Lett.* **42** 1480-1483 (apr 2017)

hal-01501412

« The implementation of the FM/AM method in dual-frequency lasers leads to a precise characterization of small α-factors »

The linewidth enhancement factor, also referred to as Henry factor or *α-factor*, quantifies the intrinsic phase-amplitude coupling in a laser gain medium. This coupling describes important characteristics of laser behavior, such as broadening of the laser linewidth and peculiar dynamics under gain modulation or optical injection. Very extensive literature exists on measurement methods for semiconductor lasers, including direct estimation of the gain asymmetry, pump induced phase modulation ("AM/FM" method) and optical injection. Unfortunately none of these methods is well-suited for solid-state lasers, which feature slower dynamics and small values of α (leading to the fact that α is usually neglected in such lasers). Very few measurements are thus reported in the literature: a value of 0.25 ± 0.13 in Nd:YVO_4 and a surprisingly large value ≈ 1 in Nd:YAG microchip lasers.

We have developed a new "FM/AM" method based on the amplitude response of the laser to a phase-modulated injection. We have shown that for an injected laser, this response is minimal for a particular value of the frequency detuning between the injected field and the laser field, and that this value is directly related to α. Furthermore, unlike standard methods that use pump modulation, we operate here at constant intracavity power, so the measurement is intrinsically free from any thermal considerations.



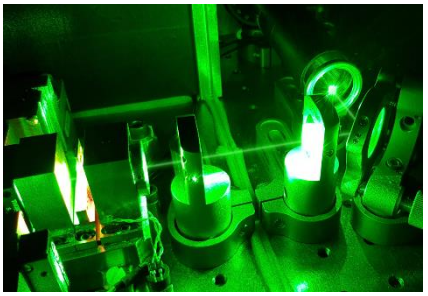
Our method greatly benefits of operating the laser in a dual frequency regime, that is, when the laser produces two orthogonal polarization modes with a tuneable frequency difference. Indeed, this regime, combined with a frequency-shifted optical feedback, allows avoiding the critical need of an external stable master laser, as one mode of the laser can be used to inject the other one. We have implemented this measurement on a home-made diode-pumped Nd:YAG laser. A well-tested rate equations model allows us to deduce α from this measurement, taking into account the coupling between the slave and master modes inside the gain medium. Performing the measurements for different injection levels has led to a rather precise characterization of a small α-factor, equal to 0.28 ± 0.04.

While such a small factor may appear to have little influence on the laser behavior, it should be taken into account when targeting applications needing stabilized lasers with very low optical phase noise. In this context, this measurement, that could be applied to other lasers, such as Er^{3+} doped bulk or fibered medium, could give clues on the potential contribution of α to the AM/FM noise conversion process during low phase noise microwave or THz generation.

More Information

- Aurélien Thorette PhD thesis (2018)
- doi.org/10.1364/OE.22.007364
- doi.org/10.1364/OL.30.003036
- doi.org/10.1103/PhysRevA.70.033809

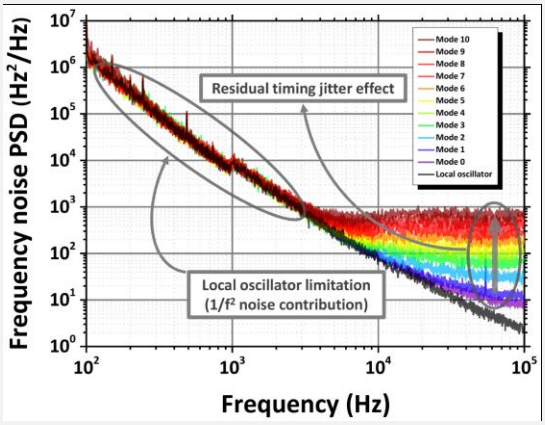
COMB OF KHZ-LINEWIDTH MODES



SP

Coherent optical frequency combs (OFCs) with a low comb-line frequency-noise are highly attractive for a variety of applications ranging from time and frequency metrology to astronomy and space science through optical communications, quantum optics, millimeter-wave generation, and frequency-comb spectroscopy. Many techniques have been demonstrated to generate OFCs, e.g., using gain switching of discrete mode lasers, Kerr effect in nonlinear micro-resonators, cascaded intensity or phase modulators, or mode-locked laser diodes (MLLDs)… The linewidth of each line or its coherency is of major importance in many applications. For instance, optical frequency combs obtained from mode-locked laser diodes are among potential candidates for wavelength division multiplexing (WDM) networks. However, their lines exhibit usually a broad optical linewidth (from 1 MHz to 100 MHz), which makes them incompatible for use in high order modulation formats WDM based systems. On the other hand, metrological techniques may induce extra-cost, like a servo-control on an atomic line.

We show that a feed-forward technique using a local oscillator (LO) could lead to interesting linewidth reduction performances. Another way to characterize coherency or linewidth of a frequency-laser line is to measure its power-spectral density (PSD) of frequency-noise, which characterizes its phase fluctuations. Frequency-noise PSD has different contributions: (i) the low-frequency noise (flicker noise) below a few 100's kHz or a few MHz, for which the origin is still an open discussion and (ii) the white FM noise arising from the laser phase fluctuations induced during the spontaneous emission process.



The feed-forward technique is applied to an active MLLD showing drastic white frequency-noise reduction up to 63 dB with respect to the central input comb line. As shown in the figure above, all modes of the MLLD have a reduced flicker noise down to that of the LO, below 4 kHz while above, the different lines are submitted to a phase diffusion due to imperfect phase-correlation between them. Thus at low frequencies the main limitation is the LO flicker-noise. Thus we have demonstrated, at the system output, an optical frequency comb source with 14 comb-lines with a reduced sub-kilohertz intrinsic-linewidth (or 21 comb-lines with reduced linewidth below 7 kHz). For an observation time of 10 ms, all lines share the same optical linewidth, almost equal to 37 kHz, thus showing the LO timing jitter impact on the technique. Finally, we propose techniques to suppress any optical filter in the setup, the LO. Flicker noise reduction could be realized through a frequency reference.

Contact

pascal.besnard@enssat.fr

Reference

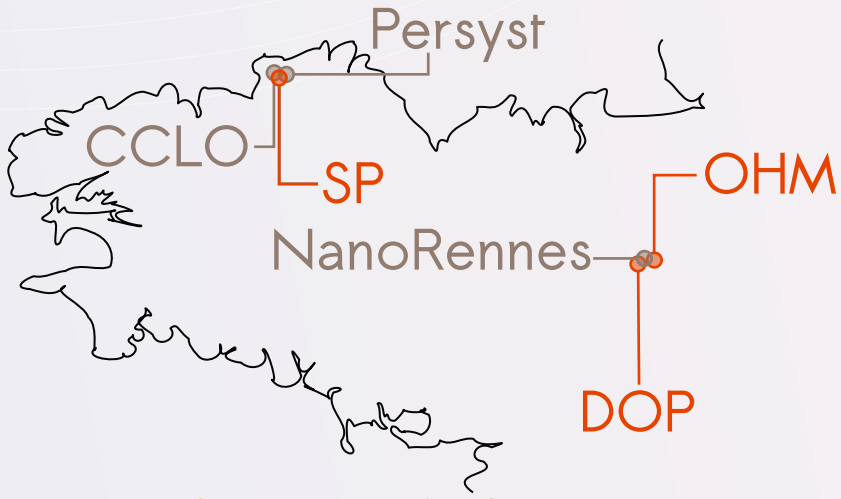
"Frequency noise reduction performance of a feed-forward heterodyne technique: application to an actively mode-locked laser diode", M.O.Sahni et al., *Opt. Lett.* **42** 19 4000-4003 (oct 2017).

hal-01959533

"Realization of an optical frequency comb source with 14 comb lines reduced to sub-kilohertz intrinsic linewidth"

Collaborations

- Dublin City University (Ireland)
- Dodd-Walls Centre for Photonic and Quantum Technologies and Department of Physics (New Zealand)



3 teams + 3 platforms

A leading-edge research in photonics

- Devices and functionalities for optical communications
- Microwave, Millimeter and Tera-Hertz Optics
- Innovative materials for Photonics
- Instrumentation, Optical Sensors and Coherent Imaging
- Advanced concepts for Photovoltaics
- Lasers Physics and Metrology

Technological transfer support, strong industrial partnerships, international collaborations

Trainings in photonics: engineering schools, master's degree, DUT...

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