INSTITUT
foton

Highlights 2019

UNIVERSITÉ DE RENNES 1

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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 **2019** 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*

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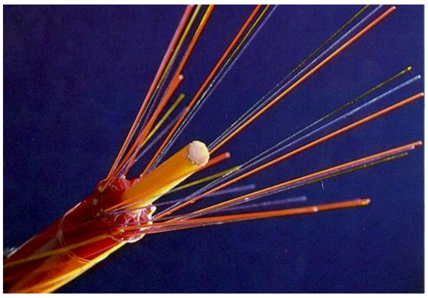


HIGHLIGHTS

DAC-LESS PAM-4 GENERATION USING A SILICON MZM MODULATOR

SP

Contacts

mathilde.gay@enssat.fr

Reference

"DAC-less PAM-4 generation in the O-band using a silicon Mach-Zehnder modulator", L.Deniel *et al.*, *Opt. Express* **27**(7) 9740-9748 (apr 2019).

hal-02270915

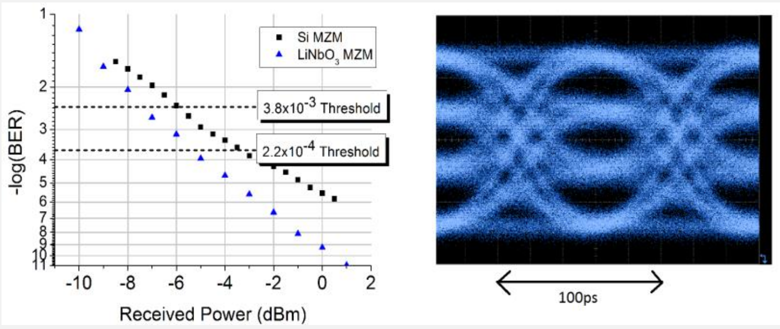
« DAC-less modulators for PAM-4 generation are of prime interest for short-reach optical communications»

Collaborations

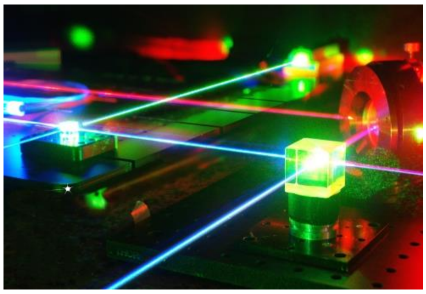
- Centre de Nanosciences et de Nanotechnologies (France)
- ST-Microelectronics (France)
- Institute for Telecommunication and Multimedia Applications (Spain)
- Research Institutes of Sweden (Sweden)

To cope with the demand of increasing bit rates and the constraint of a limited transmitter electro-optic bandwidth, 4-level pulse amplitude modulation (PAM-4) is considered as a promising economical solution to replace on-off keying (OOK) with a strong potential for large volume short-reach optical communications. For this purpose, silicon photonics is a well-suited technology, benefiting from both the complementary metal-oxyde-semiconductor (CMOS) mature fabrication process and from its possibility of integration with electronics. PAM-4 signals are usually generated in the electrical domain by means of power-hungry digital-to-analog converters (DACs), before being converted to the optical domain by the modulator. To reduce the overall power consumption, new DAC-less configurations based on dual electrode structures have been proposed, enabling the generation of the four intensity levels in the optical domain from two independent binary electrical sources.

In this work, we present a carrier-depletion based Mach-Zehnder modulator (MZM) operating in the O-band and experimentally demonstrate the generation of a 20 Gb/s PAM-4 signal without using any DAC. By applying two independent binary non-return-to-zero (NRZ) electrical signals with different peak-to-peak voltages on the two arms of the MZM operating at the quadrature point, four distinct levels are reached in the output power. In case of modulation by carrier depletion in Si PN diode, both the losses and the efficiency of the phase-shifters present a non-linear behavior. The electric field traveling through each arm will therefore go through a non-linear phase-shift and voltage-dependent losses at the same time. Modeling was used to find out the voltages required to reach 4 equally spaced power levels, while exploiting the full transmission dynamic range of the MZM transmission.



The bit-error rate (BER) obtained with the Si PAM-4 modulator is as low as 7.6×10^{-7} and a penalty of 2 dB compared to a commercial push-pull $LiNbO_3$ MZM is obtained at FEC threshold of 2.2×10^{-4}.

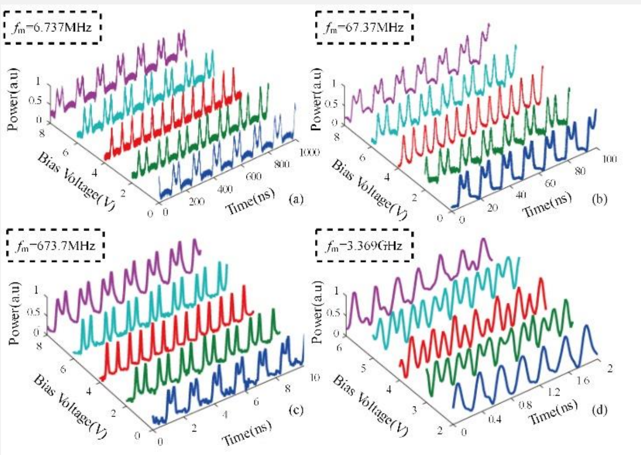


HIGH REPETITION-RATES IN EOM-BASED FREQUENCY-SHIFTING LOOPS

DOP

The Talbot effect initially refers to a self-imaging effect: specifically when a monochromatic optical wave illuminates a periodic grating, periodic grating self-imaging can be observed at certain specific distances after the grating. By analogy to the Talbot effect in space domain, an optical frequency comb is equivalent to a periodic grating in the space. When a single-frequency laser injects a frequency-shifting loop (FSL) system, constructive interferences occur periodically with time generating pulses at a repetition rate equal to (integer Talbot effect) or with a multiple of (fractional Talbot effect) the mode spacing of the comb; such "Talbot lasers" have been shown to provide high-repetition rate pulse trains and could find applications in RF-optical signal processing, spectroscopy, and ranging. They are usually based on acousto-optic frequency-shifters (AOFS).

In this work we have investigated theoretically and experimentally an all-fibered FSL which includes an Electro-Optic amplitude Modulator (EOM) and an optical amplifier, and is seeded by a continuous-wave laser. At variance with AOFS-based loops, the EOM creates at each round-trip two side-bands that recirculate inside the loop. We demonstrate an original double-pulse regime when the loop length is a multiple of the RF modulation wavelength applied to the modulator. The inter-pulse interval is then governed by both the bias voltage and modulation depth of the EOM. Besides, some typical waveforms such as saw-tooth and rectangle are experimentally obtained by properly setting operating frequency, bias voltage and the RF power. Benefiting from the high modulation frequency of the EOM, we observe a wide-bandwidth optical frequency comb (up to 40 GHz). The figure below shows the 1, 10, 100 and 500 times enhancement of the repetition rate with respect to the fundamental loop frequency. The CW laser is hence converted into a multi-GHz pulse train of ps pulses.



Our theoretical model explains the formation of pulse doublets and reproduces well all the experimental waveforms. Furthermore, the un-seeded loop driven above threshold also generates mode-locked picosecond pulse doublets with a continuously adjustable delay.

Contact

marc.brunel@univ-rennes1.fr

Reference

"Pulse doublets generated by a frequency-shifting loop containing an electro-optic amplitude modulator", H.Yang *et al.*, *Opt. Express* **27**(13) 18766-18775 (jun 2019).

hal-02163678

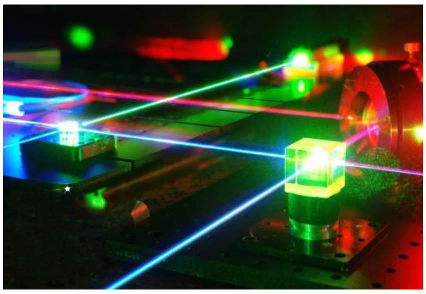
« Electro-optic modulation gives added versatility to the loops »

More Information

- doi.org/10.1364/OPTICA.3.000001
- hal.archives-ouvertes.fr/hal-02163678

Collaborations

- Beijing Institute of Technology (China)



Contact

mehdi.alouini@univ-rennes1.fr
christophe.levallois@insa-rennes.fr

Reference

"Direct measurement of the spectral dependence of Lamb coupling constant in a dual frequency Quantum Well-based VECSEL", G.Brévalle *et al.*, *Opt. Express* **27**(15) 21083-21091 (jul 2019).

hal-02290437

« Originally introduced by lamb for gas lasers, C is still relevant in SC lasers »

More Information

- doi.org/10.1103/PhysRev.134.A1429
- doi.org/10.1364/OE.18.005008
- hal.archives-ouvertes.fr/hal-01975604

Collaborations

- Ecole Polytechnique Fédérale de Lausanne (Switzerland)
- Institut d'Elctronique et des Systèmes (France)

Sensing the coupling constant in dual frequency QW-VECSEL

DOP / OHM

The coupling constant, C, is an important physical parameter in multimode lasers as it governs the dynamics of coupled modes. In dual-mode lasers, C rules the stability condition and the robustness of dual-mode operation. In semiconductor disks, a slight spatial separation between the two modes is usually introduced in order to reduce C leading to stringent shaping of the pump. Single axis laser is thus highly desired provided that the coupling constant is reduced or at least its spectral dependence is mastered. We performed the first direct measurement of C and its wavelength dependence in InGaAlAs-QW active medium by embedding the experiment within the laser oscillator itself. Thus, the wavelengths of the two modes can be tuned independently while simultaneous oscillation and perfect spatial overlap of the two modes are maintained.

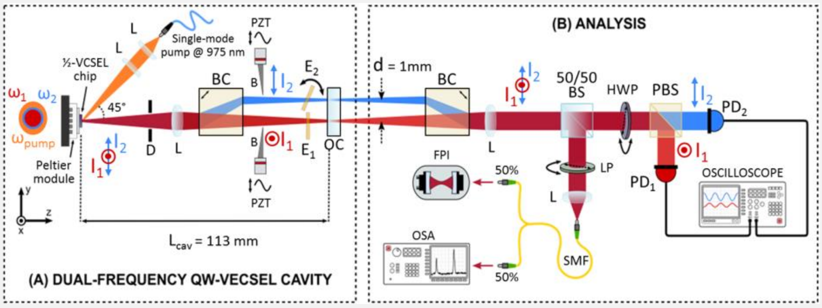


Fig. 1: *Experimental arrangement for sensing the spectral dependence of mode coupling.*

C is found to be significantly high, *i.e.*, C=0.84±0.02. More importantly, while the cross-to-self-saturation coefficients evolve with respect to wavelength, C is proven to remain constant for mode-frequency-differences ranging from 45 GHz up to 1.35 THz. This major result proves that the coupling constant, originally introduced by Lamb for gas lasers, is still a relevant physical parameter in semiconductor lasers. Further investigations are currently conducted with lower dimensionality gain structures, such as Quantum-Dash and Quantum-Dot, in order to reduce C.

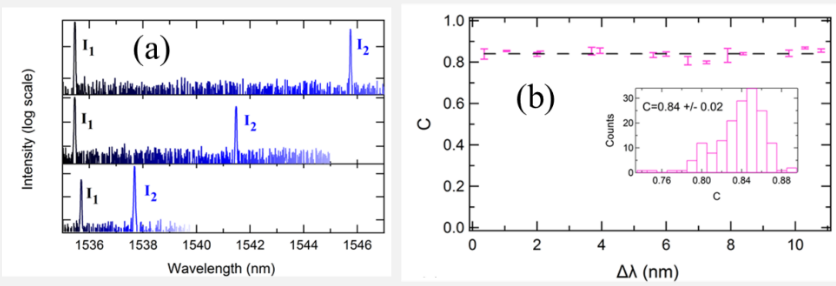
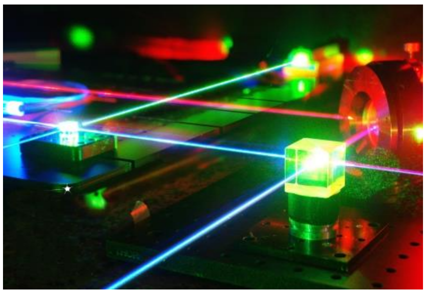


Fig. 2: *(a) Illustration of dual wavelength tunabilty. (b) Spectral dependence of the coupling constant.*

HIGH POWER 1.5µM QD VECSEL



OHM

Quantum dot nanostructures have been already used to realize a lot of innovative and/or improved devices based on QD unique properties: low threshold and temperature independent lasers, mode-locked lasers, tunable lasers, single photon emitter. The combination of QD with optically pumped vertical –external-cavity-surface-emitting lasers (VECSEL) are also very promising to realize high power laser with a larger wavelength tunability, and even for a new class of dual wavelength laser based on single axis VECSEL. This QD/VECSEL association is still very challenging. To reach this objective, we performed material development on the QD growth. We have been able to control the QD density (improving the gain), and compensate the natural redshift of the QD emitted wavelength to get QD emitting at 1.5 µm (Fig.1).

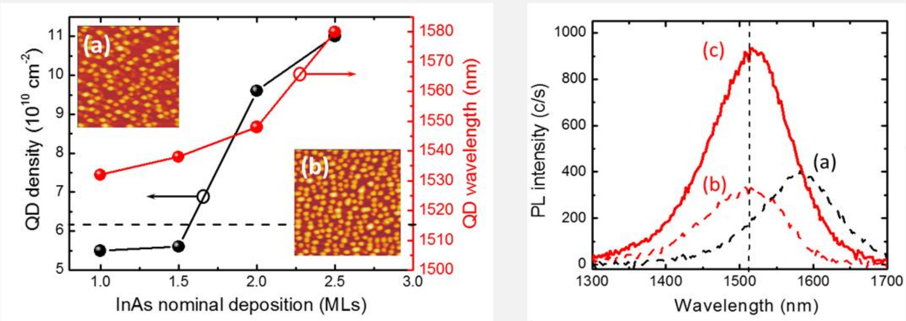


*Fig.1 : Left : QD density and emission wavelength as function of InAs nominal deposition (insets are 0.5*0.5 µm² AFM scans for 1 and 2.5 MLs of InAs). Right : Photoluminescence spectrum of as grown (a) and wavelength controlled (b) QD single layer and wavelength controlled 5 QD stack layers (c).*

With this improvement, we have been able to realize the first QD VECSEL emitting at 1.5 µm (Fig.2). A very high output power of 2.2 W is obtained; a 60 nm tuning range is demonstrated. Further investigations are conducted to evaluate QD-VECSEL potentials for dual frequency operation.

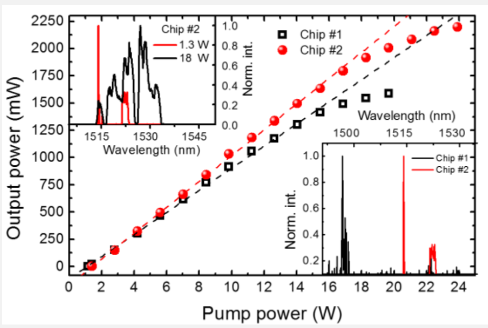


Fig.2 : Output power and threshold spectra of the free-running VECSELs, measured at 15°C. Chips #1 to 2 were taken from across the wafer, demonstrating different micro cavity resonances

Contact

cyril.paranthoen@insa-rennes.fr

Reference

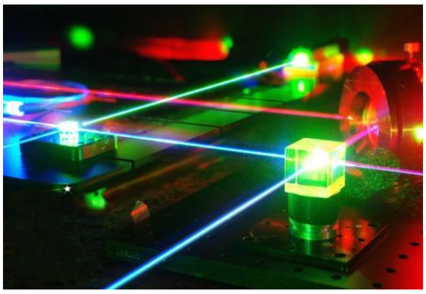
"InAs/InP quantum dot VECSEL emitting at 1.5 µm", K.Nechay *et al.*, *Appl. Phys. Lett.* **115**(17) 171105 (oct 2019).

hal-02338850

« …the first QD VECSEL emitting at 1.5 µm… »

Collaborations

- Tampere University of Technology (Finland)
- Ecole Polytechnique Fédérale de Lausanne (Switzerland)
- LakeDiamond SA (Switzerland)



Contact

patrice.feron@enssat.fr

Reference

"Dynamical Analysis of Modal Coupling in Rare-Earth Whispering-Gallery-Mode Microlasers", J.-B.Ceppe *et al.*, *Phys. Rev. Appl.* **11**, 064028 (jun 2019).

hal-02336186

« It is shown that depending on the material constituting the WGM resonator, frequency locked bidirectional emission or self-modulated regime could be reached »

Collaborations

- Ecole Nationale Supérieure de Chimie de Paris (France)

Experimental studies on modal coupling in Er-doped WGM µ-laser

SP

We have simultaneously measured the RIN spectra of the two counter-propagating signals emitted by erbium doped WGM class-B micro-lasers. In addition to noise peaks at the relaxation oscillation frequency and its harmonics, the analysis of the RIN spectrum of phosphate glass microspherical laser reveals an extra peak (Fig.1.a) due to the self-modulation operation induced by a Rayleigh backscattering induced modal coupling. Cross-correlation measurements between the co- and counter-propagating laser signals show a neat anti-phase oscillation confirming the self-modulation regime (Fig.1.b&c). We have repeated this measurement using a fluoride glass WGM laser and in this case we did not observe any beat-note up to 40 MHz (Fig.2). This can be interpreted as a laser operating in the bidirectional regime or in a self-modulated regime with a high modulation frequency. This behavior difference is well supported by the fact that Rayleigh backscattering is much stronger in our fluoride glass microspheres than in phosphate glass micro-cavities. Controlling the bidirectional feature of miniaturized WGM lasers is crucial for applications. For instance, integrated laser gyroscopes must operate in the self-modulation regime. Furthermore, a good knowledge of the physical and optical properties of materials would be of importance to properly design the microlaser gyroscope. When the modal coupling rate has been experimentally determined, the photon lifetime, which can be controlled via the evanescent coupling with the access line, can be adapted to reach the self-modulation regime. Conversely, for all-optical compact microwave-sources, a bidirectional behavior is preferred since it would avoid the apparition of spurious spikes in the RF spectrum.

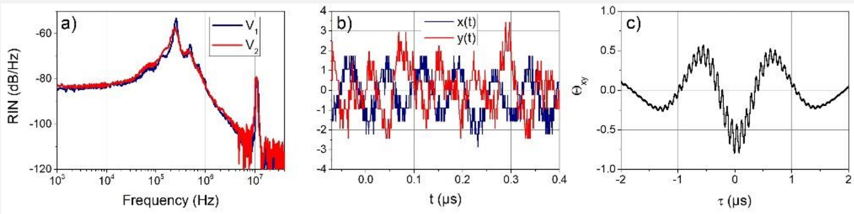


Fig.1 Experimental results obtained in a 105 µm diameter IOG-1 microsphere.

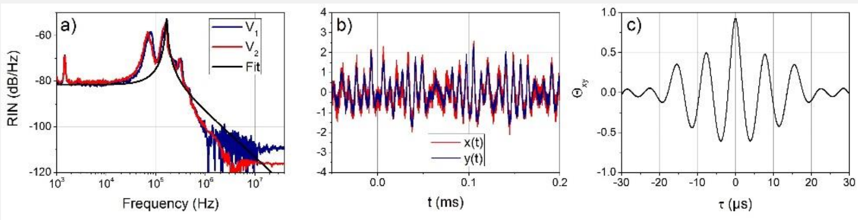
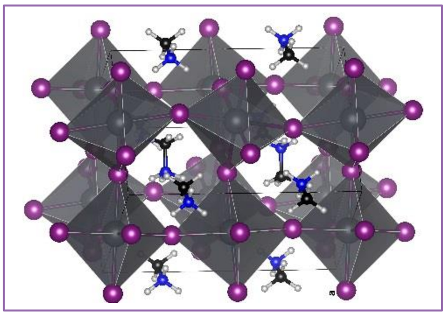


Fig.2 Experimental results obtained in a 100 µm diameter ZBLALiP microsphere.

For the two figures: a) RIN spectrum for the co- and counter-propagating emitted modes. b) Time domain series x(t) and y(t) obtained from centering and normalization of V_1(t) and V_2(t). c) Normalized cross-correlation function.



SILICON PHOTONICS HIGHLY INTEGRATED MICROWAVE SWITCHES

DOP

In modern microwave and millimeter wave (MMW) systems, agility has become a crucial aspect. In particular, for emerging wireless communications, sensing and imaging, reconfigurability is a key feature. In this context, optically controlled amplitude and phase MMW switches are extensively studied in order to overcome the limitations of fully electronic systems in terms of bandwidth and electromagnetic compatibility. However, large footprint and high optical switching powers restrict the parallel integration of such optical switches into MMW systems where compactness and low power consumption are required.

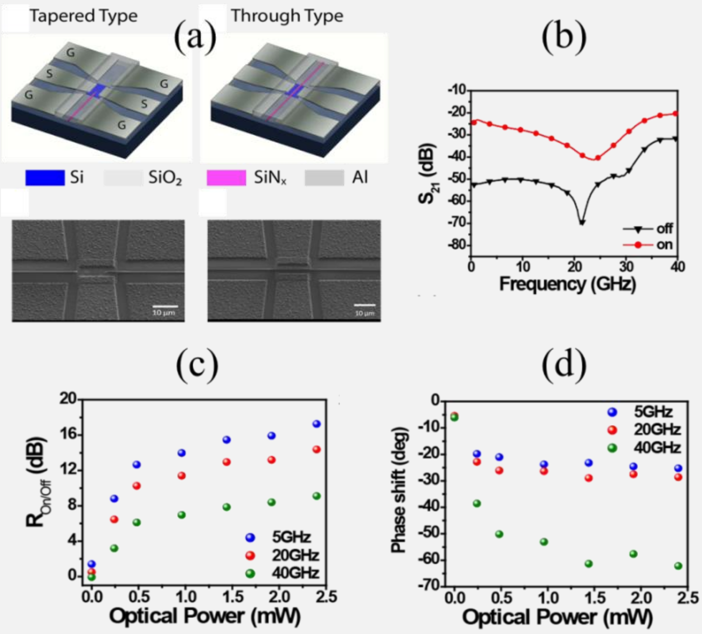


Fig. 1: ***(a)*** *Schematic and SEM images of MORIMS. Left, tapered type. Right, through type. Illustration of* ***(b)*** *RF frequency response* ***(c)*** *RF transmission contrast, and* ***(d)*** *RF phase shift of the tapered MORIMS.*

We overcame these limitations by Monolithic Optically Reconfigurable Integrated Microwave Switches (MORIMSs) fabricated in CMOS compatible silicon photonic platform. The co-integration of a microwave circuit with photonics device enables the design of a single input SiNx waveguide which routes the light toward reconfigurable switches at different locations of the chip. Because of the ultra-miniaturization of the Si photoconductive patch and high confinement of light in the waveguide, the proposed devices outperform their classical analogues in term of On/Off switching efficiency, footprint and optical power requirement lower by orders of magnitude lower than the state-of-art photoconductive switches. A monolithic optically reconfigurable integrated microwave switch building block has been also realized as a proof of concept for future application of photonic chips or antenna array in RADAR system.

Contact

mehdi.alouini@univ-rennes1.fr

Reference

"Microwave signal switching on a silicon photonic chip", C.-Y.Fang *et al.*, *Sci Rep* **9**, 11166 (aug 2019).

hal-02381369

« Silicon photonics gives birth to low power consumption optically controlled microwave switches »

Collaborations

- University of California San Diego (USA)

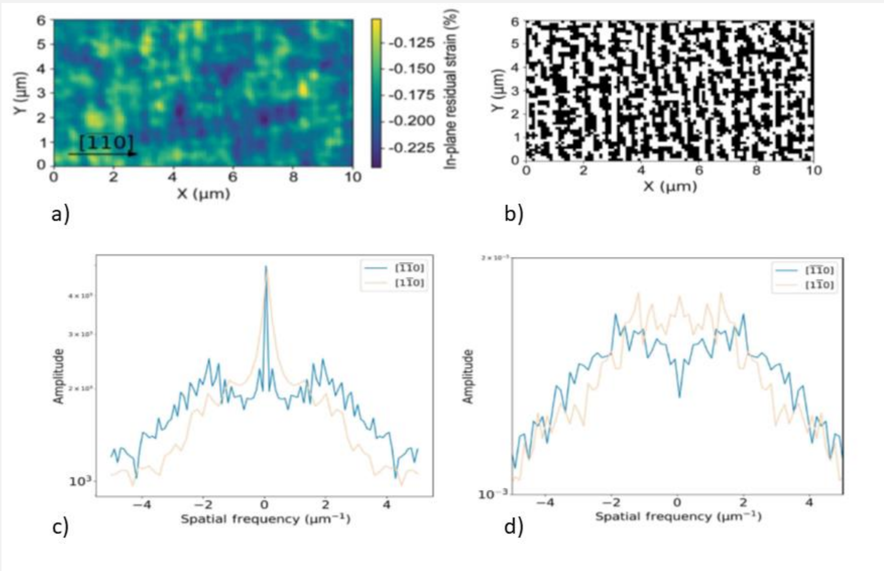
HIGHLIGHTS

STRAIN DISTRIBUTION BY SCANNING X-RAY DIFFRACTION ON GAP/SI

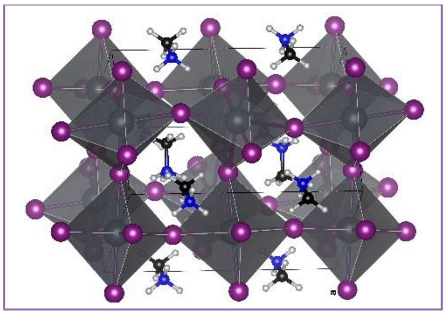
OHM

An advanced synchrotron X-ray diffraction scanning technique with a submicrometer resolution, has been employed to reveal the relaxation process in GaP/Si 200 nm layers grown for monolithic integration of III-V semiconductor on silicon (photonics & photovoltaic applications). Cross-hatch like patterns are observed in the in-plane strain mappings (fig. 1a). The origin of the in-plane local strain variations is shown to be the result of an anisotropic bunching of misfit dislocations in close relation with the substrate miscut, according also to electron microscopy observations. The relationship between the in-plane strain and the free surface roughness is finally discussed and shows the same spatial correlation.

This non-destructive technique that does not require specific sample preparation, has a great potential for further investigation of strain&stress and structural defects impacts on key devices such as PV cells, lasers and nonlinear devices within photonic integrated circuits.



(a) In-plane strain mapping (%). (b) A local binary image extracted from the residual strain mapping plotted in panel (a). (c) The spatial frequency of the lines with high strain along [110] (blue) and [110] (orange). (d) The spatial frequency from AFM measurement (not shown here) along [110] (blue) and [110] (orange).



Contact

antoine.letoublon@insa-rennes.fr

Reference

"A study of the strain distribution by scanning X-ray diffraction on GaP/Si for III–V monolithic integration on silicon", A.Zhou *et al.*, *J. Appl. Crystallogr.* **52**(4) 809-815 (2019).

hal-02289442

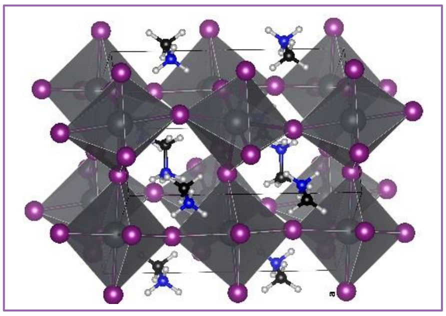
« Advanced synchrotron X-ray microscopy reveals an anisotropic relaxation process in GaP/Si epitaxial layers, in the framework of monolithic integration of III-V on silicon. »

More Information

- doi.org/10.1107/S1600576714004506
- hal.archives-ouvertes.fr/hal-01859116
- hal.archives-ouvertes.fr/hal-01770934

Collaborations

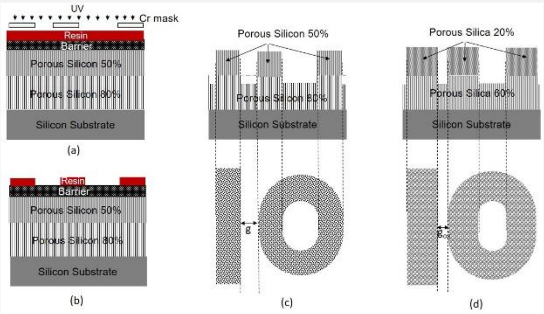
- European Synchrotron Radiation Facility (France)
- Science et Ingénierie des Matériaux et Procédés (France)
- Institut Nanosciences et Cryogénie (France)
- Centre de Nanosciences et de Nanotechnologies (France)



GAP REDUCTION FOR A POROUS SILICA RIDGE WAVEGUIDE MICRO-RESONATOR

SP

A new method of processing racetrack micro-resonator based on porous silicon ridge waveguides has been demonstrated in the objective to obtain lower gaps between the straight access waveguide and the racetrack cavity by thermal oxidation. The minimum gap that can be obtained by a standard photolithography process is limited by the resolution of the technique which is of 0.5µm. The objective is to reach lower gaps in order to reduce the coupling distance and so to further miniaturize porous silica micro-resonators. This method consists firstly in performing the standard photolithographic process (Fig. 1.a and 1.b) to fabricate the racetrack micro-resonator based on porous silicon layers. Then the integrated structure is oxidized to reduce the gap between the straight access waveguide and the racetrack cavity taking advantage of the volume expansion due to the transformation of porous silicon in porous silica (Fig. 1.c and 1d). The method previously adopted consisted in oxidizing the porous silicon layers before the process of the ridge porous silica waveguides. In both methods, a lateral etching occurs which reduces significantly the width of the ridge waveguide and increases consequently the gap. Such phenomenon results in the use of larger coupling distance in the design of the racetrack. The volume expansion is all the more accentuated when the porosity of the guiding layer is low. In this work, we demonstrated (Fig. 2) a gap reduction of about 40% that has been obtained due to the expansion phenomena with an initial porosity of 50%.



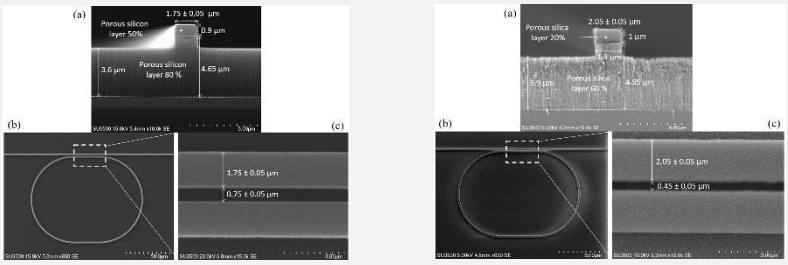


Fig. 1: Schema of the photolithographic process used for the fabrication of porous silica ridge waveguides: (a) deposit of a photosensitive resin and exposure under UV, (b) etching of UV exposed resin, c) etching of the porous silicon layers to obtain the ridge waveguide and d) volume expansion due to thermal oxidation of the porous silica ridge waveguide.

Fig. 2: SEM observations after the photolithographic process :(a) cross section of the porous silicon ridge waveguide, (b) top view of the micro-resonator with a low magnification, (c) top view of the coupling area of the micro-resonator at a higher magnification - SEM observations after the thermal oxidation : (d) cross section of the porous silicon ridge waveguide, (e) top view of the micro-resonator with a low magnification and (f) top view of the coupling area of the micro-resonator at a higher magnification.

Contact

nathalie.lorrain@univ-rennes1.fr

Reference

"Submicron gap reduction of micro-resonator based on porous silica ridge waveguides manufactured by standard photolithographic process", N.Lorrain *et al.*, *Opt. Mater.* **88,** 210-217 (feb 2019).

hal-01955831

« In this work, we demonstrated a gap reduction of about 40% »

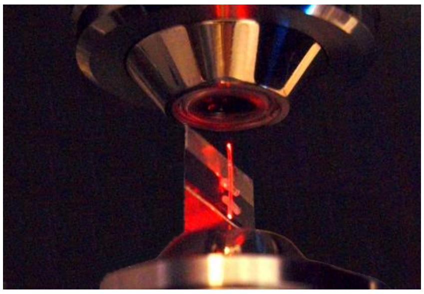
More Information

- tel.archives-ouvertes.fr/tel-02021161
- tel.archives-ouvertes.fr/tel-02384939

Thesis funded by Région Bretagne, Département des Côtes d'Armor & Lannion-Trégor Communauté

Collaborations

- Institut Mines-Telecoms Atlantique (France)



Contact

julien.fade@univ-rennes1.fr

Reference

"An all-optical technique enables instantaneous single-shot demodulation of images at high frequency", S.Panigrahi *et al.*, Nat. Commun. (accepted, in press).

arXiv:1909.05366

« A massively spatially multiplexed lock-in detection circuit in the optical domain »

More Information

- doi.org/10.1364/OE.24.016066
- Funded by IFCPAR/CEFIPRA project RITFOLD N°4606
- Patent PCT/IB2016/001445, EP3455961,10/05/2016

Collaborations

- Raman Research Institute (India)

RRI

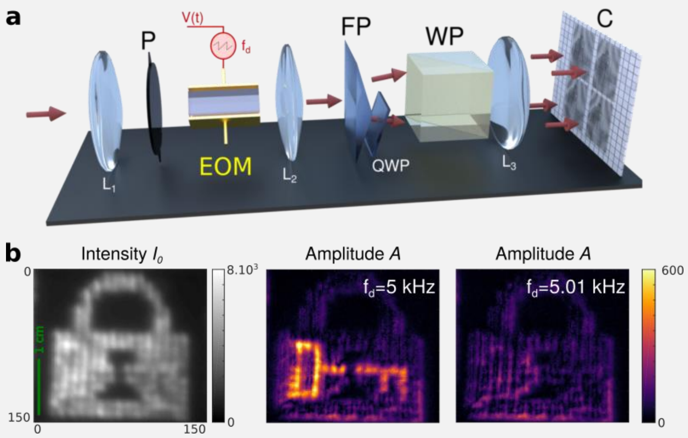
HIGHLIGHTS

HIGH-FREQUENCY QUADRATURE DEMODULATION IMAGING

DOP

Since long, optical intensity modulation/demodulation techniques have encountered numerous applications in telemetry, free-space communications or optical characterization of scattering media. Upgrading those techniques to a full-field, real-time imaging modality would allow massive information multiplexing, an essential asset not only for 3D imaging or optical communications, but also in the long term for imaging in turbid media (medical diagnosis, underwater vision, imaging in colloids, or navigational aid for safe transports).

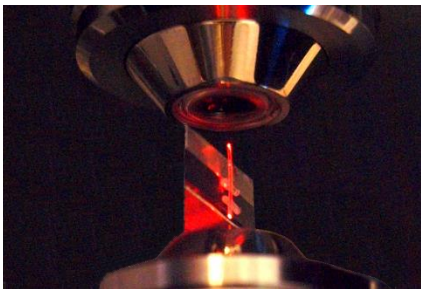
In collaboration with the Raman Research Institute (Bangalore, India), we proposed a new concept of Full-field All-optical Snapshot Technique for QUADrature demodulation imaging (FAST-QUAD). This technique, patented in 2016, is capable of wide-field real-time image demodulation, without requiring any synchronization between the receiver and the intensity-modulated source(s) in the imaged scene. This technique relies on an all-optical architecture, at the heart of which a bulk electro-optical crystal and appropriate polarization optics components make it possible to spatially multiplex four transmission « gates » in quadrature to each other (0°, 90°, 180°, 270°), addressing four sub-images detected on the same single image sensor (CCD/CMOS).



This setup thus behaves as a quadrature lock-in detection circuit operating in the optical domain and in a massively spatially multiplexed way, where the acquisition time of the image sensor is advantageously used as a low-pass integrator. This optical module can therefore be inserted in front of any standard camera, and allows the number of electronics components to be minimized. This property provides FAST-QUAD with a major asset, as its operating frequency is fully and continuously tunable in the RF range. We established the experimental proof-of-concept of this technique between 0 Hz (DC) and 500 kHz on the first prototype built in the laboratory, and we illustrated some of its high-potential applications, such as reduction of the clutter, frequency discrimination of targets and secrete information sharing through decoy image. The next challenge of this research project will be to extend the operation frequency to higher values in order to reach major applications (transports, biomedical).

GRAVITATIONAL WAVE CATALOG

DOP



Since the first discovery of a gravitational wave transient signal from the coalescence of two black holes in 2015, the maturation of the field is growing at full pace. The European Virgo detector joined in summer 2017 the American instruments to form a network with a sky positioning capability. This resulted a few weeks later in the identification of a neutron star binary coalescence also identified by multiple telescopes at various wavelengths, so that now this kind of event is believed to be the main process in the universe to create heavy elements in the Mendeleev table. After the first discoveries, with upgrade in the instrument reaching range, the network can now operate to do what is has been designed for: make multiple measurements of astrophysical interest. The first catalog of events published in 2019 is the witness of these progresses.

The catalog reports the 11 events identified as significant up to end of august 2017. The purpose of the first part is to make it clear how the statistical significance is asserted. Different algorithms are run in parallel, and results of algorithms are compared. Two algorithms implement the matched filtering of the data with patterns of the parametrized signals, another one looks for weakly modeled or non-modeled signals. The data analysis rules out the « spikes » in the data, and requires that there is coincidence on the multiple detectors. All the data processing is explained with deep statistical arguments, so that the reader is convinced that the event selection is done in the right way.

The paper discloses four signals that have not been published before. The source properties and statistical significance of all eleven signals is re-analyzed. Except from the neutron star coalescence, all other signals are coalescences of black holes with solar masses ranging from 7.9 to 50.2: while the existence of these objects was only marginally admitted five years ago, this catalog demonstrates a shift in the knowledge of these objects. The amount of signals is still too low to have definitive assertions on a possible "mass gap" of objects with masses of only with a few unit solar masses. The statistics of the spins of objects is also a bit low to understand if the objects were previously large stars pairs that collapsed keeping the partner, or kicked-out black holes captured by other black holes. The objects distances range from 320 to 2840 Mpc, except for the neutron star binary that was at a distance of 40 Mpc.

The extrapolation of the merger rates in the universe depends on the proper classification of events and on the identification of a-priori hypotheses. The high limit of the rate interval for one algorithm is still a factor 3, and the combination of all populations gives 110-3840 $Gpc^{-3}y^{-1}$.

This makes it clear that in order to improve the error bars on the estimated parameters, as well as to increase the rate of detected signals, the improvement of the instrument resolution is mandatory: the FOTON institute is involved in that task.

Contact

francois.bondu@univ-rennes1.fr

Reference

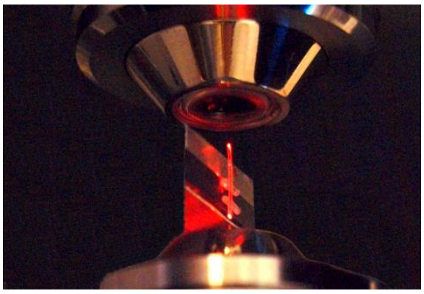
"GWTC-1: A Gravitational-Wave Transient Catalog of Compact Binary Mergers Observed by LIGO and Virgo during the First and Second Observing Runs", B.P.Abbott *et al.*, *Phys. Rev. X* **9**(3) 031040 (sep 2019).

hal-02059393

« This catalog is a sign of the maturity of the field, providing information of astrophysical interest »

Collaborations

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



Contact

jean-marc.goujon@enssat.fr

Reference

"Active Hyperspectral Mid-Infrared Imaging Based on Widely Tunable QCL Laser", C.El Fakir *et al.*, *ICTON 2019*, Angers, France, 9-13 july 2019 (sep 2019).

hal-02382528

« Active hyperspectral MIR imaging to characterize plant leaves under controlled growing conditions »

Collaborations & Funding

- Centre Mondial de l'Innovation Roullier (France)

ACTIVE HYPERSPECTRAL MIR IMAGING BASED ON WIDELY TUNABLE QCL

SP

Thermal imaging cameras and the recent availability of widely tunable infrared QCL lasers (Quantum Cascade Laser) allow us to propose an active hyperspectral imaging system operating in mid-infrared (MIR) band to obtain simultaneously large amounts of spatial and spectral information on the samples.
In order to evaluate more precisely the capacities of the active hyperspectral imaging, we propose the system shown in figure 1, composed of four powerful (10 mW range) QCL tunable lasers, in order to cover 3-5 µm and 7-11 µm wavelengths. The figure 2 shows the power spectra obtained by two cameras: an InSb cooled camera for 3-5 µm range and a bolometer one for 7-13 µm range.
The advantage of such a system is that it allows large samples to be analyzed with a field of view up to 5 cm diameter. It will provide major advances in the characterization of plant leaves under controlled growing conditions.

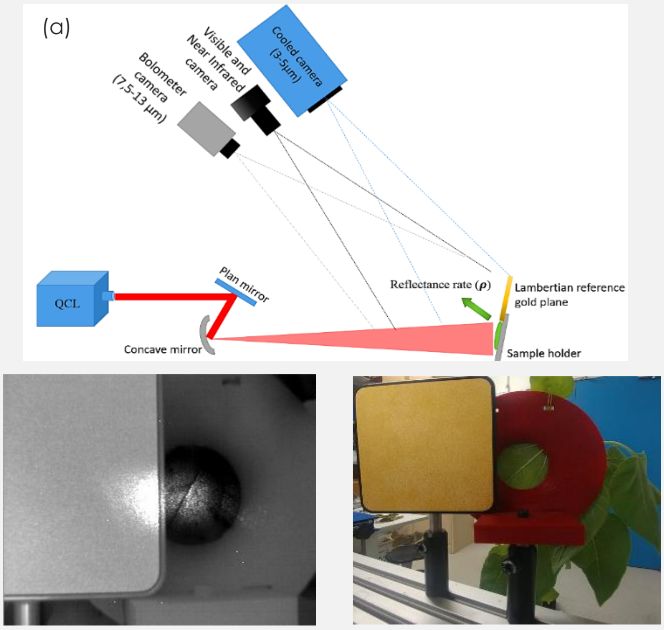


Figure 1: (a) Schematic of the experimental bench for active hyperspectral imaging, using tunable QCL and different cameras. (b) Details of the diffusing screen and sample support and (c) an example of MIR image.

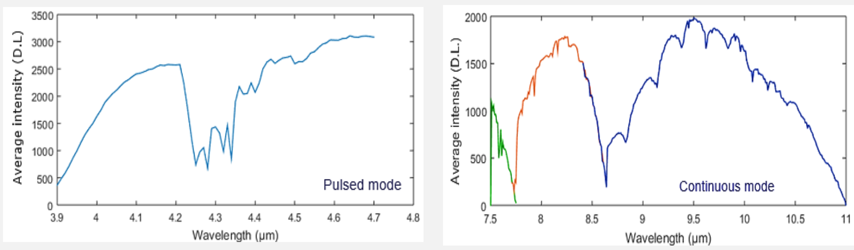
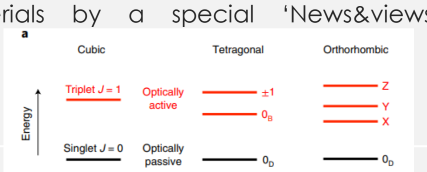


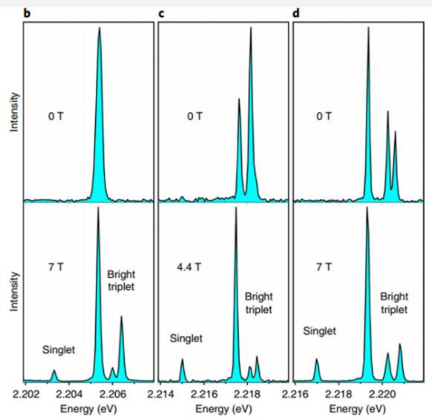
Figure 2: Infrared spectra of the laser beam after diffused reflections on a wideband IR Lambertian reference gold plane.

GROUND EXCITON STATE OF FAPBBR3 NANOCRYSTALS : SINGLE DARK STATE

OHM

Perovskite quantum dots (QDs) are promising nanostructures for optoelectronics, especially for the application to light emitting devices (LED). CsPbX3 inorganic QDs or FAPbX3 hybrid QDs (X=I, Br, Cl and FA=formamidinium) have exhibited an exceptional brillancy and high quantum yields. Two CNRS teams (LP2N and FOTON) work together on this subject since 2017. They have previously studied the exciton bright triplet fine structure in CsPbBr3 single QDs in terms of structural distortions, predicting as well a singlet dark state located below the bright triplet state. Several other groups using time resolved spectrocopy have attributed the brillancy of perovskite QDs to a slow relaxation from the bright triplet to the dark singlet, related, according to the joint LP2N/FOTON team in the case of FAPbI3 QDs, to a second order mechanism assisted by two optical phonons. The publication in the journal Nature of a paper in 2018 led to a controversy. Based essentially on a theoretical model, the brillancy of CsPbX3 QDs was attributed to a pure Rashba effect supposedly leading to a clear shift of the bright triplet below the dark singlet. This unprecedented situation extended more generally to all the perovskites as claimed by the same authors, shall put forward them as a very special class among all the other semiconductors with many theoretical and practical implications. Within this context, the joint LP2N/FOTON team associated to ETH Zurich and EMPA in Switzerland has directly evidenced for the first time the singlet dark excitonic state in perovskite QDs in a paper published by the prestidigious review Nature Materials. The spectroscopy of FAPbBr3 single QDs was performed at low temperature (5K) under magnetic field, to reveal unambigously the presence of a dark singlet state several meV below the dark triplet. This difference is consistent with a theoretical model attributing the splitting essentially to the long-range part of the exchange interaction in a weak quantum confinement regime. This new result is therefore strongly questionning the general scenario purely based on Rashba effect, being moreover fully compatible with previous interpretations. The slow relaxation from the bright triplet to the dark singlet is again related to a second order mechanism assisted by two optical phonons. This article has been further highlighted also in Nature Materials by a special 'News&views' (DOI : 10.1038/s41563-019-0376-6).





Fine structure of the bright triplet and the dark singlet exciton for FAPbBr3 NCs. (a) Diagrams of energy levels of the band-edge exciton fine structure of FAPbBr3 perovskites for three different crystal anisotropies (lattice or shape). The lowest state is a dark state while the others are optically active. (b–d) The one-line, two-line and three-line spectra of three different NCs at 4 K in zero field (upper panels) turn under magnetic fields into four-line spectra (lower panels) that reveal the entire fine structure, including the lowest-energy singlet recombination line.

Contact

jacky.even@insa-rennes.fr

Reference

"The ground exciton state of formamidinium lead bromide perovskite nanocrystals is a singlet dark state", P.Tamarat *et al.*, *Nat. Mater.* **18**(7) 717–724 (may 2019).

hal-02130647

« Here, we provide the direct spectroscopy signature of the dark exciton emission in the low-temperature PL of single FAPbBr3 perovskite nanocrystals under magnetic fields »

More Information

- doi.org/10.1021/acs.nanolett.7b00064
- doi.org/10.1038/s41467-018-05876-0
- doi.org/10.1038/s41563-019-0376-6

Collaborations

- Laboratoire Photonique, Numérique et Nanosciences (France)
- Swiss Federal Laboratories for Materials Science and Technology (Switzerland)
- Swiss Federal Institute of Technology in Zürich (Switzerland)

CONFINEMENT EFFECTS IN HYBRID PEROVSKITES SEMICONDUCTORS

OHM

Sub-nanometric control of the growth of multilayered perovskites and perovskite quantum dots, is opening up additional perspectives for this new class of semiconductors. The present article is an experimental and theoretical review of the state of the art of the confinement effects understanding in these low-dimensional nanostructures.

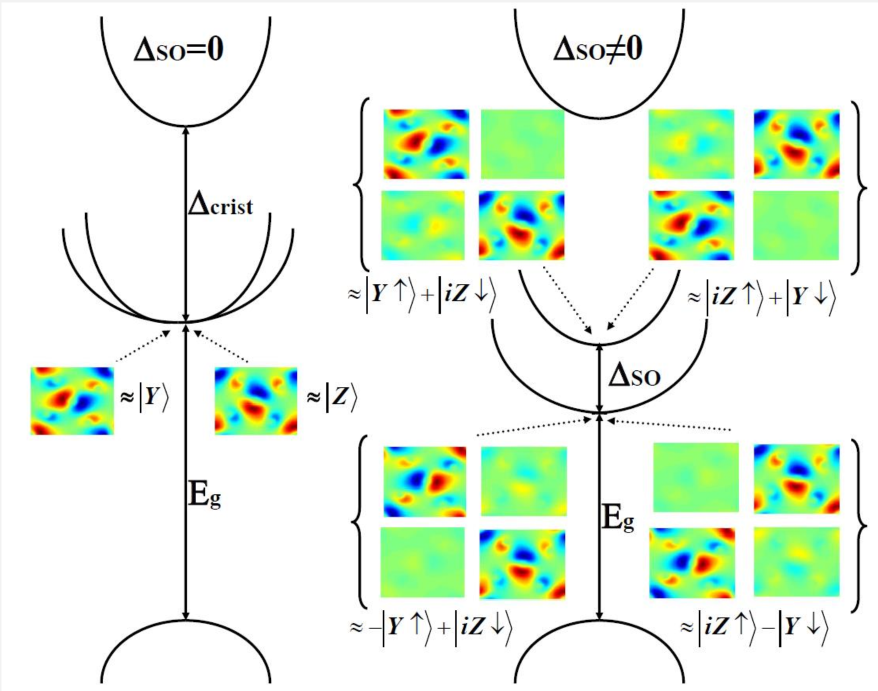
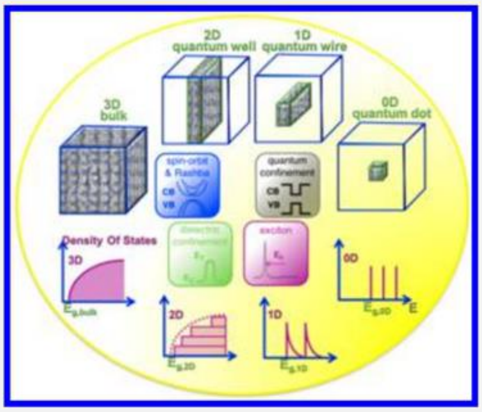


Illustration of various effects affecting the electronic band structure of layered perovskites



Contact

jacky.even@insa-rennes.fr

Reference

"Quantum and Dielectric Confinement Effects in Lower-Dimensional Hybrid Perovskite Semiconductors", C.Katan, N.Mercier and J.Even, *Chem. Rev.* **119**(5) 3140-3192 (jan 2019).

hal-01982514

« Multilayered halide perovskites and colloidal perovskite nanostructures represent nano-objects of great complexity »

More Information

- hal.archives-ouvertes.fr/hal-01760080
- doi.org/10.1126/science.1228604
- doi.org/10.1126/science.aaf9717

Collaborations

- Institut des Sciences Chimiques de Rennes (France)
- Institut des Sciences et Technologies Moléculaires d'Angers (France)

SOLAR WATER SPLITTING FROM GAPSB ALLOYS DEPOSITED ON SILICON

OHM

The hydrogen produced by the artificial photosynthesis, that is to say, dissociation of the water from the solar energy is an alternative to production and to storage solar energy

In this work the authors from FOTON Institute and University College London present water splitting from photoelectrode made up of $GaP_{0.67}Sb_{0.33}$ alloy deposited by molecular beam epitaxy on silicon substrate. The GaPSb alloy layers present a direct bandgap, allowing high absorption of the solar photons and thus high efficiency. Moreover they are deposited on silicon substrates, pledge of future drastic cost reduction.

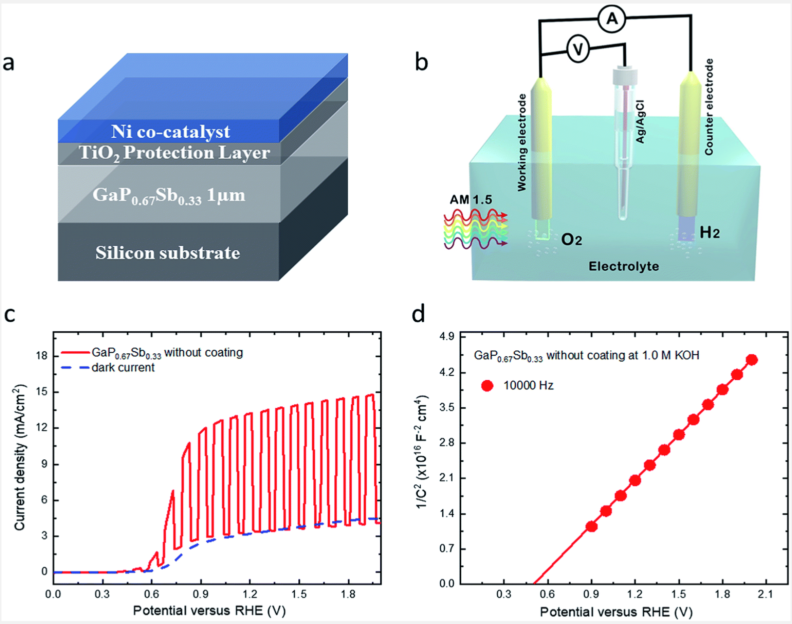


Fig. 1: Schematic diagram of the structure for the GaP0.67Sb0.33 photoanode coated with a protection layer (TiO2) and co-catalyst (Ni). (b) The experimental setup using a three-electrode system for the photoelectrochemical measurements. (c) Current density versus applied voltage (J–V) curve in 1.0 M KOH (pH=14) electrolyte under simulated AM1.5 illumination versus RHE. (d) Mott–Schottky (M–S) plot as a function of the applied potential (E).

Under one sun simulated solar light irradiation, the GaP0.67Sb0.33 photoanode shows a high photocurrent density of 4.82 mA/cm² at 1.23 V and onset potential of 0.35 V versus RHE in 1.0 M KOH (pH=14) aqueous solution. Furthermore, the photoanode was stable for 5 h without any change in the photocurrent density at 1 V vs. RHE and a high IPCE of up to 67.1 % through the visible range from 400 nm to 650 nm was achieved.

This demonstration paves the way for an low cost photoelectrochemical system in tandem configuration with a theoretical yield of 27 % from solar energy to hydrogen.

Contact

nicolas.bertru@insa-rennes.fr

Reference

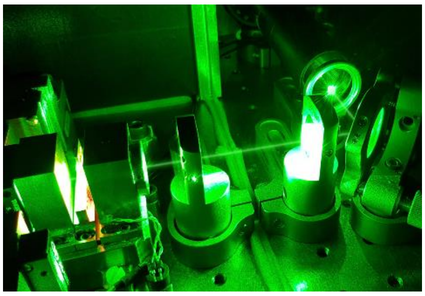
“Photoelectrochemical water oxidation of GaP 1−x Sb x with a direct band gap of 1.65 eV for full spectrum solar energy harvesting”, M.Alqahtani *et al.*, *Sustain. Energy Fuels* **3**(7) 1720-1729 (jul 2019).

hal-02178176

« Hydrogen production from solar water splitting »

Collaborations

- University College London (Great-Britain)



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mehdi.alouini@univ-rennes1.fr

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"Brillouin Assisted Optoelectronic Self-Narrowing of Laser Linewidth", G. Danion *et al.*, *IEEE Photon. Technol. Lett.* **31**(12), 975-978 (2019).

hal-02383051

« Nothing is impossible even a laser frequency noise eater»

More Information

- doi.org/10.1364/OPTICA.6.000152
- doi.org/10.1364/OL.41.002362

Collaborations

- Laboratoire de Physique des Lasers, Atomes et Molécules (France)

PhLAM

BRILLOUIN ASSISTED OPTOELECTRONIC SELF-NARROWING OF LASER LINEWIDTH

DOP

Owing to the wide field of applications addressed by narrow linewidth lasers in modern physics, they are the subject of huge research efforts addressing.

We report, for the first time to our knowledge, on the optoelectronic nibbling of a laser line in the optical domain. To this aim, part of the laser output pumps a long non-resonant Brillouin loop in order to generate a narrow-linewidth Stokes wave which is used in turn to narrow down the pump wave. This achievement relies on two mechanisms that are ensured by the same single phase-locked loop (PLL). First, this PLL enables single mode operation of the long Brillouin resonator by forbidding mode hopping. Second, the high spectral purity of the generated single-mode Stokes wave is copied to the pump wave owing to the same PLL. A dramatic reduction of the pump optical phase noise is thus achieved. The experimental demonstration is conducted in an Er,Yb:glass laser where a phase noise reduction by more than 90 dB at 100 Hz offset is demonstrated. Accordingly, the effective optical linewidth is thus narrowed down from few tens of kHz to 2 Hz. The combination of the Brillouin loop and the phase-locked loop acts as a linewidth nibbler fed by the laser under consideration itself. The proposed principle is consequently comparable to a laser intensity noise eater, but in the frequency domain. This approach being independent of the laser wavelength, it can be implemented to almost any laser. The universality and easy implementation of the proposed method open new interesting routes.

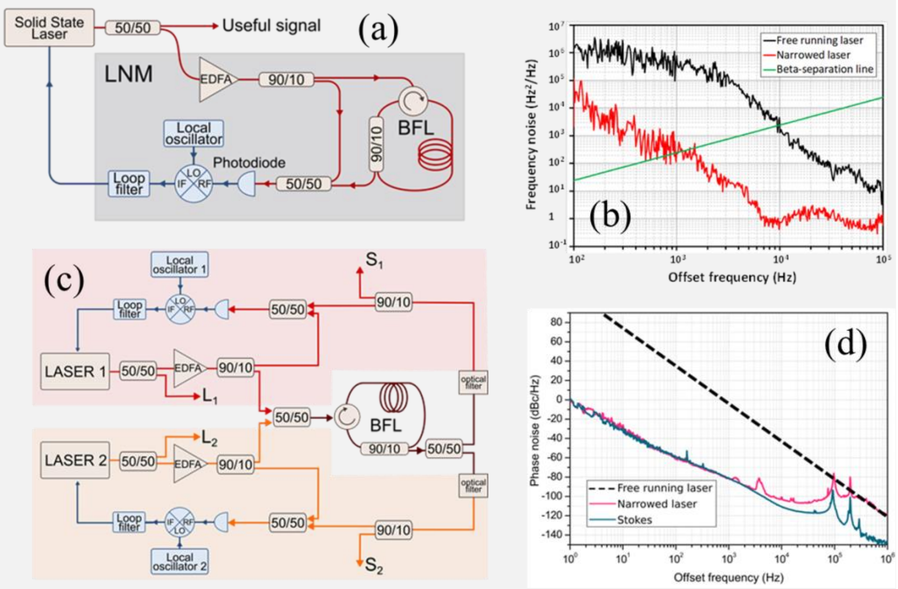
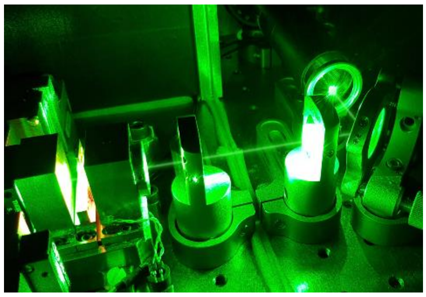


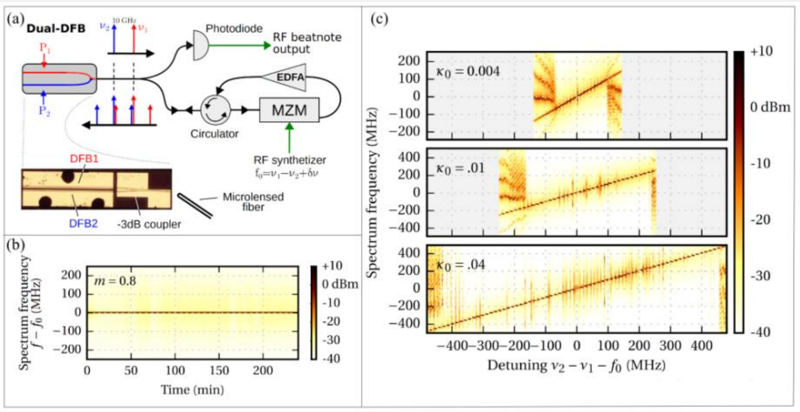
Fig.: ***(a)*** *Principle of optoelectronic laser line nibbling.* ***(b)*** *Laser frequency noise before and after optoelectronic laser line nibbling.* ***(c)*** *Comparison of two independent lasers.* ***(d)*** *phase noise of the beatnote between the two lasers*



PHASE SYNCHRONIZATION OF DFB LASERS

DOP

The experimental implementation of optically carried RF signals, in the 1-100 GHz range and beyond, is fundamental for microwave photonics applications. The technique of heterodyning two laser waves provides an interesting alternative to direct modulation of light. Indeed, it allows generating directly a single-sideband signal over an optical carrier, which is inherently insensitive to dispersion in a fiber link. It also features a 100 % modulation depth, a broad and continuous tunability. Phase-locking to electronic local oscillators results in optical beatings of very high spectral purity; furthermore, high microwave frequencies (~100 GHz) can be reached by suitable multiplication or downconversion techniques (at the expense of a degradation of the phase noise performances). In this work, we have focused on an all-optical locking technique that relies on frequency-shifted optical feedback, and allows locking the beatnote of two monolithic dash-in-a-well DFB lasers on an external electronic oscillator (see Fig(a)). This locking method is *passive*, i.e. it does not require any active control electronics. We have experimentally demonstrated that tunable, stable phase locking can be achieved over several hours, as shown on Fig(b).



Furthermore, we have investigated experimentally the various dynamical regimes occurring in the system, leading to different output spectra (Fig(c)). We have built a rate-equation model and compared it carefully with the experimental findings. In particular, we have investigated the role of the unavoidable long delay introduced by the feedback loop, and the influence of the optical feedback phases, that cannot be controlled experimentally and are prone to drifts, on the stable locking regime.

The main achievements of this work are the following: two DFB lasers coupled by frequency-shifted cross-injection and self-feedback can feature stable frequency locking on a broad range of parameters. The uncontrolled variations of the optical feedback phases do not prevent the obtention of stable phase-locking, which is more robust against perturbations when using a strong modulation rate, i.e. favoring cross-injection over self-feedback. The large delay associated to the feedback loop turns out to be preferable to a shorter one.

Contact

marco.romanelli@univ-rennes1.fr

Reference

"Synchronization of Two DFB Lasers Using Frequency-Shifted Feedback for Microwave Photonics", A.Thorette, M.Romanelli and M.Vallet, *IEEE J. Quantum Electron.* **51**(1), 2200108 (feb 2019).

hal-02383118

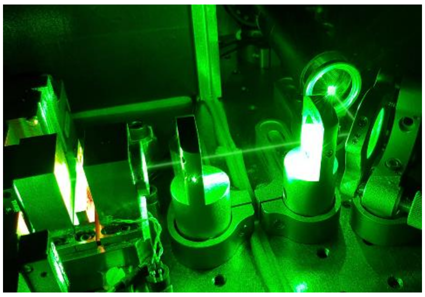
« The sensitivity of the locking to the optical feedback phases is mitigated by using strong cross-injection »

More Information

- hal.archives-ouvertes.fr/hal-01970482

Collaboration

- III-V Lab (France)



Contact

yannick.dumeige@univ-rennes1.fr

Reference

"Infrared laser threshold magnetometry with a NV doped diamond intracavity etalon", Y. Dumeige *et al.*, *Opt. Express* **27**(7) 1706-1717 (jan 2019).

hal-02107654

« Our simulations show that a photon shot-noise limited sensitivity of about 700fT/√Hz can be reached »

More Information

- doi.org/10.1038/nphys1075
- doi.org/10.1038/nature07278
- doi.org/10.1088/1367-2630/18/1/013015

Collaborations

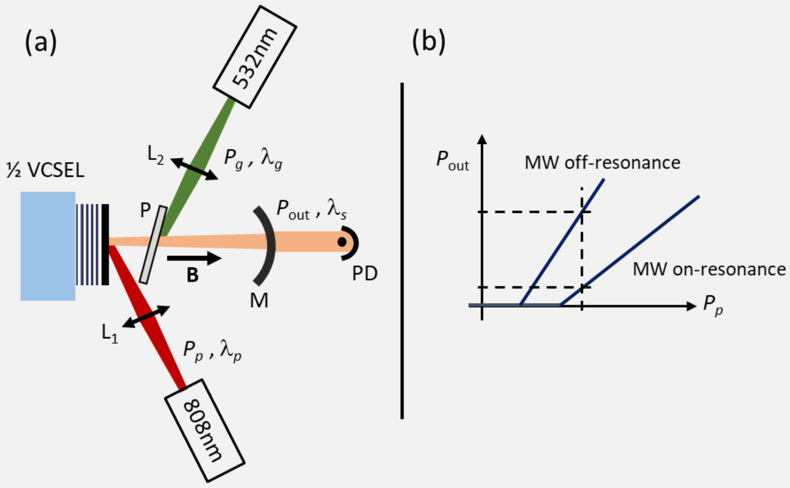
- Laboratoire Aimé Cotton (France)
- Thales Research and Technology (France)
- Center for High Technology Materials (USA)
- Universität des Saarlandes (Germany)
- Johannes Gutenberg University of Mainz (Germany)
- Lawrence Berkeley National Laboratory (USA)

LASER THRESHOLD MAGNETOMETRY

SP

Magnetometers with sensitivity in the range of 1 pT/√Hz have applications in security and control, petrol or mineral prospection and also in magnetic induction tomography (MIT). In particular, for MIT, the compactness of the magnetic sensor would be useful to increase the spatial resolution and the signal to noise ratio by reducing the distance between the sensor and the material under investigation. Spatially resolved MIT will find applications in noninvasive human brain imaging (magnetoencephalography) or heart rate monitoring in emergency situations (magnetocardiography).

It has been proposed to use the spin resonance of the diamond NV color center, which can be optically to probe magnetic field. This solid-state system, which consists of the bonding in the diamond lattice between a Nitrogen impurity (N) with a vacancy (V), can be considered as an artificial atom embedded in a solid-state matrix. Its electronic spin in the ground electronic state with a very long dephasing time even at room temperature can be optically polarized using an intense green pump beam (at λ_g=532 nm) and read out by monitoring its visible luminescence (around 637 nm) or its infrared (IR) absorption at λ_s=1042 nm.



To circumvent the drawback of the poor visible luminescence collection it was very recently proposed to operate the NV center transition in the stimulated emission regime so that the NV center levels provides the optical gain of a laser. By setting the laser at threshold, sensitivities about 1 fT/√Hz have been anticipated. Nevertheless, the stimulated emission is strongly reduced by the excited state absorption. In this paper we propose to combine the IR absorption method and the laser threshold magnetometry. In our laser architecture the gain is provided by a vertical external cavity surface emitting laser and the diamond sample plays the role of an intra-cavity etalon whose optical losses are modulated by the magnetic field. Our calculation show that a sensitivity less than 1 pT/√Hz is reachable without the use of an additional external low frequency noise laser as it is the case in usual IR NV center magnetometry schemes.

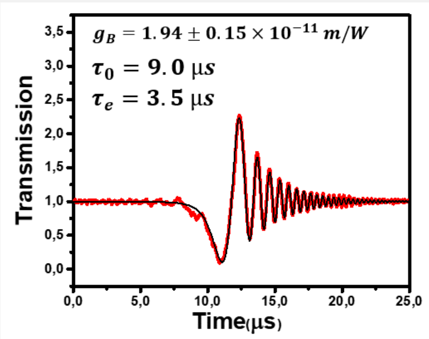
BRILLOUIN GAIN EXTRACTION INSIDE A HIGH-Q CAVITY

SP

The constant needs for laser spectral purity improvements are driven by the growing panel of applications in fundamental and applied physics, which require such coherent sources. One of the most promising approach to generate compact and narrow linewidth lasers is based on the stimulated Brillouin scattering (SBS) optical nonlinearity. Impressive frequency-noise reduction, when compared to that of the pump, was reported for Brillouin lasers. To reach such low-noise laser-performances, one of the most important parameters to evaluate is the material-gain coefficient.

Usually, the Brillouin gain may be estimated through classical pump-probe experiments, self-heterodyne, Fabry-Perot interferometry or threshold power determination. In those methods, the SBS phenomenon is generated by feeding a single pass waveguide with a pump power signal. Those methods suffer from several drawbacks. Firstly, to reach the SBS threshold, either a long waveguide or a high pump power has to be used. These requirements are not always suitable, depending on the material and cavity design (waveguide, microresonator). Secondly, with conventional measurement methods, the gain parameter is inferred at the expense of knowing material constants, which are not systematically available.

We report on a technique based upon the cavity ring-down method that enables to extract directly the Brillouin gain coefficient using a laser high-Q cavity. Material gain, optical cavity parameters, and lasing properties can be determined from the transient response of the high-Q cavity within a single experiment (see figure below). We have shown that the fast sweeping ring-down technique allows Brillouin gain to be characterized.

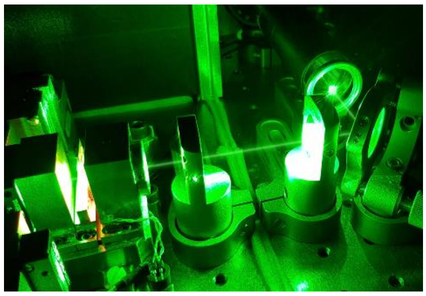


Transient response of the probed mode from a silica fiber ring resonator. The red curve corresponds to the experimental measurement. Fitting (black curve) allows to retrieve an estimation of the Brillouin gain (g_B) as well as the cavity parameters (τ_0, τ_e).

The proof of concept has been experimentally demonstrated with a silica fiber ring resonator. This allowed us to determine

- unambiguously the coupling regime, through the lifetime constants, τ_0 (intrinsic photon lifetime due to cavity losses) and τ_e (coupler lifetime related to the coupling coefficient),
- the Brillouin gain coefficient of the material, which is part of the resonator without the needs of material constants knowledge.

The results are in good agreements with usual pump-probe techniques. This cavity ring-down method can be applied to any kind of resonators allowing for example, the determination of Brillouin gain coefficient in microresonators, exotic material fiber rings and whispering gallery mode resonators.



Contact

pascal.besnard@enssat.fr
stephane.trebaol@enssat.fr

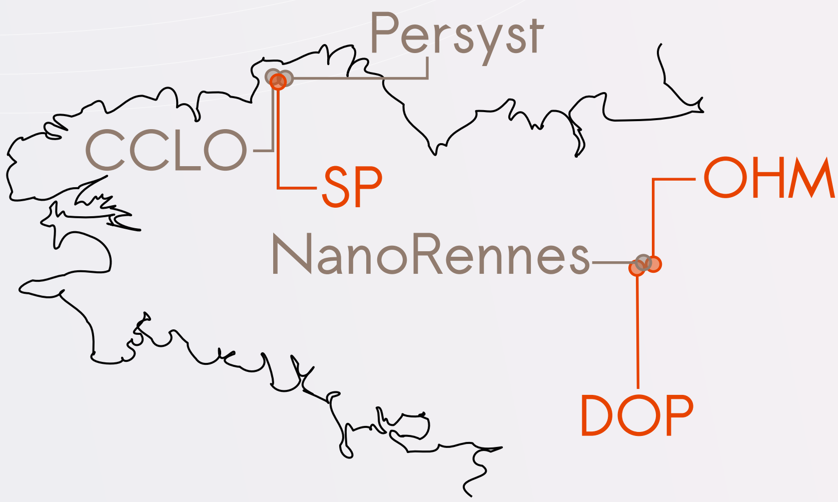
Reference

"Intracavity Brillouin gain characterization based on cavity ring-down spectroscopy," Ananthu Sebastian, Stéphane Trebaol, and Pascal Besnard, OSA Continuum 2, 3539-3545 (2019) *hal-02450541*

« To reach such low-noise laser-performances in Brillouin lasers, one of the most important parameters to evaluate is the material gain coefficient »

More Information

- doi.org/10.1364/JOSAB.25.002073
- doi.org/10.1364/OL.16.000393



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