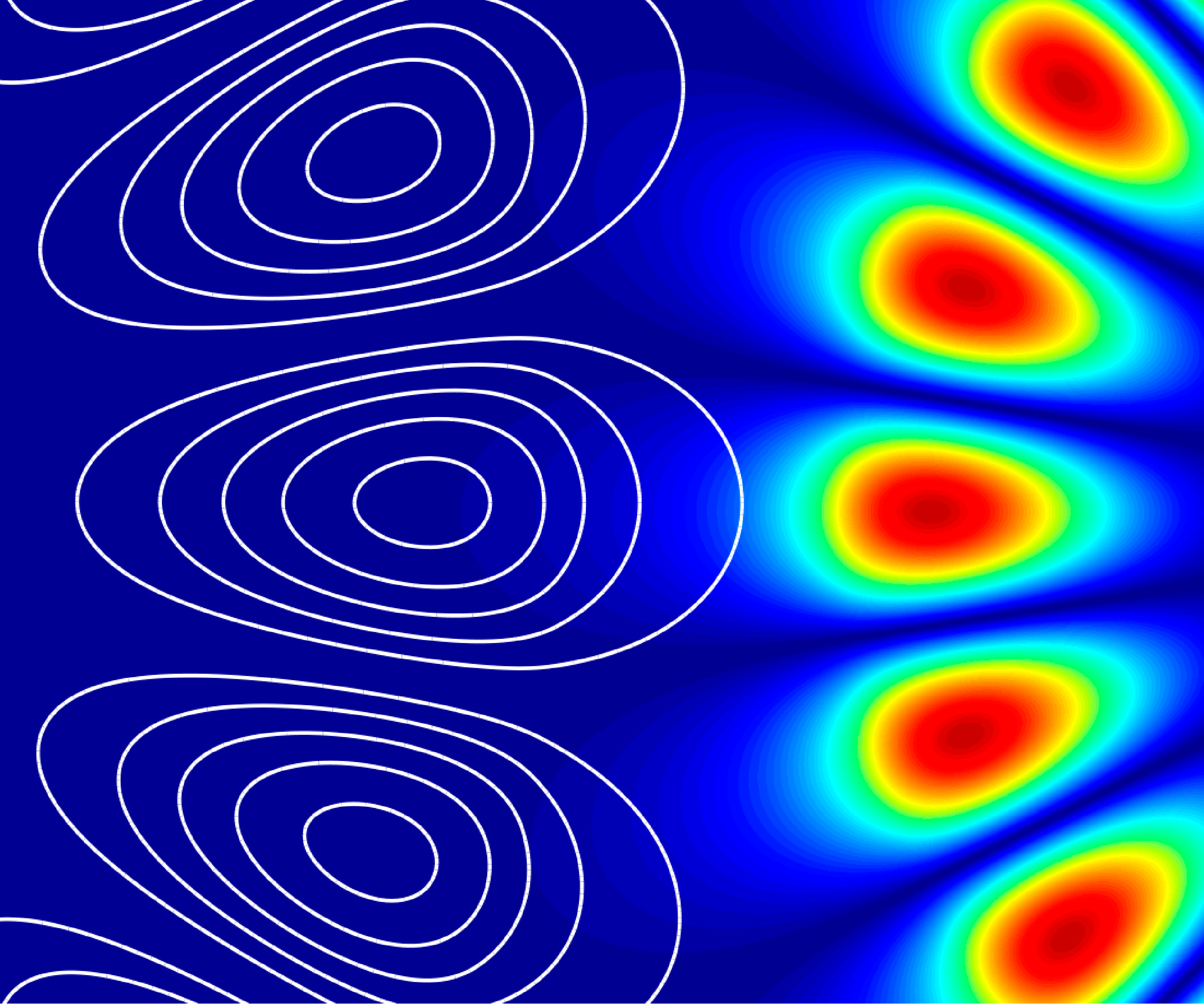


OWTNM

31st International Workshop on Optical Wave & Waveguide Theory and Numerical Modelling

8–10 April 2025

Nottingham Trent University, Nottingham, UK

IOP Institute of Physics

Tuesday April, 8, 2025

8:30 AM - 09:10 AM	**Registration**
9:10 AM – 09:15 AM	**Welcome Address**
09:15 AM - 10:15 AM	**Session 1** Chair: **Peter Bienstman** **9:15 AM - 9:45 AM Antonio Hurtado:** Photonic spiking neurons and spiking neural networks for light-enabled neuromorphic computing and sensing **9:45 AM – 10:00 AM Wendy Otieno:** Three-neuron neuromorphic circuit composed of diffusive memristors **10:00 AM - 10:15 AM Jordan McConnell:** Data-driven control of high-power states in mode-locked lasers with reinforcement learning
10:15 AM – 11:00 AM	**Coffee Break**
11:00 AM - 12:00 PM	**Session 2** Chair: **Allard Mosk** **11:00 AM - 11:15 AM Moritz Riedel:** Radiative and lateral losses in finite-size deep-UV Photonic Crystal Surface Emitting Lasers **11:15 AM - 11:30 AM Moritz Riedel:** Comparison of Coupled Wave Theory and Guided Mode Expansion for Photonic Crystal Surface Emitting Lasers with Hexagonal Lattice **11:30 AM - 11:45 AM Ben Lang:** Mode Switching in Photonic crystal Surface Emitting lasers **11:45 AM - 12:00 PM Shiang-Yu Huang:** Designing compact vertical on-chip coupler with bottom reflector using topology optimization
12:00 PM - 1:00 PM	**Lunch Break**

1:00 PM - 2:15 PM	**Session 3** Chair: **Alessia Pasquazi** **1:00 PM - 1:30 PM Viktor Myroshnychenko:** Efficient modelling of nonlinear wavefronts in dielectric metasurfaces **1:30 PM - 1:45 PM Gregor Tanner:** A Non-diffractive Resonant Angular Filter **1:45 PM - 2:00 PM Anne-laure Fehrembach:** Second harmonic generation in cavity-resonator integrated grating couplers **2:00 PM - 2:15 PM Nicolas Lebbe:** Asymptotic homogenization of Mie-resonant metasurfaces
2:15 PM - 3:00 PM	**Tea Break**
3:00 PM - 4:15 PM	**Session 4** Chair: **Olivier J.F. Martin** **3:00 PM - 3:30 PM Alexander Nosich:** Full-wave electromagnetic engineering of threshold conditions for plasmonic micro and nano lasers with patterned-graphene resonators **3:30 PM - 3:45 PM Jérémy Itier:** Nonlinear slab: rigorous modelling of the scattering vector problem **3:45 PM - 4:00 PM Maike Lenz:** Coupled-mode theory modelling of fibre bragg gratings in multimode fibers for imaging applications **4:00 PM - 4:15 PM Ali Pour Mohammad Qoli Vafa:** Reciprocal space optimization of light trapping for solar absorbers
4:30 PM - 5:30 PM	**Welcome Reception and Networking**

Wednesday, April 9, 2025

8:30 AM - 9:00 AM	**Registration**
9:00 AM - 10:15 AM	**Session 5** Chair: **Francesco Ferranti** **9:00 AM - 9:30 AM Peter Bienstman:** Neuro-inspired time-series processing with silicon integrated photonics **9:30 AM - 9:45 AM Simone Ferraresi:** Performance evaluation of lithium niobate-based reconfigurable photonic switches **9:45 AM - 10:00 AM Hussein Talib:** Photonic matrix multiplication using double racetrack resonators lattice **10:00 AM - 10:15 AM Anne-laure Fehrembach:** Design of transmission cavity resonator integrated grating filters
10:15 AM - 10:45 AM	**Coffee Break**
10:45 AM - 12:00 PM	**Session 6** Chair: **Ana Vukovic** **10:45 AM - 11:15 AM Professor David Marpaung:** Brillouin optomechanics in scalable photonic integrated platforms **11:15 AM - 11:30 AM Andrew Cooper:** Parametric interaction of laser cavity-solitons with an external cw pump **11:30 AM - 11:45 AM Aadithya Suresh:** Hysteresis in laser cavity-solitons **11:45 AM - 12:00 PM Vittorio Cecconi:** Spatiotemporal engineering of terahertz pulses in disordered media
12:00 PM - 1:00 PM	**Lunch**

1:00 PM - 2:15 PM	**Session 7** Chair: **Alexander Nosich** **1:00 PM - 1:30 PM Alessia Pasquazi:** Self-emergence of laser cavity solitons in microcombs: the role of slow nonlinearity **1:30 PM - 1:45 PM Tom Sheppard:** Universal topological localisation in time from parity-time-reversal symmetry **1:45 PM - 2:00 PM Almut Beige:** Local photons and the momentum of light **2:00 PM - 2:15 PM Ya Yan Lu:** Super-bound states in the continuum in a simple grating
2:15 PM - 3:00 PM	**Tea Break**
3:00 PM - 4:15 PM	**Session 8** Chair: **Viktor Myroshnychenko** **3:00 PM - 3:30 PM Olivier J.F. Martin:** Lattice resonances in plasmonic systems **3:30 PM - 3:45 PM Parmenion Mavrikakis:** Self-Consistent Modeling of Coupled Maxwell-Rate Equations with the Finite-Difference Time-Domain Method **3:45 PM - 4:00 PM Roman Gelly:** Numerical modeling of time-modulated metasurfaces with a Discontinuous Galerkin method **4:00 PM - 4:15 PM Brian Stout:** Resonant state formulations for Wave-guide response functions
6:30 PM - 9:30 PM	**Conference Dinner at the Crowne Plaza Nottingham**

Thursday April 10, 2025

8:30 AM - 9:00 AM	**Registration**
9:00 AM - 10:15 AM	**Session 9** Chair: **David Marpung** **9:00 AM - 9:30 AM Allard Mosk:** Programmed all-optical switching in a multistable photonic molecule **9:30 AM - 9:45 AM Manfred Hammer:** Guided modes of integrated optical thin-film lithium niobate channels **9:45 AM - 10:00 AM Abhishek Paul:** Towards 4-Dimensional Terahertz Near-Field Tomography **10:00 AM - 10:15 AM Matt Lovell:** Maximising the Benefits of Membership
10:15 AM - 10:45 AM	**Coffee Break**
10:45 AM - 12:00 PM	**Session 10** Chair: **Antonio Hurtado** **10:45 AM - 11:15 AM Lina Jaurigue:** Noise induced modulations in the pulse arrival times of passively mode-locked semiconductor lasers with optical feedback **11:15 AM - 11:30 AM Jacob Seifert:** Optimizing illumination for precise multi-parameter estimation in coherent diffractive imaging **11:30 AM - 11:45 AM Callum Wilson**: Recovering optical fibre transmission matrices from partial measurements **11:45 AM - 12:00 PM Gleb Anufriev:** Photonic Reservoir Computing: From Principles to Neuromorphic Sensing
12:00 PM - 1:00 PM	**Lunch**

1:00 PM - 2:15 PM	**Session 11** Chair: **Lina Jaurige** **1:00 PM - 1:30 PM Francesco Ferranti:** Adaptive wavelength sampling and machine learning in nanophotonics **1:30 PM - 1:45 PM Gervasio Adriano D'Anzieri:** Multi-objective optimization of a large-area silicon grating coupler **1:45 PM - 2:00 PM Dan-Nha Huynh:** Inverse metalens design and simulation **2:00 PM - 2:15 PM Oliver Kuster:** Inverse design of 3d nanophotonic devices feasible for additive manufacturing
2:15 PM - 2:30 PM	**Final Remarks and Close**

Photonic Spiking Neurons and Spiking Neural Networks for Light-Enabled Neuromorphic Computing and Sensing

A. Adair, D. Black, G. Donati, D. Owen-Newns, J. Robertson, A. Hurtado
[1]*Institute of Phtoonics, SUPA Dept. Physics, University of Strathclyde, Glasgow G1 1RD, UK*
*antonio.hurtado@strath.ac.uk

We review our work on fast, efficient and compact photonic spiking neurons and spiking neural networks and their operation in complex tasks. We also outline their prospects for use in future light-enabled neuromorphic processing and sensing platforms.

Photonic approaches emulating the powerful computational capabilities of the brain are receiving increasing interest for radically new paradigms in ultrafast Neuromorphic Computing and Sensing. We review our work on novel photonic spiking neurons and spiking neural networks (SNNs), able to process information using ultrafast (down to sub-ns rates) neuron-like optical spikes. We introduce the properties and performance of the photonic devices used for the implementation of optical spiking neurons. These include vertical cavity surface emitting lasers (VCSELs) [1-4], resonant tunneling diodes (RTDs) [5-7] and passive resonators [8], Fig. 1. We also discuss the strategies pursued for their network connectivity, and the techniques and algorithms realised for their application to complex tasks (e.g. pattern recognition, image processing, data classification, time-series prediction), see exemplar results in Fig. 2. We also describe the potential of these spike-based photonic systems for ultrafast, low-energy and high-accuracy performance in neuromorphic sensing and computing functionalities, benefitting from hardware-friendly implementations and fully capitalizing on spike-based training methods with reduced complexity.

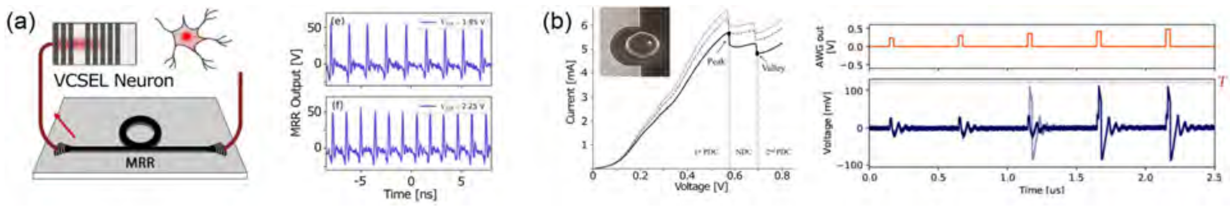


Fig. 1. Exemplar photonic spiking neurons; (a) VCSEL-neuron firing sub-ns optical spikes when perturbed coupled to a micro-ring resonator to achieve spike rate information encoding [4]; (b) RTD photo-detecting spiking neuron, including SEM image of the device, measured IV curves under dark and illumination conditions and deterministic spiking in the RTD neuron [6].

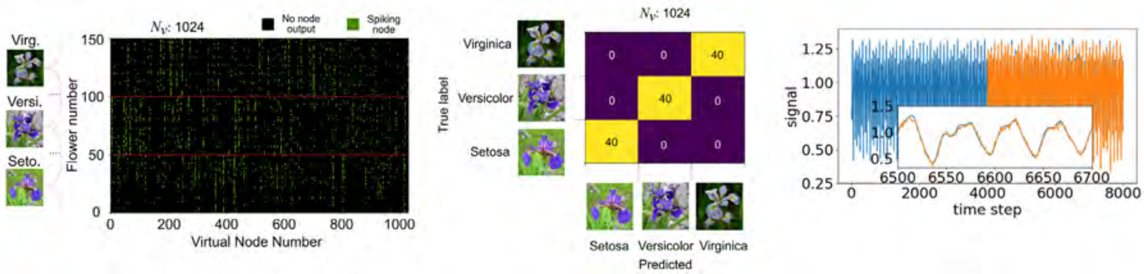


Fig. 2. (Left) Patterns of sub-ns optical spikes from a VCSEL-neuron demonstrate successful operation in complex tasks: (middle) Iris Flower dataset classification [2]; (right) chaotic time-series prediction (next-value prediction of the Mackey-Glass time-series) [3].

We acknowledge support by the European Commission (EIC Pathfinder 'SpikePRO' project) and the UKRI Turing AI Acceleration Fellowships Programme (EP/V025198/1).

[1] J. Robertson et al, Sci. Reps., 12, 4874 (2022)
[2] D. Owen-Newns et al., IEEE JSTQE, 29, 1500110 (2023)
[3] D. Owen-Newns et al, arXiv:2412.09233 (2024)
[4] M. Hejda et al, Neuromorph. Comput. Eng., 4, 024011 (2024)
[5] J Robertson et al, Neuromorph. Comput. Eng., 4, 014010 (2024)
[6] Q. Al-Taai et al, Neuromorph. Comput. Eng., 3, 034012 (2023)
[7] W. Zhang et al, Neuromorph. Comput. Eng., 4, 044006 (2024)
[8] G. Donati et al, Optica Open. Preprint. https://doi.org/10.1364/opticaopen.28297334.v1 (2025)

Three-Neuron Neuromorphic Circuit Composed of Diffusive Memristors

W. Otieno [1], A. Gabbitas [1], D. Pattnaik [1], A. Balanov [1], P. Borisov [1], S. Savel'ev [1]

[1] *Department of Physics, Loughborough University, Loughborough LE11 3TU, UK*
W.Otieno@lboro.ac.uk

We introduce a neuromorphic circuit containing three blocks of diffusive memristors that can emulate a simple decision-making biological system. The spiking behaviour of the circuit is theoretically simulated with two blocks forming spiking inputs and one block serving as an integrate and fire neuron.

Introduction

Diffusive memristors show great promise as key intelligent components of next generation neuromorphic devices. This is due to their unique capabilities in mimicking rich and unique behaviour observed in biological neurons and synapses. They are composed of a dielectric film sandwiched between two Pt or Au electrodes and experience resistive switching via the diffusion of Ag nanoparticles [1]. Blocks of diffusive memristors can embody the parallel and distributive architecture of biological sensory systems in the brain which are beneficial in fast processing speed and power efficiency.

Methodology and Results

We model a three-neuron circuit model (see Fig 1) governed by nine coupled stochastic differential equations by extending a single particle model in [1]. We study the stochastic behaviour of exhibited spikes by implementing shaken potential and varying the external voltages and noise. At the same time, we fabricate the circuit using thin film diffusive memristors composed of $Si0_2$ with embedded Ag clusters and perform experimental studies. By quantifying the irregularity of the spike trains (CV_1, CV_2), we find that theoretical simulations and experimental studies closely match (peaking at $(CV_1, CV_2) \approx (0.5, 0.5)$) and observe that our neuromorphic system can emulate a visual sensory system responsible for visual information processing and interpretation.

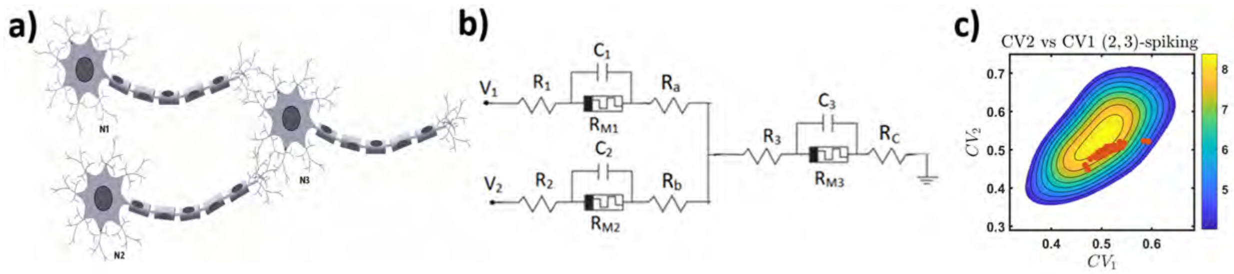


Fig. 1.: Our neuromorphic circuit (b) composed of three diffusive memristors R_{M_i} each parallel to a capacitor C_i and in series to a resistor R_i biologically resembles a biological system composed of three neurons N1, N2 and N3 (a). Quantifying the irregularity of the spike trains (CV_1, CV_2) leads to $(CV_1, CV_2) \approx (0.5, 0.5)$ (c) for both theoretical simulations (contours) and experimental studies (scatter plots).

Conclusion

We theoretically model a three-neuron circuit composed of diffusive memristors. Varying external voltages and noise generate different spiking variations. Adding random potential to our theoretical model leads to experimental studies and theoretical simulation closely matching as (CV_1, CV_2) approximately peak at $(0.5, 0.5)$ falling in between (CV_1, CV_2) values of cortical neurons that reside in the visual cortex.

References

[1] Z. Wang, S. Joshi, S. E. Savel'ev, H. Jiang, R. Midya, P. Lin, M. Hu, N. Ge, J. P. Strachan, Z. Li, et al., *Memristors with diffusive dynamics as synaptic emulators for neuromorphic computing,* Nature materials 16, 101 (2017).

Data-driven control of high-power states in mode-locked lasers with reinforcement learning

J. McConnell, J. Brooks, A. Cutrona, A. Pasquazi, M. Peccianti, J. S. Totero Gongora*
Emergent Photonics Research Centre (EPICX), Department of Physics, Loughborough University, Loughborough LE11 3TU, United Kingdom
*j.totero-gongora@lboro.ac.uk

We discuss the development of a data-driven control approach based on reinforcement learning (RL) to stabilise mode-locked fibre lasers and achieve high-energy, stable states in experimental scenarios, addressing nonlinear dynamics and complex reward landscapes.

Achieving high emission states in mode-locked fibre lasers (MLFLs) requires precise control over the system parameters, including gain, dispersion and nonlinear locking mechanisms. The interplay between competing mechanisms and environmental conditions leads to a complex dynamical landscape featuring multiple local minima. As a result, there is increasing demand for automated control approaches to systematically optimise the MLFL dynamics [1]. However, traditional approaches based on feedback control and heuristic-based optimisation methods (e.g., genetic algorithms) are time-consuming and not consistently effective. In this context, Reinforcement Learning (RL) is a promising approach to tackling complex nonlinear systems in practical scenarios [2]. RL control is a machine learning approach in which an agent learns to make decisions by receiving rewards or penalties based on its actions. In control applications, RL can learn optimal control strategies, rather than simply maximising a fitness function and can adapt to changing conditions, provided that the right reward strategy is implemented. In this work, we discuss the application of RL for the automatic optimisation of an experimental MLFL based on nonlinear polarisation rotation. In our approach, inspired by recent works [3,4], an RL algorithm such as Deep Q-Networks (DQN) or Soft Actor-Critic (SAC) learns to identify the best parameter trajectory required to steer the system towards high-power states.

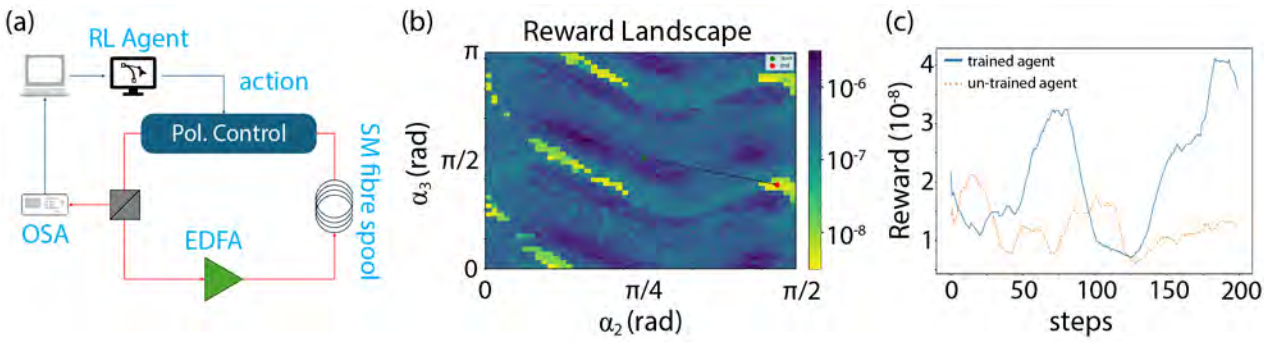


Figure 1 (a) Schematics of the mode-locking fibre laser. (b) Reward landscape of the MLFL as a function of waveplates configuration. (c) Average Reward evolution for a trained (blue) and un-trained agent.

References

[1] Liu *et al.*, “Comprehensive exploration: Automatic mode-locking technology and its multidisciplinary applications,” Infrared Phys. Technol. **138**, 105247 (2024).
[2] Degrave *et al.*, Magnetic control of tokamak plasmas through deep reinforcement learning. *Nature* **602**, 414–419 (2022).
[3] Sun *et al.*, “Deep reinforcement learning for optical systems: A case study of mode-locked lasers,” Mach. Learn. Sci. Technol. **1**, 045013 (2020).
[4] Li, *et al.*, “The soft actor-critic algorithm for automatic mode-locked fibre lasers,” Opt. Fiber Technol. **81**, 103579 (2023).

Radiative and lateral losses in finite-size deep-UV Photonic Crystal Surface Emitting Lasers

Ulrich T. Schwarz[1,*], Moritz Riedel[1], Lukas Uhlig[1], Lars Persson[2], Åsa Haglund[2]
[1]*Institute of Physics, Chemnitz University of Technology, 09111 Chemnitz, Germany*

[2] *Photonics Laboratory, Department of Microtechnology and Nanoscience, Chalmers University of Technology, 41296 Gothenburg, Sweden*

* ulrich.schwarz@physik.tu-chemnitz.de

We estimate losses from the photonic crystal band structure of a laterally infinite PCSEL We calculate thresholds and predict the mode selection in our recently demonstrated deep-UV PCSELs, which agrees well with our experimental results, as with standard coupled wave theory approach including finite-sized effects.

Background

A deep-UV photonic crystal surface emitting lasers (PCSEL) with a photonic crystal (PC) consisting of round holes in a hexagonal lattice, was realized in the AlGaN materials system, lasing at 279 nm when optically pumped. Lasing occurred at different branches of the photon dispersion, depending on the PC filling factor (FF), i.e. hole to unit cell area, and the tendency for 1D lasing instead of proper 2D in-plane coupling also depended on FF.

Results

Being able to calculate radiative and lateral losses in finite-sized PCSELs is crucial to predict and understand and optimize the devices. From the photon dispersion of the infinite PCSEL, we estimate the radiative and lateral losses by integrating over the finite area in photon momentum space, where the area in momentum is calculated from the pump area in real space assuming a diffraction limited spot. Radiative losses for finite lateral momentum, in the vicinity of the Γ point, and lateral losses by photons propagating out of the pumping area can thus be estimated. This approach allows for a physical interpretation of the radius dependency of PCSEL threshold and mode selection. The results are compared to size- and branch-dependent losses from a coupled wave theory approach [1].

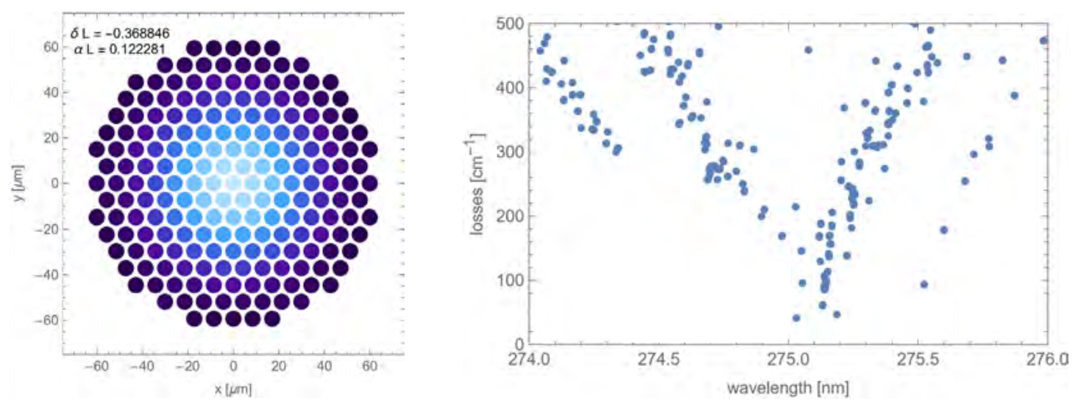


Fig. 1. (left) Intensity distribution of the fundamental (lowest loss) mode and (right) wavelength and losses map for a r=60 μm radius PCSEL.

References

[1] Y. Liang et al., Opt. Express 20, 15945-15961 (2012).

Comparison of Coupled Wave Theory and Guided Mode Expansion for Photonic Crystal Surface Emitting Lasers with Hexagonal Lattice

M. Riedel [1,*], L. Uhlig [1], L. Persson [2], Å. Haglund [2], U.T. Schwarz [1]

[1] *Institute of Physics, Chemnitz University of Technology, 09111 Chemnitz, Germany*
[2] *Department of Microtechnology and Nanoscience, Chalmers University of Technology, 41296 Gothenburg, Sweden*
moritz.riedel@s2020.tu-chemnitz.de

Photonic Crystal Surface Emitting Lasers exhibit promising features such as large lasing areas, leading to low beam divergence and high output power. We compare Coupled Wave Theory and Guided Mode Expansion as frequency domain approaches incorporating plane waves with characteristic vertical profiles as basis functions.

Methods and Results

Efficient simulations of Photonic Crystal Surface Emitting Lasers (PCSELs) are crucial for predicting field distributions, wavelengths and modal losses. While Guided Mode Expansions (GME) generally take a large number of plane wavevectors, $\mathbf{G}$, for the expansion into account [1], Coupled Wave Theory (CWT) formulations usually consider only the fundamental reciprocal lattice vectors with smallest magnitudes, where coupling with higher order and radiative waves is achieved solely by perturbation theory [2]. Figure 1 shows the band structure of a deep-UV-PCSEL with a hexagonal photonic crystal lattice with different numbers of wavevectors included in the expansion. Especially for the higher number of basis functions, we observe significant discrepancies between the two methods. These are assumed to emerge from important interactions among higher order waves, that are covered by GME, while CWT only describes coupling between fundamental and higher order waves.

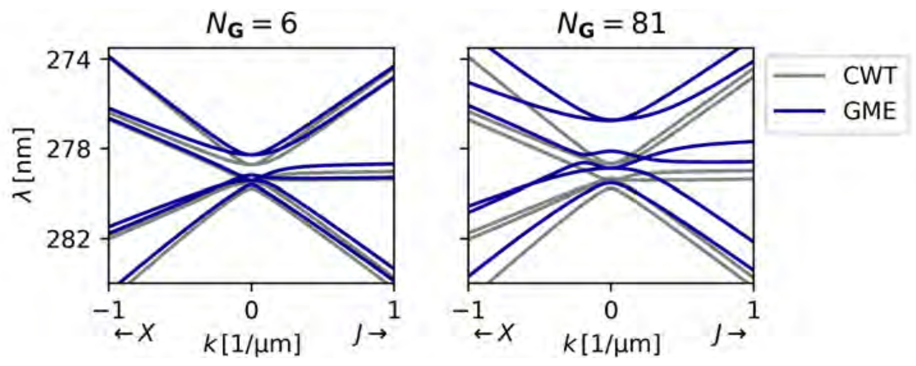


Fig. 1. Photonic band structure in the vicinity of the second order Γ point based on CWT (grey) and GME (blue) for different numbers of considered reciprocal lattice vectors, $N_\mathbf{G}$.

Moreover, we estimate size-dependent radiative and lateral losses both by numerical simulation of the finite sized PCSEL using CWT [2] and by inference from the dispersion of the infinite system, which is calculated by CWT as well as GME.

References

[1] Lucio Claudio Andreani and Dario Gerace. *Phys. Rev. B*, 73:235114, Jun 2006.
[2] Yong Liang, Chao Peng, Kenji Ishizaki, Seita Iwahashi, Kyosuke Sakai, Yoshinori Tanaka, Kyoko Kitamura, and Susumu Noda. *Opt. Express*, 21(1):565–580, Jan 2013.

Mode Switching in Photonic crystal Surface Emitting lasers

Ben Lang[1], Ana Vukovic[1], Phillip Sewell[1], Karl Boylan[2], Samir Rihani[2], Graham Berry[2], Nannicha Hattasan[2], Richard Spalding[2], David Moodie[2],

[1] *George Green Institute for Electromagnetics Research, University of Nottingham, Nottingham NG7 2RD, UK* [2] *Huawei Technologies Research and Development, Ipswich, United Kingdom*

ben.lang@nottingham.ac.uk

Through detailed numerical simulations and experimental measurements we identify interference effects that can harm PCSEL performance. Using an intuitive analytic model for the underlying mechanism we are able to show how parameters should be chosen to avoid it.

Main

Photonic Crystal Surface Emitting Lasers (PCSELS) are a new category of laser that achieve high performance by including a nanoscale pattern of air holes, collectively known as the photonic crystal. Typical PCSELs make use of two air holes of different depths in each unit cell [1] (see fig. 1). This can be thought of as two different photonic crystal layers containing different patters (one layer containing both holes, one only the deeper set).

PCSELs also typically contain a reflector at the back, to direct the laser output to the front. The combination of these two features (a back reflector and two different photonic crystal layers) gives rise to interesting new interference effects. For example, the reflector is a different distance from each of the two layers, meaning that light scattered towards the reflector by each layer returns with a different round-trip phase.

Using a Coupled Mode Theory approach [2], combined with careful Green's function treatment of the vertical direction we find that the lasing switching from modes below the band gap to above it in response to small changes in the hole depths. We identified this switching in all three of numerical simulations, analytic toy models, and experimental measurement. As this switching is harmful to laser performance we identified the parameters needed for its avoidance, which agree well with measurements.

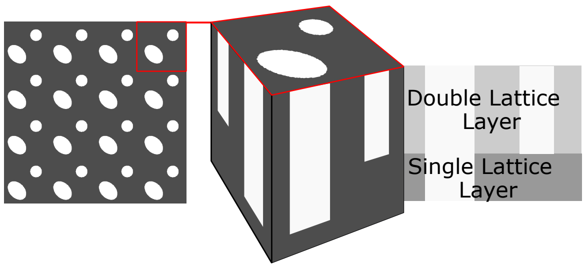


Fig. 1. Diagram of the photonic crystal in a PCSEL. Grey: dielectric, White: air.

References

[1] Qifa Liu and Minjia Meng and Shang Ma and Meixin Feng, *Design of double-lattice GaN-PCSEL based on triangular and circular holes,* Opt. Express, **31**, 43615–43629, 2023.

[2] Liang, Yong and Peng, Chao and Sakai, Kyosuke and Iwahashi, Seita and Noda, Susumu, *Three dimensional coupled-wave model for square-lattice photonic crystal lasers with transverse electric polarization: A general approach,* Phys. Rev. B **84**, 195119, 2011.

Designing Compact Vertical On-Chip Coupler with Bottom Reflector using Topology Optimization

Shiang-Yu Huang [1,*], Stefanie Barz [1,2],

[1] *Institute for Functional Matter and Quantum Technologies, University of Stuttgart, 70569 Stuttgart, Germany*
[2] *Center for Integrated Quantum Science and Technology, University of Stuttgart, 70569 Stuttgart, Germany*
shiang-yu.huang@fmq.uni-stuttgart.de

In this work, we design a fiber-to-chip vertical coupler incorporating a metal bottom reflector using topology optimization. The spatial footprint of the final design is 14 µm × 14 µm with a coupling efficiency of −0.35 dB at the wavelength of 1550 nm.

Designing photonic integrated devices using inverse design methods has led to innovations in various research fields, such as photonic quantum applications [1]. As one of the building blocks in photonic systems, on-chip couplers operating in telecom C band play a central role in interfacing photonic integrated circuits and off-chip devices. Despite the demonstration in previous publications [2, 3], the vertical fiber-to-chip grating couplers, i.e. the coupling angle is 0°, are usually suboptimal due to either the large spatial footprint or the inadequate coupling efficiency.

To address the need for a compact vertical coupler with sub-decibel efficiency, we inversely design an on-chip one on the silicon-on-insulator platform [4]. The final design of the coupler has a coupling efficiency of −0.35 dB and a compact size of 14 µm × 14 µm. The inclusion of the bottom reflector in the optimization design process reduces the direct transmission toward the substrate and is important to acquire a flat spectral response within the operating wavelength. Our investigation paves the way to applying highly efficient topology-optimized couplers in diverse photonic integrated systems.

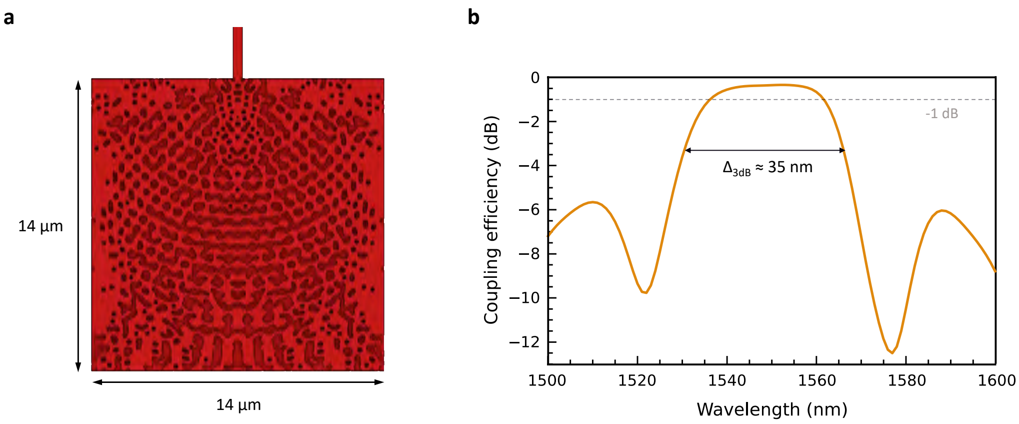


Fig. 1. (a) Schematic of the designed vertical coupler using topology optimization. (b) Coupling efficiency of the desinged coupler versus wavelength.

References

[1] He, Lu, et al. *Super-compact universal quantum logic gates with inverse-designed elements,* Sci. Adv. 9, eadg6685 (2023).

[2] Liu, Jie et al. *High-performance grating coupler array on silicon for a perfectly-vertically mounted multi-core fiber,* J. Light. Technol. 40, 5657–5659 (2022).

[3] Hammond, Alec M et al. *Multi-layer inverse design of vertical grating couplers for high-density, commercial foundry interconnects,* Opt. Express 17, 31058–31072 (2022).

[4] Huang, Shiang-Yu and Barz, Stefanie *Compact inverse designed vertical coupler with bottom reflector for sub-decibel fiber-to-chip coupling on silicon on insulator platform,* Sci. Rep. 15, 2925 (2025).

Efficient modelling of nonlinear wavefronts in dielectric metasurfaces

D. Hähnel, J. Förstner, V. Myroshnychenko *

Theoretical Electrical Engineering & CeOPP, Paderborn University, Paderborn, Germany

* *viktor.myroshnychenko@uni-paderborn.de*

We present an effective optimization approach for tailoring the third-harmonic wavefront generated by dielectric metasurfaces. We demonstrate optimized metasurfaces acting as third harmonic beam deflectors and exhibiting a strong harmonic generation originating from a multi-mode Fano mechanism.

Introduction

Generation of nonlinear light on a subwavelength scale using metasurfaces has attracted booming attention due to their ultrathin compact profile and advanced functionalities relevant for modern integrated photonics. Tailoring phase and amplitude of a nonlinearly generated wave with a high emission efficiency is a challenging task that often requires state-of-the-art numerical methods. We propose a simple and robust sampling method in conjunction with Monte Carlo (MC) simulation to design and optimize a nonlinear wavefront of Huygens all-dielectric metasurfaces with a high harmonic yield.

Methods and results

We demonstrate our approach for a metasurface composed of elliptical nanodisks made of silicon placed on a silicon dioxide substrate (Fig. 1a). A MC simulation is employed to explore a geometrical parameter space and find optima with enhanced conversion efficiency. Information about the nonlinear phase and amplitude are locally encoded through an adjustment of the lateral dimensions of nanodisks in the unit cell. The sampling method is then applied to select a collection of resonators generating a third harmonic (TH) field with a required phase and enhanced amplitude. This allows us to design metasurfaces operating as TH beam deflectors capable of steering light into a desired direction with a record calculated conversion efficiency (Fig. 1b,c) [1]. We also demonstrate optimal metasurface design where extremely enhanced TH is generated by the interaction of three higher order Mie-modes forming a multi-mode Fano resonance (Fig. 1d) [2]. We achieve a THG enhancement up to 900 compared to an unpatterned amorphous silicon film of the same thickness.

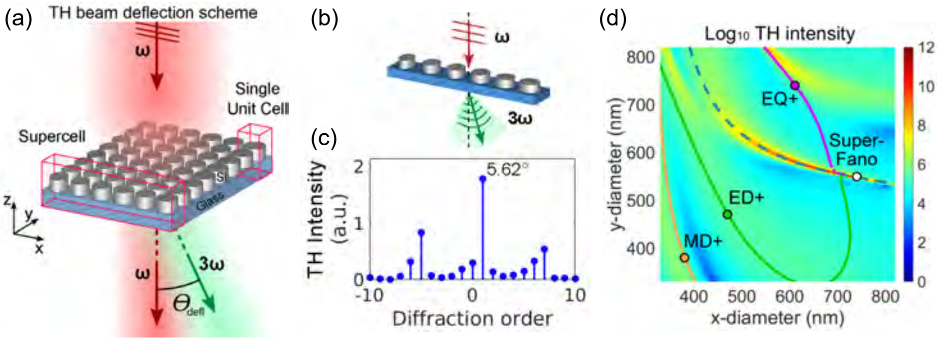


Fig. 1. (a) Schematic view of a dielectric metasurface for nonlinear beam generation. (b) Designed supercell of the structure for TH beam deflection and (c) discrete diffraction spectra of TH field. (d) TH intensity map as a function of elliptical diameters of the resonator. Colored curves highlight the paths of the Mie-resonances.

References

[1] D Hähnel, J. Förstner, V. Myroshnychenko, Efficient modeling and tailoring of nonlinear wavefronts in dielectric metasurfaces, *ACS Photonics*, 10, 2502–2510, 2023.

[2] D. Hähnel, C. Golla, M. Albert, T. Zentgraf, V. Myroshnychenko, J. Förstner, C. Meier, A multi-mode super-fano mechanism for enhanced third harmonic generation in silicon metasurfaces, *Light: Science & Applications*, 12, 97, 2023.

A Non-diffracting Resonant Angular Filter

T. M. Lawrie[1,2,*], G. Tanner[1], G. J. Chaplain[2]

[1]*School of Mathematical Sciences, University of Nottingham, United Kingdom*

[2]*Centre for Metamaterial Research and Innovation, Department of Physics and Astronomy, University of Exeter, United Kingdom*

*tristan.lawrie@nottingham.ac.uk

We present a non-diffracting resonant angular filter forms of beyond nearest neighbor (BNN) unit cell couplings [1]. The filter's properties are studied analytically via quantum graph theory where unit transmission at a given customizable angle is achieved through a resonance condition.

Introduction

We study the transmission properties of an acoustic field incident on the filter shown in Fig.1(a). The field has frequency $\omega = ck$, where c is the speed of sound, and k is the wave number. The filter is formed of an infinite array of junctions connected to a grating with period ℓ, where each junction is connected to its μ^{th} nearest neighbour via channels of length ℓ_μ.

Results

We show the transmission coefficient of the filter in terms of the tangential wave vector κ_y, which for particular choice of parameters, gives the Kronecker-delta function.

$$t_\mu = \frac{i\sin(k\ell_\mu)}{\cos(\kappa_y \mu \ell) - \cos(k\ell_\mu) + i\sin(k\ell_\mu)} = \begin{cases} 1, & \text{if } k\ell_\mu = p\pi \text{ and } \kappa_y = \kappa_y^{(q)} = q\pi/\mu\ell \\ 0, & \text{if } k\ell_\mu = p\pi \text{ and } \kappa_y \neq \kappa_y^{(q)}. \end{cases} \quad (1)$$

The resulting scattered field is simulated via FEM in Fig. 1 (b) and (c).

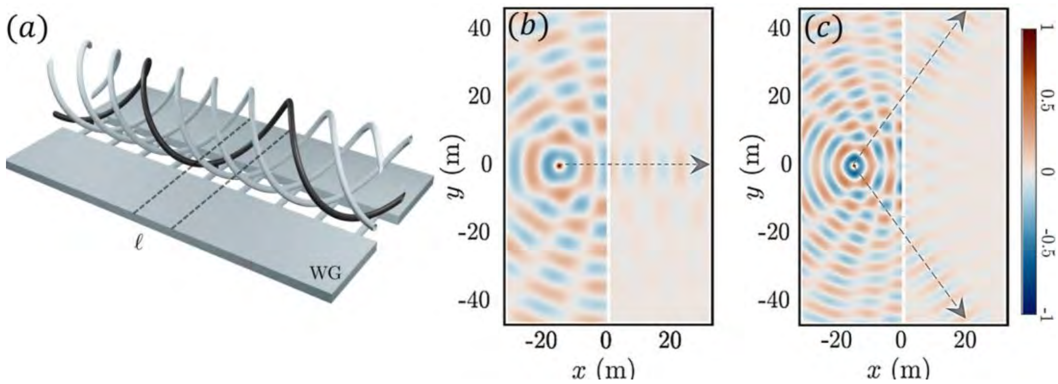


Fig. 1. (a) shows the filter device between two slab waveguides, coupled by thin channels that form a grating. (b) and (c) show the discrete unit transmission angles at resonant frequencies.

Conclusion

We introduce a novel angular filter and demonstrate its functionality using analytical expressions obtained from quantum graph theory. The filter maintains full reflectivity due to a resonance condition that switches off at a set of discrete angles, due to a change in the effective boundary condition which switch from Dirichlet to periodic.

References

[1] Lawrie, T et. al. 2024. A Non-diffracting Resonant Angular Filter. *preprint arXiv:2410.17329*.

Second harmonic generation in cavity-resonator integrated grating couplers

A .-L. Fehrembach [1], E. Popov [1], H. Tortel [1], E. Hemsley [2],
A. Monmayrant [2], O. Gauthier-Lafaye [2], S. Calvez [2]
[1] *Aix Marseille Univ, CNRS, Centrale Marseille, Institut Fresnel, Marseille, France*
[2] *LAAS-CNRS, Université de Toulouse, CNRS, Toulouse, France*
mailto:anne-laure.fehrembach@fresnel.fr

Cavity resonator integrated grating filters (CRIGF) [1] are composed with a sub-wavelength coupling grating of a few tens of periods (GC), surrounded with two distributed Bragg reflectors (DBR), etched on a multilayer stack of lossless dielectric materials (see Fig. 1). Illuminated with an incident beam overlying the GC, CRIGF exhibit resonances characterized by a strong electromagnetic field. We are currently exploiting this property to enhance second harmonic generation (SHG) [2].

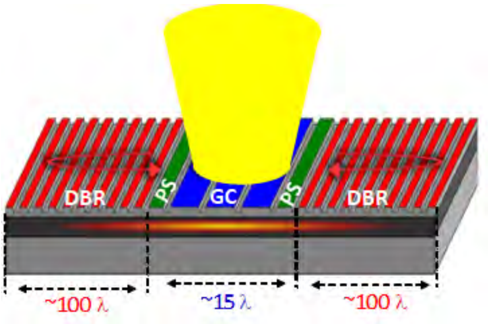


Fig. 1. Representation of a CRIGF.

In our first work [2], we reached numerically and experimentally a conversion efficiency $\eta = P_{2\omega}/[P_\omega]^2$ of the order of 8x10^{-6}W^{-1} (P_ω is the incident power and $P_{2\omega}$ is the power generated by SHG). This conversion efficiency is one order of magnitude higher than those achievable with infinite resonant gratings, but two orders of magnitude lower than those of the much longer ribbon guide components. In this presentation, we will show that the SHG conversion efficiency of the CRIGF can be improved by increasing the quality factor Q (ratio of the resonance wavelength to its spectral width) of the resonance at ω. We will describe two ways to achieve this: using a quasi-dark mode [3], or a GC with a bi-atom base pattern [4]. The high quality factors achieved (above 10^5) highlight the existence of a critical coupling regime [5,6], for which the SHG conversion rate is maximal. We demonstrate numerically conversion efficiencies of the order of a few tenths.

Acknowledgements: this work was supported by the AID (ANR-ASTRID RESON project).

References

[1] K. Kintaka et al. *Cavity-resonator-integrated grating input/output coupler for high-efficiency vertical coupling with a small aperture* Opt. Lett. 35, pp. 1989-1991, 2010.
[2] F. Renaud et al. *Second-harmonic-generation enhancement in cavity resonator integrated grating filters* Opt. Lett. 44, pp. 5198-5201, 2019.
[3] Fehrembach et al. *Dark mode-in-the-box for enhanced second-harmonic generation in corrugated waveguides* Opt. Expr. 29 (25), pp 40981 (2021).
[4] Fehrembach et al. *Cavity-resonator integrated bi-atom grating coupler for enhanced second-harmonic generation* Opt. Expr. 30 (21), pp 38789 (2022).
[5] A. Yariv *Universal relations for coupling of optical power between microresonators and dielectric waveguides* Electron. Lett. 36 (4), pp321-322 (2000).
[6] Popov et al. *Extreme enhancement of the quality (Q)-factor and mode field intensity in cavity-resonator gratings* Opt. Expr. 30 (14), pp25390 (2022).

Asymptotic homogenization of Mie-resonant metasurfaces

N. Lebbe [1,*], A. Maurel [2], K. Pham [3],

[1] *LAPLACE, CNRS, INPT, UPS, France*
[2] *ESPCI Paris, PSL University, CNRS, Institut Langevin, France*
[3] *LMI, ENSTA Paris, Institut Polytechnique de Paris, France*
nicolas.lebbe@laplace.univ-tlse.fr

The asymptotic homogenization theory is used to replace deeply-subwavelength Mie-resonant metasurfaces with effective transition conditions involving dispersive surface susceptibilities. The derivation is made for both TE and TM polarizations and their fundamentally different behaviors are analyzed in detail.

Introduction: effective transition conditions for metasurfaces

Over the last few decades, homogenization models have been developed that reduce the geometric complexity of a metasurface into a flat interface on which effective transitions conditions are applied; see Fig. 1. In electromagnetics, these conditions relies on surface susceptibilities $\overline{\overline{\chi}}_{ee}$ and $\overline{\overline{\chi}}_{mm}$ [1].

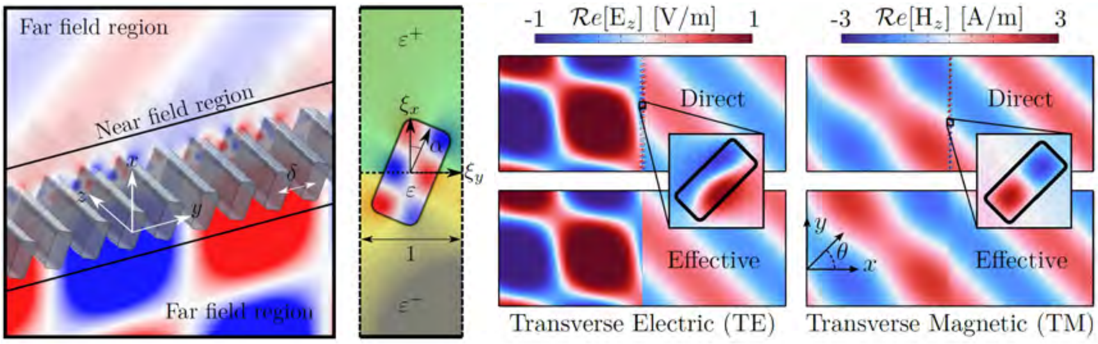


Fig. 1. (left) A Mie-resonant metasurface: deeply-subwavelength particles with high permittivity ε. (right) Comparison between direct FEM simulations and our effective model at $\theta = \pi/4$.

Resonant metasurfaces: results from the asymptotic homogenization

For *plasmonic metasurfaces*, we have shown [2] that the dispersion relation of $\overline{\overline{\chi}}_{\iota\iota}$ is obtained through the solution of a single plasmonic eigenvalue problem. In this presentation, we will show that *Mie-resonant metasurfaces* can exhibit resonances in both TE and TM polarizations and that their behavior can be homogenized. We will in particular show how to obtain the dispersive surface susceptibilities through the eigenmodes of two elementary problems; see Fig. 2.

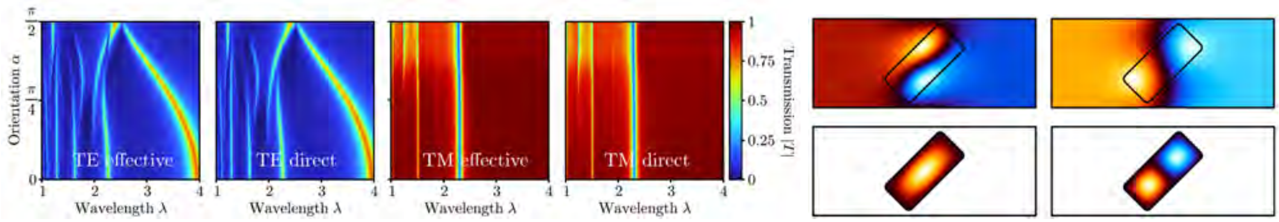


Fig. 2. (left) Comparison between direct FEM simulations and our effective model for $|T|$ at different λ and orientation α of the particles (see Fig. 1) (right) First two eigenmodes associated with the TE (top) and TM (bottom) polarization; the eigenmodes can be compared with the fields in Fig. 1(right).

References

[1] N. Lebbe et al. *Stable GSTC formulation for Maxwell's equations*, IEEE TAP, 2022.
[2] N. Lebbe et al. *Homogenized transition conditions for plasmonic metasurfaces*, PRB, 2023.

Full-Wave Electromagnetic Engineering of Threshold Conditions for Plasmonic Micro and Nano Lasers with Patterned-Graphene Resonators

A. I. Nosich

Laboratory of Micro and Nano Optics, Institute of Radio-Physics and Electronics NASU
Kharkiv, 61085, Ukraine

anosich@yahoo.com

Quoting one of the giants on whose shoulders we stand, Niels Bohr
"… each time when we need something working, we have to descend from the heights of quantum theory to the Maxwell equations, and sometimes even to the Newton equations" (letter to a friend).

Basic ideas and some results

Research into plasmonic micro and nanoscale lasers is on the leading edge of today's photonics. Here, accurate and trusted preliminary modeling is able to shorten the development time and reduce expenses. In the laser configurations where the plasmonic modes exist on the noble-metal resonant elements, the lasing is observed in the visible and near-infrared ranges with rather high thresholds as metals possess considerable losses. Besides, neither the metal particle plasmonic mode frequencies nor thresholds are tunable. Unlike noble metals, graphene has moderate losses and its electron conductivity is electrically tunable that makes graphene a promising alternative plasmonic material in the terahertz (THz) and far-infrared (FIR) ranges. We present the essentials and some results of the accurate full-wave study of the natural-mode emission threshold conditions for the plasmonic laser configurations equipped with patterned graphene elements and their arrays. This is done through developing adequate full-wave electromagnetic models and efficient meshless computational algorithms that have mathematically guaranteed convergence. We consider micro- and nanolasers with graphene resonant elements as open resonators equipped with active regions, filled in with the gain material. Then, mathematical and numerical modeling of the laser modes at the threshold can be done using the boundary eigenvalue problem for stationary Maxwell equations with exact boundary conditions on the surfaces of passive and active regions and graphene elements, as well as the radiation condition. Here, the complex surface impedance of graphene will be included into this semi-classical model via the Kubo formalism. This Lasing Eigenvalue Problem (LEP) is specifically tailored to extract the emission frequencies and the associated values of the active-region threshold gain as two real components of the same mode-specific eigenvalue pair [1]. Using the approach called the method of analytical regularization we cast various LEPs to well-conditioned determinantal equations. Dependences of the plasmon-mode emission frequencies and thresholds on the parameters, such as graphene's chemical potential, are presented [2]. Additionally, in periodic configurations the lattice modes are found and studied. They do not have plasmonic nature and are caused by the periodicity. The lattice modes are weakly tunable, however, can display ultralow thresholds.

Expectation

This study is expected to lead to elaboration of engineering rules for designing tunable THz and FIR quasi-single-mode patterned graphene based plasmonic micro- and nanolasers and their arrays.

References

[1] D. Herasymova, et al., Threshold conditions for transversal modes of tunable plasmonic nanolasers shaped as single and twin graphene-covered wires. Nanotechnol., vol. 33(49), art. no 495001, 2022

[2] Other publications related to LEP studies of various lasers, http://ire.kharkov.ua/LMNO/publ.html

Nonlinear slab: rigorous modelling of the scattering vector problem

Jérémy ITIER [1,*], Gilles RENVERSEZ [1], Frédéric ZOLLA [1],

[1] *Aix Marseille Univ, CNRS, Centrale Med, Institut Fresnel, Marseille, France*
jeremy.itier@fresnel.fr

We developed a new method to compute the scattering of light by an anisotropic nonlinear slab, for conical incidence and arbitrary polarization. The 2-dimensional full-vector problem is reduced to a 1-dimensional problem using symmetry arguments, which is then solved using the finite element method.

Introduction

A theoretical framework for nonlinear optics has been developed since the invention of the laser in the 1960s [1], but to date few papers present fully satisfactory numerical models. The case of the second harmonic generation (2HG) in the slab was modeled for the first time in 1994 [2], but only at normal incidence and in the scalar case. Since, many improvements have already been proposed. We develop a new numerical method to account for various nonlinear effects applied here to the specific case of 2HG in a nonlinear anisotropic slab at conical incidence. This work can be generalized to other 2^{nd} and 3^{rd} order nonlinearities even if mixed together, including in the full vector case. The simulations were carried out using an iterative algorithm coupled with the finite element method, using two open-source software programs *gmsh* and *getdp*. Energetic considerations are also addressed in order to validate our approach and test the convergence properties of the method.

Results

A plot of the electric field is shown in Fig. 1 in the case of a nonlinear KTP slab. An increasing second harmonic is generated as the wave passes through the slab, while the fundamental field decreases: there is an energy transfer between the two waves as expected, the widely used assumption of non-depletion of the pump wave cannot apply here. It is worth mentioning the effect of the phase mismatch on the generation of the second harmonic after $0.5\mu m$: the propagating part of the harmonic interferes destructively with the newly generated part, resulting in a decrease of its amplitude.

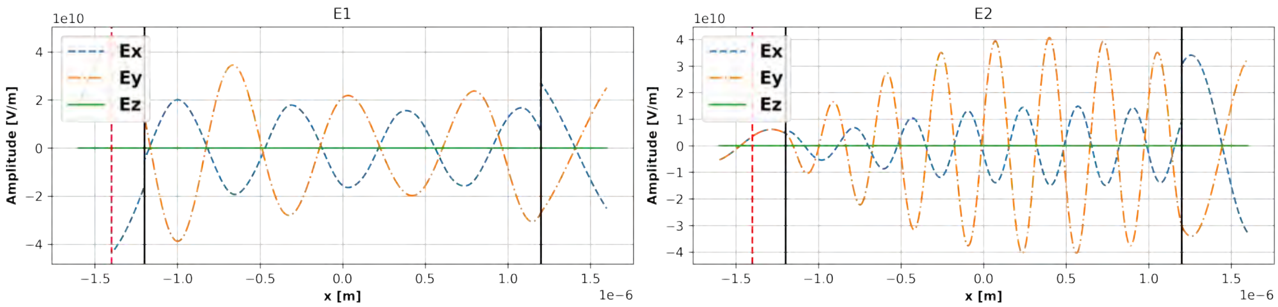


Fig. 1. Nonlinear scattering by a KTP slab. The real amplitude of the fundamental $\mathbf{E}_1$ (left) and the second harmonic $\mathbf{E}_2$ (right) are shown along the x axis, for a TM incident plane wave with an amplitude of $E_0 = 7.10^{10} V/m$ and an angle of incidence $\theta = \pi/4\ rad$. The two solid black vertical bars represent the slab interfaces, while the dashed red bar represents the virtual antenna generating the incident wave.

References

[1] Nicolaas Bloembergen. *Nonlinear Optics*. World Scientific, 4 edition, 1996.
[2] Gang Bao and David C. Dobson. *Journal of Mathematical Physics*, 35(4):1622–1633, 1994.

Coupled-Mode Theory Modelling of Fibre Bragg Gratings in Multimode Fibers for Imaging Applications

M. Lenz[1,*], E. Sutu[1], J. Fells[1], D. Phillips[2], P. Salter[1], M. Booth[1]

[1]*Department of Engineering Science, University of Oxford, Oxford OX1 2JD, UK*

[2]*Department of Physics and Astronomy, University of Exeter, Exeter EX4 4PY, UK*

*maike.lenz@eng.ox.ac.uk

This study presents a coupled-mode theory approach to simulate Fibre Bragg Gratings in multimode optical fibres, aimed at correcting bending-induced distortions. The model allows for the optimisation of grating designs for advanced imaging applications.

Introduction

Multimode optical fibres (MMFs) are hair-thin endoscopic probes that have allowed minimally invasive *in vivo* neuroimaging in deep-brain regions. MMFs efficiently deliver light to an imaging site with a footprint of only around 150 μm while simultaneously achieving diffraction-limited spatial resolution. However, there is a major limitation to MMF imaging – overcoming distortions induced by fibre deformations. Fibre bending destroys the focus quality of light travelling through a MMF and, hence, significantly worsens image quality. We use reflective Fibre Bragg Gratings (FBGs) inscribed in the MMF to correct these bending-induced distortions, ultimately working towards a fully flexible hair-thin endoscope.

In order to design these fibre devices, a novel approach based on coupled mode theory was developed to model mode interactions in complex FBG structures inside MMF. The method provides a computationally efficient means to compute spectral properties, which are critical for the design of these MMF imaging probes.

Results

The employed model simulates FBGs in MMFs by solving mode coupling differential equations as laid out in [1] directly, rather than using numerical or iterative approaches [2]. Based on this framework, we optimised the FBG profiles for specific applications. We were able to design a grating that maximises overlap with a desired wavefront of light travelling through the fiber, thereby enhancing reflection efficiency.

Initial results demonstrate the model's capability to predict key spectral properties of complex FBG structures, such as gratings with intricate transverse profiles and axially varying gratings. These findings are expected to advance the development of MMF probes for biomedical imaging and other advanced sensing applications. Further work will focus on experimental validation.

Conclusion

This study adapts a computational framework based on coupled-mode theory to simulate FBGs in MMFs. The results contribute to the development of enhanced fibre-based devices for applications in biomedical imaging and advanced sensing. Future work will involve experimental validation and further refinement of the model to optimise its application in real-world scenarios.

References

[1] Kashyap, R. (2010). Fiber Bragg Gratings. In *Fiber Bragg Gratings* (pp. 1–13). Elsevier. https://doi.org/10.1016/b978-0-12-372579-0.00001-6

[2] Sutu, E. (2024). *Adaptive optics correction for bent multimode fibres for use in biological imaging*.

Reciprocal Space Optimization of Light Trapping for Solar Absorbers

A. Vafa[1, *], M. Florescu[2]
[1]*Advanced Technology Institute, University of Surrey, Guildford GU2 7XH, UK*
[2] *Optoelectronics Research Centre, University of Southampton, Southampton SO17 1BJ, UK*
*ap02323@surrey.ac.uk

We introduce a novel approach for the design and optimisation of textured thin silicon film solar cells for enhanced absorption in the visible and near-infrared wavelengths. Our approach employs a spinodal density wave framework, and the resulting optimal structures absorb over 82% of the incident solar radiation.

Introduction

Engineering the next generation of ultra-thin solar cells, that can deliver efficient onsite power generation, is of utmost importance given the recent surge in the proliferation of AI-driven smart devices permeating various aspects of modern life. Light-trapping nanostructures, tailored in periodic or disordered configurations of subwavelength features, have been introduced to enhance the absorption of light in the otherwise bare slab of absorbing material by properly scattering light.[1] Broadband optimisation of such textures to obtain maximum absorption in the visible and near-infrared wavelengths has proved challenging due to the limitations of numerical methods. Here, we optimise the parameters $\boldsymbol{q}_i$ and θ_i of a so-called spinodal density wave in the reciprocal space, defined by: $\varphi(\boldsymbol{r}) = \sum_{i=1,N} cos(\boldsymbol{q}_i \cdot \boldsymbol{r} + \theta_i)$. This is subsequently binarized to construct a two-phase distribution, to which we refer as spinodal texture. By properly choosing $\boldsymbol{q}_i$ values from a set of reciprocal lattice vectors, we enforce periodicity.

Results

The figure below illustrates the structure and absorption spectrum of the optimal solar absorber. This design features a 1 micron-thick Si slab, mounted on silver, with the top 300 nm section textured with an optimal spinodal shape. This patterned region is filled and coated with a low-refractive-index medium (LRM) with n = 1.4.

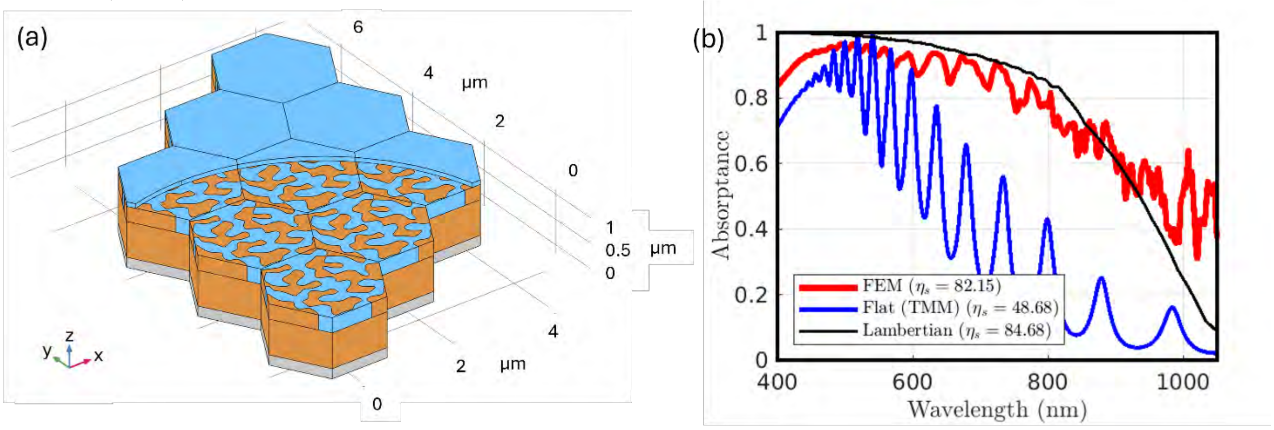


Fig. 1. Structure (a) and absorption profile (b) of the optimal thin-film silicon solar absorber calculated using FEM (red) compared to nontextured (blue) and Lambertian (black) profiles. Inset shows solar radiation absorption efficiency for each case.

Conclusion

We show that by defining the optimisation problem in the reciprocal space it is possible to obtain maximum absorption in a thin solar absorber device.

References

[1] N. Tavakoli et al., "Over 65% Sunlight Absorption in a 1 μm Si Slab with Hyperuniform Texture," ACS Photonics, vol. 9, no. 4, pp. 1206–1217 (2022).

Neuro-inspired time-series processing with silicon integrated photonics

P. Bienstman
Ghent University/imec, Ghent, Belgium
Peter.Bienstman@UGent.be

We will present different applications using the reservoir computing paradigm to process time series using photonic integrated chips.

Results

We will discuss how integrated photonic reservoir computing is a promising approach for solving a number of problems in telecommunications, e.g. non-linear dispersion compensation. We have shown experimentally that using a reservoir consisting of only 20 nodes can achieve sub-FEC error performance on on-off keying (OOK) signals at 32 Gbaud/s. Such a neuromorphic approach has the potential for being a high-speed low-power alternative for traditional electronic DSP [1].

We also showed in simulations that the scheme can be extended from simple modulation formats like OOK to complex coherent formats like 64QAM. We used the Kramers-Kronig (KK) detector configuration to achieve below-FEC-error-limit communications at 64 Gbaud/s, by including the nonlinear KK receiver in the training procedure [2].

Additionally, we have shown experimentally a completely new self-learning paradigm of optimising the weights inside a recurrent neural network, without relying on an offline algorithm or on a generated error feedback signal. Our network consists of ring resonators covered by a phase change material. By feeding the network with different binary sequences to be recognised, at powers above the plasticity threshold for the phase change material, we have shown that the network self-organises to better identify these sequences, without external intervention.

References

[1] S. Sackesyn, Optics Express 29, 20, pp. 30991-30997 (2021)

[2] S. Masaad, Nanophotonics, https://doi.org/10.1515/nanoph-2022-0426 (2022)

Performance evaluation of lithium niobate-based reconfigurable photonic switches

S. Ferraresi [1,*], M. Khalid [2], S. Massimo [2], G. Bellanca [1], V. Petruzzelli [2], G. Calò [2],

[1] *Department of Engineering, University of Ferrara, Ferrara, Italy*
[2] *Department of Electrical and Information Engineering, Polytechnic University of Bari, Bari, Italy*
simone.ferraresi@unife.it

Reconfigurable photonic switches are advanced optical devices which are essential for enabling non-mechanical signal routing and processing [1]. These reconfigurable switches have a wide range of applications in various fields, for example, in data centers and optical networks for dynamic control and high-speed data transfer, in low-cost LiDAR on autonomous vehicles for beam steering and scanning, and in augmented reality for directing light paths [2, 3].

The introduction of thin-film lithium niobate has sparked an increasing interest in the field of photonics due to its superior electro-optic and nonlinear optical properties. We conduct an optimization and performance analysis of lithium niobate (LN) based reconfigurable optical switches. The reconfigurability of the optical switches is achieved by applying a suitable phase shift using electro-optic phase shifters. We also present a comparison to assess the performance of the optical switches within different material and geometrical configurations. The scheme of the $N \times N$ reconfigurable optical switch is depicted in Figure 1. The optical switches exploit the Optical Phased Arrays (OPAs) both at the transmitting and receiving end. Recently, the behavior of such OPAs has been investigated by considering the Silicon-on-Insulator (SOI) technology[4, 5]. Using numerical simulations, we demonstrate that these reconfigurable optical switches based on OPAs can be used to address different in-plane receivers, with low power and improved performance.

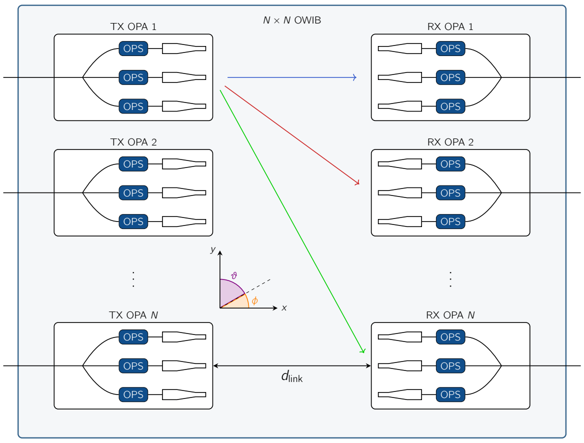


Fig. 1.: Schematic representation of $N \times N$ reconfigurable optical switch based on OPAs.

References

[1] H. Hu et al., "Silicon-based optical phased array with a reconfigurable aperture for "gaze" scanning of lidar," *Photonics Research*, vol. 12, no. 5, pp. 932–940, 2024.

[2] J. Notaros, "Integrated optical phased arrays: Ar displays, 3d printing, biophotonics, and beyond," in *2023 IEEE Photonics Conference (IPC)*, IEEE, 2023, pp. 1–2.

[3] M. Zhang, C. Wang, P. Kharel, D. Zhu, and M. Lončar, "Integrated lithium niobate electro-optic modulators: When performance meets scalability," *Optica*, vol. 8, no. 5, pp. 652–667, 2021.

[4] G. Calò et al., "4× 4 integrated switches based on on-chip wireless connection through optical phased arrays," in *Photonics*, MDPI, vol. 10, 2023, p. 367.

[5] M. Khalid et al., "Lnoi wireless switches based on optical phased arrays for on-chip communication," *IEEE Journal on Selected Areas in Communications*, 2024.

Photonic matrix multiplication using double racetrack resonators lattice

H. Talib[1,*], P. Sewell[1], A. Vukovic[1], S. Phang[1]

[1]*George Green Institute for Electromagnetics Research, University of Nottingham, Nottingham NG7 2RD, UK*

*hussein.talib@nottingham.ac.uk

Abstract

This work proposes a programmable integrated photonic circuit for an arbitrary matrix multiplication that uses cosine-sine decomposition of unitary matrix completion. Programmable mesh circuits of different sizes are designed and validated using a full-wave 3D simulation.

Introduction Programmable photonic integrated circuits can be realised as waveguide meshes, utilising a unitary building block consisting of waveguides, 2×2 double racetrack resonators and phase shifters. These 2×2 building blocks can be arranged on a triangular or rectangular grid pattern and can permit forward only or re-circulating light flow [1]. Judicious design of the building blocks parameters enables development of photonic circuit capable of performing complex linear computations, like multiply-accumulate matrix products operation. These circuits are promising platforms for neuromorphic photonics and quantum computing [1]. In this work, we propose a scalable and efficient approach for constructing a photonic circuit capable of arbitrary matrix multiplication, which is designed using cosine-sine unitary matrix completion method [2] and validated by 3D full-wave simulation.

Results We investigated the effects of varying the coupling region, ring size, positional offset, and inter-ring gap in double racetrack resonators through 3D simulation. Subsequently, we designed and simulated 3×3 integrated circuit using a mesh of double racetrack resonators demonstrating enhanced functionality. We extended the simulation for larger size (e.g., 4×4, 5×5, 6×6, 7×7, 10×10, and 13×13. The normalised square error has been calculated for each configuration.

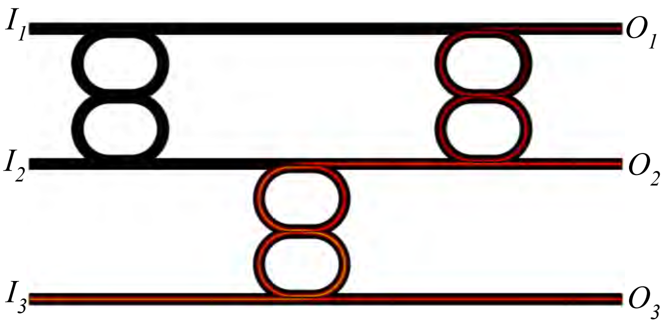


Fig. 1. Light flows through a 3×3 waveguide mesh implementing photonic processor.

Conclusion The work presents a method for developing photonic processors with the capability for arbitrary matrix multiplication and analyses its scalability to different mesh networks size.

References

[1] J. Capmany and D. Pérez, *Programmable Integrated Photonics*. Oxford University Press, 2020. doi: 10.1093/oso/9780198844402.001.0001.

[2] H. Talib, P. D. Sewell, A. Vukovic, and S. Phang, "Photonic circuit of arbitrary non-unitary systems," *Optical and Quantum Electronics*, vol. 57, no. 99, 2025. DOI: 10.1007/s11082-024-07957-5..

Design of transmission cavity resonator integrated grating filters

A .-L. Fehrembach [1], E. Popov [1], A. Moreau [1], J. Lumeau [1], K. Kumar [2], S. Calvez [2], O. Gauthier-Lafaye [2], A. Monmayrant [2]

[1] *Aix Marseille Univ, CNRS, Centrale Marseille, Institut Fresnel, Marseille, France*
[2] *LAAS-CNRS, Université de Toulouse, CNRS, Toulouse, France*
mailto:anne-laure.fehrembach@fresnel.fr

Cavity resonator integrated grating filters (CRIGF) consist of a sub-wavelength coupling grating (GC) with a few tens of periods, flanked by two distributed Bragg reflectors (DBR), etched onto a multi-layer dielectric stack. When illuminated by a focused incident beam, CRIGF exhibit resonances characterized by a strong electromagnetic field, and a strong reflectivity, or transmittivity, depending on whether the stack is weakly or highly reflective off-resonance. Previously, we exploited the high reflectivity and angular acceptance of CRIGF to serve as end-reflector in extended-cavity laser [1], and the strong field enhancement to improve the second-harmonic generation effect (SHG) [2].

Currently, we are developing a transmission filter based on a CRIGF and a multilayer stack mirror (see Fig. 1 left). This approach offers advantages over traditional Fabry-Perot filters, such as easier tuning of the transmission wavelength by adjusting a parameter of the structuration, rather than layer thicknesses, during fabrication. Furthermore, the CRIGF's large angular acceptance exceeds that of guided mode resonance filters (GMRF). A prior proof of concept exists in the literature [3].

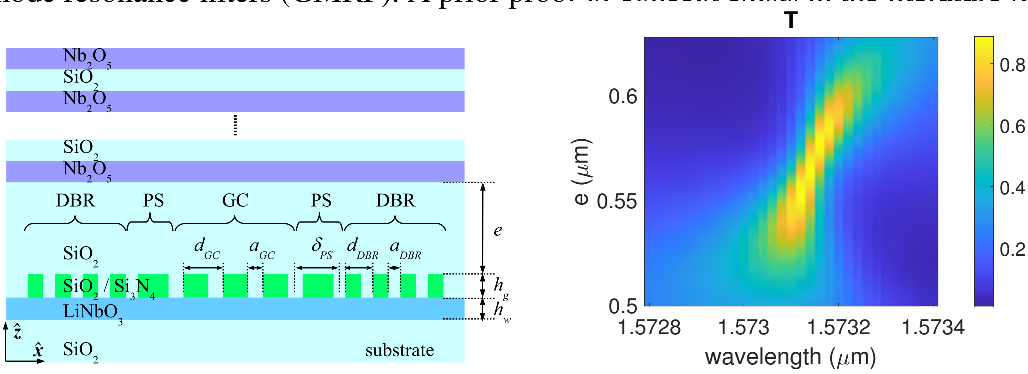


Fig. 1. (left) Transmission CRIGF structure. (right) Transmission versus the wavelength and buffer thickness.

Our work outlines the design rules for the multilayer stack, focusing on its eigenmodes and reflectivity. We present rigorous numerical calculation of the device's spectral characteristics, interpreted using simplified models (see Fig. 1 right). We compare the use of a simple GMRF (guided mode resonance filter) versus a CRIGF. Finally, we analyze the tolerance of the transmission spectrum to the incident beam angular divergence.

Acknowledgements: this work is supported by the Centre National d'Etudes Spatiales

References

[1] Augé et al. *Extended cavity quantum cascade laser with cavity resonator integrated grating filter* Opt. Expr. 4 (28), pp 4801 (2020).
[2] Fehrembach et al. *Cavity-resonator integrated bi-atom grating coupler for enhanced second-harmonic generation* Opt. Expr. 30 (21), pp 38789 (2022).
[3] Kintaka et al. *Cavity resonator-integrated guided mode resonance mirror with high-confinement channel structure for improvement of reflectance* Opt. Review 26, pp 436-441 (2019).

Brillouin Optomechanics in Scalable Photonic Integrated Platforms

D. Marpaung[1]
[1]*Nonlinear Nanophotonics group, MESA+ Institute of Nanotechnology, University of Twente, Enschede, 7500AE, the Netherlands*
*david.marpaung@utwente.nl

In this work, we investigate modelling and experiment of stimulated Brillouin scattering (SBS) in multiple photonic integrated platforms, including silicon nitride, silicon-on-insulator, and thin-film lithium niobate.

Summary

Stimulated Brillouin scattering (SBS) is a coherent optomechanical interaction between light and gigahertz acoustic waves [1] that can unlock promising technologies including narrow-linewidth lasers, microwave photonic signal processing, and on-chip nonreciprocal light propagation. Recently, SBS has extensively been studied in integrated waveguides. Achieving high on-chip SBS gain requires a large Brillouin gain coefficient, low propagation loss, and large optical power handling capability, which are difficult to be satisfied simultaneously in most photonic integrated platforms. Recently, SBS has extensively been studied in integrated waveguides. However, many implementations rely on complicated fabrication schemes, using suspended waveguides, or non-scalable materials. The absence of SBS in standard and mature fabrication platforms prevents large-scale circuit integration and severely limits the potential of this technology.

Fig. 1 shows the cross sections of six different scalable photonic for on-chip SBS process considered in this work, namely, double-stripe silicon nitride [2] (Fig. 1a), silicon oxynitride (SiON, Fig. 1b and Fig. 1c), 3 µm thick silicon [3] (Fig. 1d), thin-film lithium niobate (Fig. 1e), and tellurite-covered silicon nitride waveguides (Fig. 1f). All six platforms have relatively low propagation loss.

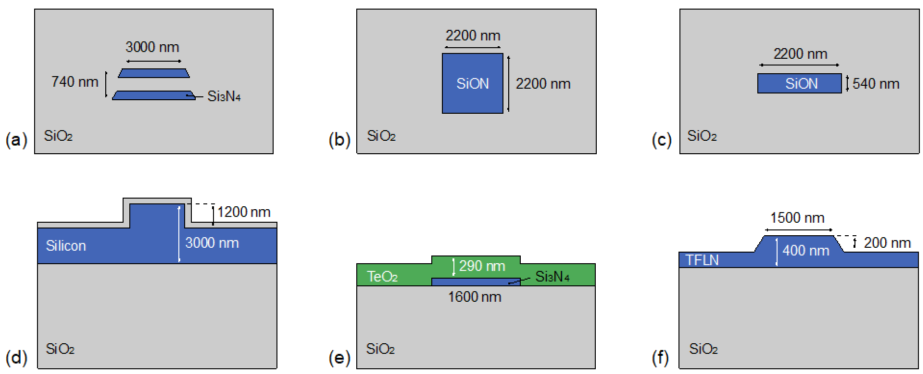


Fig. 1. Cross sections of different scalable photonic integrated platforms for on-chip SBS process

References

[1] B. J. Eggleton, C. G. Poulton, P. T. Rakich, M. J. Steel, and G. Bahl, “Brillouin integrated photonics,” Nature Photonics, 2019.

[2] R. Botter et al., “Guided-acoustic stimulated Brillouin scattering in silicon nitride photonic circuits,” Science Advances, vol. 8, p. 2196, 2022

[3] Kaixuan Ye, et al. Stimulated Brillouin scattering in a non-suspended ultra-low-loss thick-SOI platform. APL Photonics 1 February 2025

Parametric Interaction of Laser Cavity-Solitons with an External CW Pump

Andrew Cooper[1], Luana Olivieri[1], Antonio Cutrona[1], Debayan Das[1], Luke Peters[1], Sai Tak Chu[2], Brent Little[3], Roberto Morandotti[4], David J Moss[5], Marco Peccianti[1], and Alessia Pasquazi[1,*]

[1]*Emergent Photonics Research Centre, Dept. of Physics, Loughborough University, Loughborough, LE11 3TU, England, UK*

[2]*Department of Physics, City University of Hong Kong, Tat Chee Avenue, Hong Kong SAR, China*

[3]*QXP Technologies, Xi'an, China*

[4]*INRS-EMT, 1650 Boulevard Lionel-Boulet, Varennes, J3X 1S2, Québec, Canada*

[5]*Optical Sciences Centre, Swinburne University of Technology, Hawthorn, and the ARC Centre of Excellence COMBS, VIC 3122, Victoria, Australia*

*a.pasquazi@lboro.ac.uk

Laser cavity-soliton (LCS) microcombs are known to be robust and controllable [1-3], but their interaction with external sources is unexplored. Multi-source pumping has been extensively investigated in externally-driven microcomb configurations to enhance cavity-soliton properties, such as improving conversion efficiency [4], enhancing stability, and the exploration of novel soliton states [5].

We report the first experimental study of a LCS microcomb interacting with an externally coupled, co-propagating tunable continuous-wave pump. This interaction induces parametric Kerr effects resulting in the stable generation of LCS comb replicas via cross-phase modulation (XPM) and four-wave mixing (FWM). We demonstrate the dependence of the parametrically generated combs on the cavity-soliton and pump parameters, and control of the resulting spectra via detuning of the CW pump. The parametric nature of the process is verified via numerical simulations. This work provides a route to extension of LCS microcomb bandwidths, and enhancement of this type of microcomb via multi-source pumping techniques.

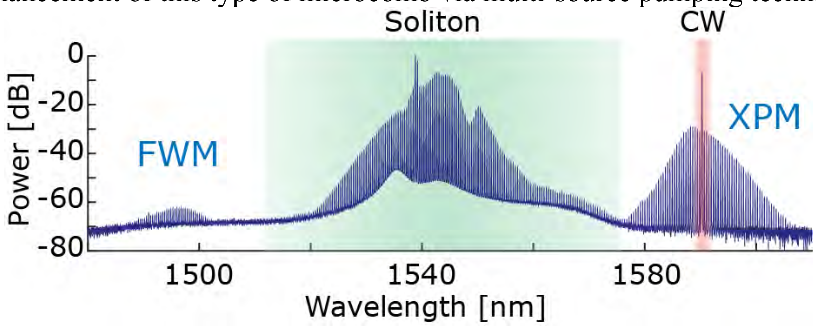


Fig. 1. Sample spectra of a LCS and external CW interaction, generating XPM and FWM comb replicas.

References

[1] H. Bao et. al., "Laser cavity-soliton microcombs," Nature Photonics **13**, 384 (2019).

[2] M. Rowley et al., "Self-emergence of robust solitons in a microcavity," Nature **608**, 303–309 (2022).

[3] A. Cutrona et al., "Stability of laser cavity-solitons for metrological applications", Appl. Phys. Lett. **122**, 121104 (2023).

[4] T. Hansson and S. Wabnitz, "Bichromatically pumped microresonator frequency combs," Physical Review A **90**, 013811 (2014).

[5] G. Moille et al., "Parametrically driven pure-Kerr temporal solitons in a chip-integrated microcavity," *Nat. Photon.* **18**, 617–624 (2024)

Hysteresis in Laser Cavity-Solitons

Aadithya Suresh[1], Antonio Cutrona[1], Juan Sebastian Totero Gongora[1], Marco Peccianti[1] and Alessia Pasquazi[1*]

[1]*Emergent Photonics Research Centre, Department of Physics, Loughborough University, Loughborough LE11 3TU, United Kingdom*
*a.pasquazi@lboro.ac.uk

We show repeatable hysteresis behaviour in the energy of laser cavity-solitons when the gain of the system is varied following opposite trajectories induced by the slow nonlinearities of the microcomb laser.

Hysteresis is a phenomenon associated with bistability in a system and constitutes a form of memory. Laser cavity-solitons (LCS) offer a self-emergent, robust microcomb platform [1]. An important characteristic of the appearance of such states in microresonator fibre laser systems is that it is intrinsically connected to the slow, energy-dependent nonlinearities of the laser. While the bistability arising from ultrafast Kerr nonlinearity has been extensively explored in soliton state formation, the connection between bistable behaviour induced by slow, energy-dependent nonlinearities and soliton formation remains less examined. In Fig. 1a, we present the experimental setup used to demonstrate hysteresis in LCS. When the pump power is swept in opposite directions, different states with distinct power levels are formed (see Fig. 1b). Our focus is on the transitions between single-soliton (see Fig. 1c) and two-soliton (see Fig. 1d) states. We observe a distinct region where the system consistently exhibits bistability (see Fig. 1b). Our results confirm the presence of hysteresis in LCS, paving the way for microcomb-based optical processing using fully coherent, broadband soliton states.

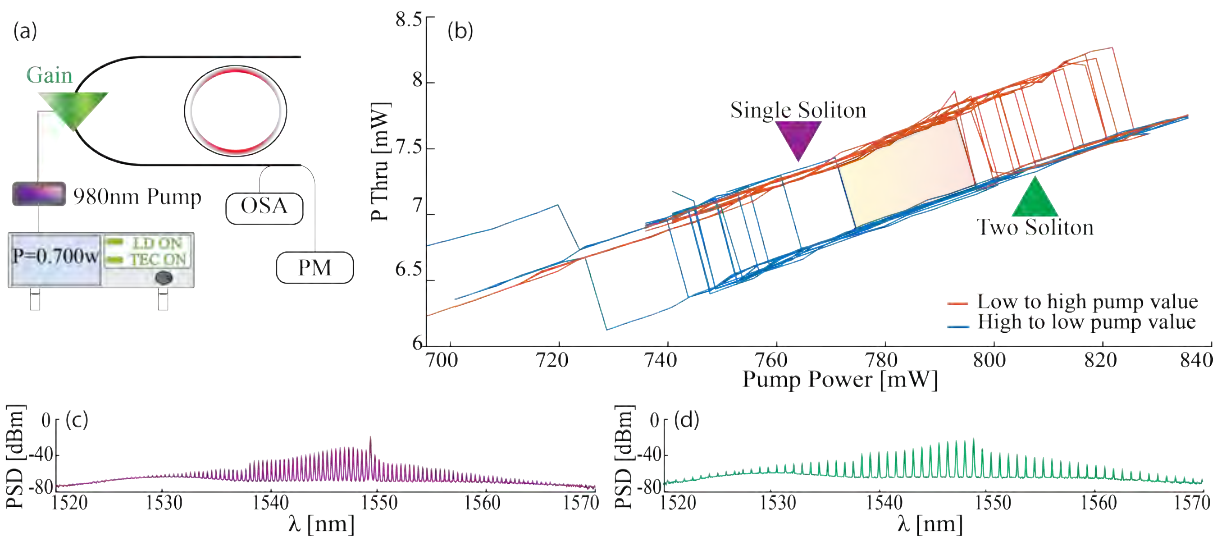


Fig. 1. (a) A four port microresonator nested into an amplifying fibre loop is used for the experiment [1]. The amplifier's pump is connected to a diode controller to change its power, while the through port is connected to optical spectrum analyser (OSA) and power meter (PM). (b) A hysteresis behaviour on the through power is found in transitioning from single soliton to two solitons, while ramping up and down the pump power. The repeatability of hysteresis is shown by stacking 16 hysteresis loops. The shaded region at the centre is the region of repeatable bistability. (c,d) The one- (c) and two- (d) soliton states in the hysteresis loop.

References

[1] M. Rowley, et al. "Self-emergence of robust solitons in a microcavity," Nature **608**(7922), 303–309 (2022).

Spatiotemporal Engineering of Terahertz Pulses in Disordered Media

Vittorio Cecconi[1*], Vivek Kumar[2], Juan Sebastian Totero Gongora[1], Antonio Cutrona[1], Luke Peters[1], Luana Olivieri[1], Jacopo Bertolotti[3], Alessia Pasquazi[1], Marco Peccianti[1]

[1]*Emergent Photonics Research Centre and Dept. of Physics, Loughborough University, Loughborough, UK*

[2] *Emergent Photonics (EPic) Laboratory, Dept. of Physics and Astronomy, University of Sussex, UK*

[3]*Dept. of Physics and Astronomy, University of Exeter, Exeter, UK*

*v.cecconi@lboro.ac.uk

Summary

This work presents an experimental demonstration of full-field control and manipulation of broadband terahertz (THz) pulses propagating through random scattering media [1], building upon the pioneering work by Mosk and colleagues [2]. By employing the time-domain nonlinear ghost imaging technique in conjunction with a genetic algorithm, we demonstrated the ability to synthesise an arbitrarily defined spatiotemporal THz waveform at desired spatial positions within complex disordered systems. The key innovation lies in coherently detecting the scattered electric field at a specific target point facilitated by THz time-domain spectroscopy. Unlike conventional optical approaches [3], our method enables direct waveform synthesis at the field level. This is achieved by optimising the incident spatial patterns, either through genetic algorithms or by measuring the transfer matrix[4], utilising a nonlinear crystal—building on prior numerical work [5], [6]. The experimental results reveal exceptional spatiotemporal focusing, the recovery of transform-limited pulses with a null carrier-envelope phase, and precise control over the absolute time delay of the transmitted waveforms (see figure).

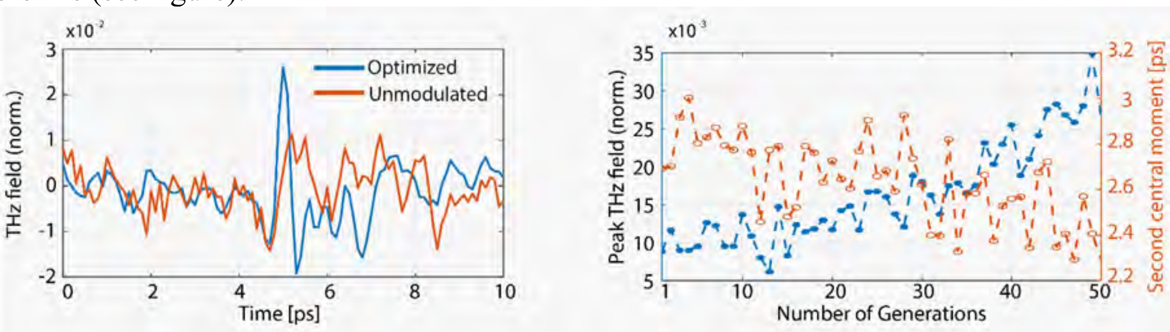


Figure. The spatiotemporal focus of a THz pulse.

References

[1] V. Cecconi *et al.*, ‘Terahertz Spatiotemporal Wave Synthesis in Random Systems’, *ACS Photonics*, vol. 11, no. 2, pp. 362–368, Feb. 2024, doi: 10.1021/acsphotonics.3c01671.

[2] A. P. Mosk, A. Lagendijk, G. Lerosey, and M. Fink, ‘Controlling waves in space and time for imaging and focusing in complex media’, *Nature Photon*, vol. 6, no. 5, Art. no. 5, May 2012, doi: 10.1038/nphoton.2012.88.

[3] A. Boniface, I. Gusachenko, K. Dholakia, and S. Gigan, ‘Rapid broadband characterization of scattering medium using hyperspectral imaging’, *Optica, OPTICA*, vol. 6, no. 3, pp. 274–279, Mar. 2019, doi: 10.1364/OPTICA.6.000274.

[4] V. Kumar *et al.*, ‘Terahertz Microscopy Through Complex Media’, Dec. 09, 2024, *arXiv*: arXiv:2412.06427. doi: 10.48550/arXiv.2412.06427.

[5] V. Cecconi, V. Kumar, A. Pasquazi, J. S. Totero Gongora, and M. Peccianti, ‘Nonlinear field-control of terahertz waves in random media for spatiotemporal focusing’, *Open Res Europe*, vol. 2, p. 32, Mar. 2022, doi: 10.12688/openreseurope.14508.1.

[6] V. Kumar *et al.*, ‘Deterministic Terahertz Wave Control in Scattering Media’, *ACS Photonics*, vol. 9, no. 8, pp. 2634–2642, Aug. 2022, doi: 10.1021/acsphotonics.2c00061.

Self-emergence of laser cavity solitons in microcombs: the role of slow nonlinearity

[1]*Emergent Photonics Research Centre, Department of Physics, Loughborough University, Loughborough LE11 3TU, United Kingdom*
*a.pasquazi@lboro.ac.uk

We summarise the properties of laser cavity solitons in a Kerr microresonator within an amplifying loop, highlighting their stability, energy efficiency, and spontaneous formation, supported by slow nonlinearities.

Optical frequency combs generated in microresonators, commonly referred to as *microcombs*, consist of a series of evenly spaced spectral lines. These are typically formed within nonlinear microcavities through the action of Kerr nonlinearity. A major milestone in the field was the discovery of dissipative temporal cavity solitons, which enabled the generation of broad and smooth spectra, ideally suited for metrological comb applications.
We demonstrated that localized pulses could be produced when a microcavity is embedded within a fibre laser loop [1], leading to the observation of laser cavity solitons. By combining the features of microresonators and multimode systems, our approach introduces a route for generating, stabilizing, and controlling solitary optical pulses in microcavities.
In this framework, it is important to emphasise the key physical properties of these waveforms, notably their energy efficiency and dynamical behaviour, both critical for system initiation and recovery. Moreover, we recently demonstrated that these waves can arise spontaneously and exhibit robust recovery [2], even while interacting with other states within the system [3].
In this talk, I will present the fundamental mechanism that establishes laser cavity solitons as the dominant attractors in a microcomb system. The platform is based on a Kerr microresonator embedded in an amplifying cavity. I will particularly highlight the role of slow nonlinearities in the system and how they support the stable formation of solitary waves. In addition, I will outline the mathematical modelling used to describe our experimental observations.

References

[1] H. Bao, et al. Laser Cavity-Soliton Microcombs. *Nat. Photonics* **13**, 384 (2019).

[2] M. Rowley,. *et al.* Self-emergence of robust solitons in a microcavity. *Nature* **608**, 303–309 (2022).

[3] A. Cutrona, *et al.* Nonlocal bonding of a soliton and a blue-detuned state in a microcomb laser. *Commun Phys* **6**, 259 (2023).

Universal Topological Localisation in Time from Parity-Time-Reversal Symmetry

Tom Sheppard[1], Sebastian Weidemann[2], Alexander Szameit[2], Joshua Feis[2], and Hannah M. Price[1,*]

[1]*School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom*
[2]*Institute of Physics, University of Rostock, Rostock, Germany*

Time is fundamentally different from space: objects obey causality. This difference dictates a new approach is required to uncover topological effects that are intrinsically linked to time, rather than space. By examining models whose only dimension is time, we identify such an approach and break new ground in the rapidly developing field of time topology[1,2,3]. We show that time, both in isolation from space and paired with any number of spatial dimensions, features a topological effect: temporal localisation of the wavefunction. This effect is underpinned by non-Hermiticity and parity-time-reversal symmetry.

Results and Discussion

At the centre of our new approach is an intuitive physical principle: to discover the topological effects of time, we begin with a system that has time as its only dimension. In particular, we study two-level models that have two essential properties: (1) they are non-Hermitian, and (2) they are parity-time-reversal (PT) symmetric. These models are widely used as a minimal settings to study the effects of PT symmetry in photonics[3]. By studying their spectral properties, we find a novel topological invariant describing these systems in the PT-broken phase. We show that this topology underpins the robust localisation of the wavefunction at a time interface, where this invariant is abruptly mismatched.

Moving beyond purely temporal models, we reflect that time is the universal dimension; it is common to all physical systems regardless of their spatial properties. In correspondence with this universality, we find that the localisation effect observed in two-level models has counterparts in every other dimension. Two-band models, which have PT symmetry, feature topologically time-localised states independently of their spatial dimension. These models have been realised in photonic time crystals[1], synthetic photonic lattices[4], and waveguide arrays[5]. The topological origin of these states can be traced back to the two-level model, where its topological invariant underpins novel momentum-based topological features of the bandstructure. Remarkably, we find that there exist no fundamental constraints on the spatial profile of this time-localised state. Here temporal topology enforces a robust localisation in time, whilst leaving the spatial profile free to engineer. This discovery enriches and expands upon previous observations[2,3] of time-localised states in $(1+1)$d, where a momentum bandstructure[1] approach was used.

Our results connect three exciting and rapidly developing areas: (1) PT symmetry and non-Hermiticity in photonics, (2) time-dependent photonic systems, including photonic time crystals, and (3) topological photonics. The widespread familiarity of the featured models suggests that photonics is incredibly well-placed to experimentally observe this topological effect of time, as well as find potential practical applications of the robust temporal localisation.

References

[1] E. Lustig, Y. Sharabi, and M. Segev, Topological Aspects of Photonic Time Crystals, Optica **5**, 1390-1395, (2018).
[2] Y. Ren et al., Observation of Momentum-Gap Topology ..., Nat. Comms. **16**, 707 (2025).
[3] J. Feis, S. Weidemann, T. Sheppard et al., Spacetime-Topological Events ..., Nat. Photon. (*accepted*, 2025).
[4] C. E. Rüter et al., Observation of Parity–Time symmetry in Optics, Nat. Phys. 6, 192 (2010).
[5] A. Regensburger et al., Parity–Time Synthetic Photonic Lattices, Nature **488**, 167 (2012).
[6]M. Kremer et al., Demonstration of a Two-Dimensional PT-symmetric Crystal, Nat. Comms. **10**, 435 (2019).

* h.price.2@bham.ac.uk

Local photons and the momentum of light

Almut Beige [1,*], Gabriel Waite [1,2], Daniel Hodgson [1], Ben Lang [3], Varghese Alapatt [1]

[1] *The School of Physics and Astronomy, University of Leeds, Leeds, LS2 9JT, UK*
[2] *Centre for Quantum Software and Information, School of Computer Science, Faculty of Engineering and Information Technology, University of Technology Sydney, NSW 2007, Australia*
[3] *The School of Physics and Astronomy, University of Nottingham, Nottingham NG7 2RD, United Kingdom*
a.beige@leeds.ac.uk

Recently, we introduced a local photon approach which allows us to assign wave functions to single photons. It also allows us to define the momentum of light in a unique way and to gain more insight into the Abraham-Minkowski controversy. Surprisingly, quantum physics teaches us something new about classical optics.

Introduction. This contribution takes an alternative approach to the quantisation of the electromagnetic field [1, 2]. First, we notice that the basic solutions of Maxwell's equations support localised wave packets of light which travel at the speed of light and without dispersion in their respective direction of propagation. This observation motivates the introduction of localised field excitations—so-called blips (bosons localised in position)—as the basic building blocks of the electromagnetic field. These are carriers of electric and magnetic fields in a similar way as massive objects, like planets, are carriers of gravitational fields. Most importantly, our local photon approach can be used to assign wave functions $\psi(x,t)$ to individual photons, as required by wave-particle duality.

Results. One advantage of our approach is that allows us to associate the momentum of light with the generator for the spatial translation of photonic wave packets. The resulting momentum of light aligns with the definition of the momentum of quantum mechanical point particles [3]. Moreover, our local photon theory can be used to construct a locally-acting mirror Hamiltonian and to analyse the dynamics of the momentum of light transitioning from air into a dielectric medium. Our calculations shine new light onto the so-called Abraham-Minkowski controversy which highlights the intrinsic complexities of identifying the momentum definition of light [4]. Previously, our approach has been used to obtain a more intuitive picture of the Casimir effect [5] and the Doppler effect [6]. Since working in position space is often more intuitive, we expect that the local photon approach which we present here will also find many applications in the modelling of photonic devices.

References

[1] J. Southall, D. Hodgson, R. Purdy and A. Beige, Locally-acting mirror Hamiltonians, J. Mod. Opt. **68**, 647 (2021).

[2] D. Hodgson, J. Southall, R. Purdy and A. Beige, Local photons, Front. Photon. **3**, 978855 (2022).

[3] G. Waite, D. Hodgson, B. Lang, V. Alapatt and A. Beige, Local photon model of the momentum of light, Phys. Rev. A **111**, 023703 (2025).

[4] S. Barnett and R. Loudon, The enigma of optical momentum in a medium, Phil. Trans. Roy. Soc. A **368**, 927 (2010).

[5] D. Hodgson, C. Burgess, M. B. Altaie, A. Beige and R. Purdy, An intuitive picture of the Casimir effect, arXiv:2203.14385 (2025).

[6] D. Hodgson, S. Kanzi and A Beige, A simple quantum picture of the relativistic Doppler effect, Symmetry **16**, 279 (2024).

Super-bound states in the continuum in a simple grating

Nan Zhang, Ya Yan Lu*

Department of Mathematics, City University of Hong Kong, Kowloon, Hong Kong
mayylu@cityu.edu.hk

In a periodic structure, near a bound state in the continuum (BIC), there are resonant modes with quality factor $Q \sim 1/|\beta - \beta_*|^m$, where β_* and β are the Bloch wavenumbers of the BIC and the resonant mode, respectively. For a simple grating, we show super-BICs with $m = 4$, 6, 8, 10.

Introduction

Bound states in the continuums (BICs) have found important applications in photonics. In a structure with a 1D periodicity, a BIC is associated with a real frequency ω_* and a real Bloch wavenumber β_*. For any real β near β_*, there is always a resonant mode with a complex ω and a quality factor $Q \sim 1/|\beta - \beta_*|^m$. Usually, $m = 2$. If $m \geq 4$, the BIC is a super-BIC [1]. Super-BICs are particularly attractive for applications.

Results

In a 2D structure that is invariant in x, periodic in y, bounded in z, and surrounded by air, a TE polarized BIC has the electric field component $E_x = e^{i\beta_* y}\phi(y, z)$, where ϕ is periodic in y and tends to zero as $z \to \pm\infty$, and $\omega_*/c > |\beta_*|$. For a simple grating with each period consisting of two segments, we have found eight different types of BICs listed in the table below, where NZ means

BIC type	1	2	3	4	5	6	7	8
β_*	0	NZ	0	NZ	0	NZ	0	0
symmetry in y	odd	PT	even	PT	odd	PT	even	odd
m	2	2	4	4	6	6	8	10
N	0	0	1	1	1	2	2	2

$\beta_* \neq 0$, odd, even and PT mean $\phi(-y, z) = -\phi(y, z)$, $\phi(-y, z) = \phi(y, z)$ and $\overline{\phi}(y, z) = \phi(-y, z)$, respectively, m is the power in the asymptotic relation of Q, N is the number of structural parameters needed to find the BIC. If $N = 1$, the BIC exists as a curve in the plane of two parameters. If $N = 2$, the BIC corresponds to a single point in the plane of two parameters, and a curve in the space of three parameters. BICs of type 1 and 2 are robust, since they exist without the need to tune any parameter. Super-BICs with $m \geq 4$ can only be found by tuning at least one parameters (i.e. $N \geq 1$). BICs of types 6 and 7 are new. A theory is developed to reveal the number N for different kinds of BICs. An efficient numerical method is developed to find the super-BICs with $m \geq 4$ and $N \geq 1$ efficiently.

Conclusion

A comprehensive theory and an efficient computational method for super-BICs in dielectric structures with a 1D periodicity are developed, and numerical results for a simple 1D grating are presented.

References

[1] N. Zhang, Y. Y. Lu, *Perturbation theory for resonant states near a bound state in the continuum*, Physical Review Letters **134**, 013803 (2025).

Lattice resonances in plasmonic systems

Olivier J.F. Martin
[1]Nanophotonics and Metrology Laboratory, Swiss Federal Institute of Technology Lausanne (EPFL)
CH-1015 Lausanne, Switzerland
olivier.martin@epfl.ch

Different phenomena that occur in a periodic array of plasmonic nanostructures are investigated in terms of periodicity and multipoles.

In this presentation, we revisit the resonances that exist in periodic plasmonic systems, Fig. 1. Starting with some basic concepts such as the difference between Wood and Rayleigh anomalies, as well as the influence of the surrounding medium, we move to more advanced concepts, such as bound state in the continuum – which are receiving significant research interest today – and also the Kerker effect that can control absorption in the system and its scattering in specific directions. All these effects are associated with the excitation of multipolar surface lattice resonances and studying the evolution of these resonances as a function of the different geometrical parameters provides significant insights into the underlying physics [1]. These phenomena are also closely related to Fano resonances, since they stem from the interaction between different modes in the system, leading to an asymmetric lineshape [2]. Especially for bound states in the continuum, their very sharp spectral features stem from the interaction with propagating modes, which can be lattice resonances or guided modes. The latter echo strongly with the field of resonant waveguide gratings, which flourished almost fifty years ago [3].

Finally, we will show that these resonances do not only influence the linear behaviour of the system, but also its nonlinear response. For example, the strong absorption produced by the Kerker effect at the fundamental frequency can enhance the generation of second harmonics.

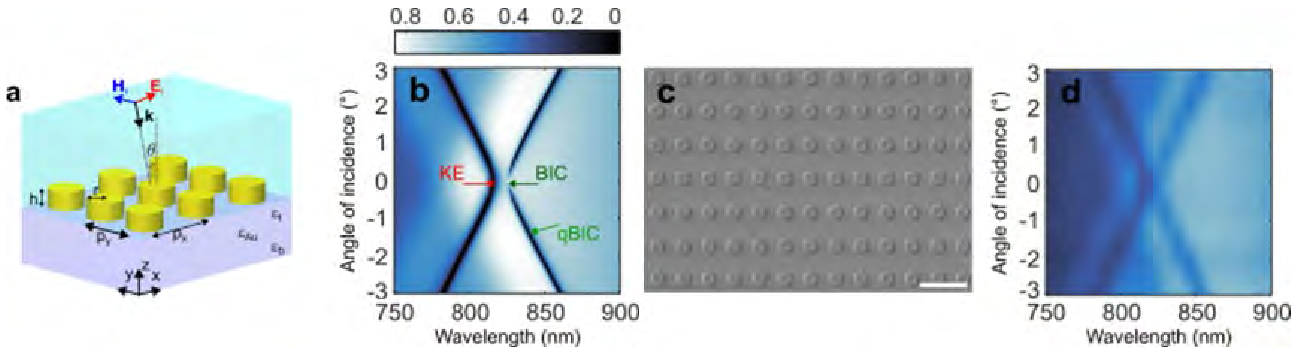


Fig. 1. Typical system studied in this presentation: (a) geometry with an array of Au scatters on a substrate, (b) computed and (d) measured transmittance; (c) fabricated sample.

References

[1] M. Riccardi et al., *Multipolar expansions for scattering and optical force calculations beyond the long wavelength approximation*, Phys. Rev. B. **106**, 115428, 2022.

[2] B. Gallinet, O.J.F. Martin, *Influence of electromagnetic interactions on the line shape of plasmonic Fano resonances*, ACS Nano **5**, 8999, 2011.

[3] G. Quaranta, G. Basset, O.J.F. Martin, B. Gallinet, *Recent Advances in Resonant Waveguide Gratings*, Laser & Photon. Rev. **12**, 1800017, 2018.

Self-Consistent Modeling of Coupled Maxwell-Rate Equations with the Finite-Difference Time-Domain Method

P. Mavrikakis [1,*], S. Athanasiou [1], O. J. F. Martin [1],
[1] *Nanophotonics and Metrology Laboratory, EPFL, CH-1015 Lausanne, Switzerland*
parmenion.mavrikakis@epfl.ch

In this study, we introduce a semi-classical finite-difference time-domain (FDTD) framework for modeling molecule-plasmon interactions in three dimensions. By integrating molecular rate equations with electromagnetic field calculations on the Yee grid, the approach provides a self-consistent analysis of the dynamic coupling between molecular processes and plasmonic fields.

Introduction

The interaction between molecules and plasmonic nanoparticles is a cornerstone of modern nanophotonics, necessitating a rigorous description of both quantum molecular dynamics and classical electromagnetic fields. Existing methodologies often lack the capacity to resolve the temporal and spatial intricacies of these coupled systems. To address this challenge, we present a self-consistent semi-classical framework based on the finite-difference time-domain (FDTD) method. This approach integrates molecular rate equations directly within the electromagnetic field calculations, enabling detailed investigations of the dynamic coupling between molecular and plasmonic processes.

Results

The presented FDTD framework effectively captures the near-field and far-field optical responses of molecule-plasmon systems under various excitation conditions, including pulsed and continuous-wave inputs. Simulations reveal intricate energy exchange processes and elucidate the role of plasmonic fields in influencing molecular excitation and radiative emission dynamics. Numerical stability and accuracy are preserved across the spatial and temporal scales relevant to molecule-plasmon interactions. These results establish the framework as a robust computational tool for advancing the theoretical understanding and design of nanophotonic systems.

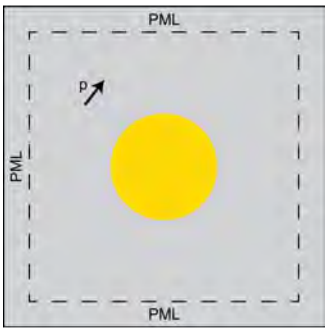


Fig. 1. 2D cross section of a molecule (dipole) and plasmonic (gold) nanoparticle 3D geometry.

References

[1] Yee, K. S., "Numerical solution of initial boundary value problems involving Maxwell's equations in isotropic media," *IEEE Trans. Antennas Propag.*, Vol. 14, No. 3, 302–307, 1966.

[2] Warren, C., A. Giannopoulos and I. Giannakis, "gprMax: Open source software to simulate electromagnetic wave propagation for Ground Penetrating Radar," *Computer Physics Communications* , Vol. 209, 163–170, 2016.

Numerical modeling of time-modulated metasurfaces with a Discontinuous Galerkin method

M. Elsawy [1], R. Gelly [1], S. Lanteri [1],

[1] *Atlantis project-team, Université Côte d'Azur, Inria, CNRS, LJAD, Sophia Antipolis, France*

The overarching goal of this work is to propose and develop a novel numerical methodology for the design of time-modulated metasurfaces. Here, we present a first step in this direction with the introduction of a Discontinuous Galerkin (DG) method for the solution of time-domain Maxwell's equations for time-varying materials.

Introduction

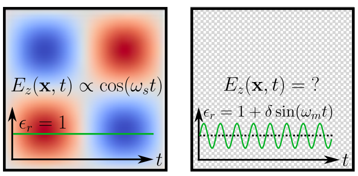
Metasurfaces [1] are thin artificial materials composed of an array of light-scattering nanometric elements, called *nano-resonators*. They have been proven to be a flexible medium to manipulate the light properties for a given optical function and have been applied to the fields of imaging, polarimetry and holography. Metasurfaces have generally a fixed optical function. However in the recent years, the concept of *time-modulated* metasurfaces [2] emerged, which relies on external stimulation to leverage a time-varying optical response thus allowing novel physical effects and applications.

Methodology

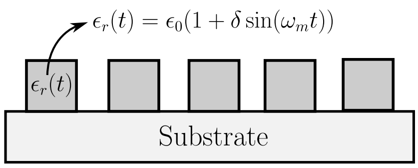
To numerically study time-modulated metasurfaces, we model their interaction with electromagnetic waves by solving Maxwell's equations in heterogeneous and time-varying media. Most of the works dedicated to the subject are based on the Finite-Difference Time-Domain (FDTD) method which is simple to implement, although it can loose accuracy when dealing with complex geometries. In our case, we use the Discontinuous Galerkin Time-Domain (DGTD) method [3] which is similar to the Finite Element (FE) method and allows to account for the discontinuities in the electromagnetic fields.

Preliminary results

We first validated our time-domain solver using a manufactured solution (Fig. 1a). We are currently considering the extension of the proposed DGTD method to deal with time-modulated diffraction gratings (Fig. 1b) proposed by [4].



(a)



(b)

Fig. 1.: **(a)**: Manufactured solution: time-modulated resonant cavity. **(b)**: Time-modulated diffraction grating.

References

[1] N. Yu *et al.*, Science, vol. 334, no. 6054, pp. 333–337, 2011.
[2] E. Mikheeva *et al.*, ACS photonics, vol. 9, no. 5, pp. 1458–1482, 2022.
[3] J. Viquerat, PhD Thesis, 2015.
[4] S. Inampudi *et al.*, Opt. Mater. Express, vol. 9, no. 1, p. 162, 2019

Resonant state formulations of Wave-guide response functions

Brian Stout [1],
[1] *Aix Marseille Univ, CNRS, Centrale Marseille, Institut Fresnel, Marseille, France*

The guided modes of a system are shown to fit within the same response function framework as its scattering Quasi-Normal Modes (QNMs). This correspondence enables new forms of analysis for guided mode systems since the response function framework imposes sum rule constraints on the system's eigenvalues. We explore the use of these sum rules in developing approximation strategies for guided modes response functions.

Summary

Wave guiding structures, like optical fibers, guide waves that are introduced via the appropriate illumination conditions (like end-fire or evanescent illumination), but they also scatter waves when subject to conventional propagative illumination. Under such scattering conditions, the system's response can be characterized by frequency-dependent response functions, such as S- and T-matrices. The frequency dependence of these response functions is largely determined by their singularities (along with more slowly varying non-resonant contributions).

Over the past decade, significant progress has been made in approximating scattering response functions within a restricted frequency range using Resonant States, also known as Quasi-Normal Modes (QNMs). Such modes, obtained as eigen-solutions of the source-free equations of motion with outgoing boundary conditions, typically dominate the scattering behavior in a desired frequency range. This approach is motivated by the fact that solving eigenvalue equations is numerically more tractable than directly computing response functions in their full generality. Nevertheless, reconstructing response functions from QNM eigenvalues presents its own challenges, notably in the need for novel normalization techniques to handle the exponential divergence of QNM eigenfunctions in the far field.

Studies of guided mode propagation are in fact quite analogous to the Quasi-Normal Mode (QNM) approach. One typically also solves for propagation eigenvalues within a desired frequency range rather than trying to solve for the complete response functions. Since guided modes are principally spatially confined within the system, they are generally normalized based on their energy propagation through a system cross-section. However, we have recently observed that guided modes can alternatively be normalized within the same framework as QNMs that describe scattering responses. This insight enables a unified description where guided and scattered field modes are both formulated in terms of response functions. This opens up new approximation strategies for analyzing guided modes based on the fact that response functions impose constraints on a system's total response, which can take the form of eigenvalue sum rules. This presentation explores applications of this approach through concrete examples.

References

[1] *Derivation of the Transient and Steady Optical States from the Poles of the S-Matrix,* Ben Soltane *et al*, Laser & Photonics Reviews, 2200141, (2022).

[2] *Spectral expansions of open and dispersive optical systems: Gaussian regularization and convergence* Stout *et al*, New Journal of Physics 23, 083004, 2021.

Programmed all-optical switching in a multistable photonic molecule

Karindra Perrier[1], Jerom Baas[1], Sylvain Combrié[2] Alfredo de Rossi[2], Sanli Faez[1], and Allard P. Mosk[1]

[1] *Nanophotonics, Debye Institute for Nanomaterials Science, and Department of Physics, Utrecht University, Princetonplein 1, 3584 CC Utrecht, The Netherlands*

[2] *Thales Research and Technology, Route D\'{e}partementale 128, 91767 Palaiseau, France*

*a.p.mosk@uu.nl

We demonstrate all-optical control over a multistable photonic molecule, a system of thermally and optically coupled nanoresonators on a photonic crystal membrane, using an out-of-plane control laser.

Introduction

A system of coupled photonic crystal nanocavities can be controlled by addressing it with an out of plane control laser, as illustrated in Fig. 1. An out of plane laser [1] adresses the individual resonators.

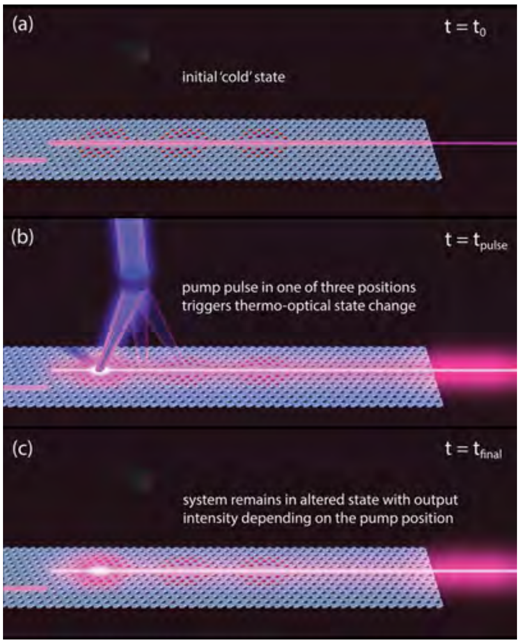


Fig. 1. An illustration of thermo-optical control of multiple photonic crystal nanocavities.

Results

Depending on the sequence of control pulses we can select any of several stable states of the nonlinear multi-cavity system. Interpretation of the results depends on simultaneously solving the system's optical and thermal response.

References

[1] E. Yüce *et al.*, A*daptive Control of Necklace States in a Photonic Crystal Waveguide*, ACS Photonics **5**, 3984–3988 (2018).

Guided modes of integrated optical thin-film lithium niobate channels

Manfred Hammer*, Behnood Taheri, Henna Farheen, Jens Förstner

Theoretical Electrical Engineering, Paderborn University, Paderborn, Germany
* *manfred.hammer@uni-paderborn.de*

The modes of rib or strip waveguides made with TFLN / LNOI technology are influenced, among other parameters, by the crystal configuration, the symmetry, and the on-chip orientation of the channels. We highlight the effects of the core anisotropy on modal hybridization and polarization conversion.

TFLN / LNOI photonic circuitry

Owing to advantageous nonlinear and electrooptic properties, thin-film lithium niobate (TFLN) or lithium niobate on insulator (LNOI) features among the currently most popular technological platforms for integrated optics. Waveguides are typically of rib or strip type, with slanted sidewalls, prepared from TFLN slabs of standard thickness. Parts (a) and (b) of Fig. 1 illustrate the geometry. With this contribution we survey the influence of the many parameters that enter, with emphasis on the effects of the core anisotropy, for waveguides of X- and Z-cut types.

Properties of guided modes

Effective index levels and polarization characteristics are computed by rigorous numerical analysis on the basis of the JCMwave finite element solvers [1]. We restrict to the linear regime. Material dispersion and the anisotropy of the lithium niobate core medium are fully taken into account. Besides the channel width as the most tangible parameter, for X-cut configurations we look in particular at the waveguide orientation. Fig. 1(c) shows an example. Our simulations can rely on tight limits for effective indices (thin gray lines in Fig. 1(c)) as provided by analytical solutions for respective TFLN slabs [2]. Implications of the channel symmetry and of a non-diagonal core permittivity for the modal parity, and thus for the analysis procedures, are discussed. Fields can become pronouncedly hybrid. If excited with balanced relative amplitudes, the modes with the profiles in Fig. 1(d) effect a full periodic conversion between TM_{00}- and TE_{01}-like guided fields.

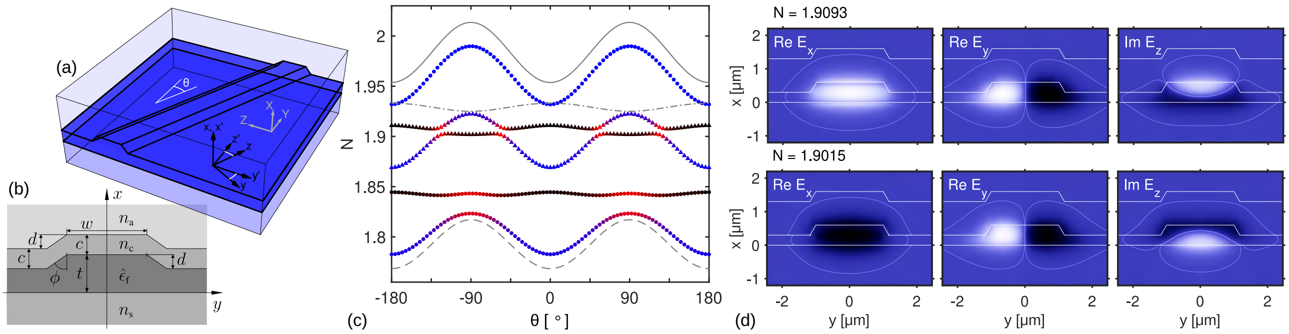


Figure 1: X-cut TFLN rib waveguide, schematic (a) and cross section (b); crystal, device, and channel coordinates $\{X, Y, Z\}$, $\{x', y', z'\}$, and $\{x, y, z\}$; (c): effective indices N versus channel angle θ, (d): electric profiles of hybrid first and second order guided modes for $\theta = 55.9°$, half-beat length $L_c = 100\,\mu$m for complete polarization conversion. Parameters: $t = 0.6\,\mu$m, $d = t/2$, $c = 1\,\mu$m, $w = 2\,\mu$m, $\phi = 30°$, material parameters for SiO_2 and TFLN media at wavelength $1.55\,\mu$m. Marker colors in (c) indicate polarization: blue: TE-like, black: TM-like, red: intermediate.

References

[1] JCMwave GmbH, Berlin, Germany; https://www.jcmwave.com.

[2] M. Hammer, H. Farheen, and J. Förstner. Guided modes of thin-film lithium niobate slabs. *Optics Continuum*, 3(11):2024–2043, 2024. TFLNS solver, online: https://www.siio.eu/tflns.html.

Towards 4-Dimensional Terahertz Near-Field Tomography

Abhishek Paul[1], Akash Dominic Thomas[1], Luana Olivieri[1], Luke Peters[1], Vittorio Cecconi[1], Juan Sebastian Totero Gongora[1], Alessia Pasquazi[1], Marco Peccianti[1*]

[1]*Emergent Photonics Research Centre, Department of Physics, Loughborough University, Loughborough LE11 3TU, United Kingdom*

*m.peccianti@lboro.ac.uk

We establish a theoretical and numerical methodology to extract hyperspectral information from deeply subwavelength features embedded in microscopic volumes, paving the way for full 4-dimensional THz near-field tomography.

Nonlinear Ghost Imaging (NGI) is a form of imaging suitable for implementing Time-Domain Terahertz imaging systems with resolution surpassing the diffraction limit. [1,2] NGI allows the 'refocusing' of an arbitrary plane in the near-field region via transformation of the detected field information, giving access to the depth information in microscopic volumes typical of many biological and technological settings. [3] Our approach (Fig 1) formalises the NGI to reconstruct the spectral response of two highly subwavelength spatial features (~λ/10) in a microscopic volume. We show how the effects of the first plane (green plot in Fig 1a) containing one feature is gradually decoupled from the reconstructed spectrum of the subwavelength feature on the second plane (blue plot in Fig 1c). Fig 1b shows the reconstruction ability for a case of two metallic letters on distinct planes. Fig 1e and Fig 1d compare the extracted image with and without deconvolving the spatio-temporal coupling induced by the near-field propagation. Our results achieving hyperspectral reconstruction of sparse microscopic 3D objects will be presented in detail.

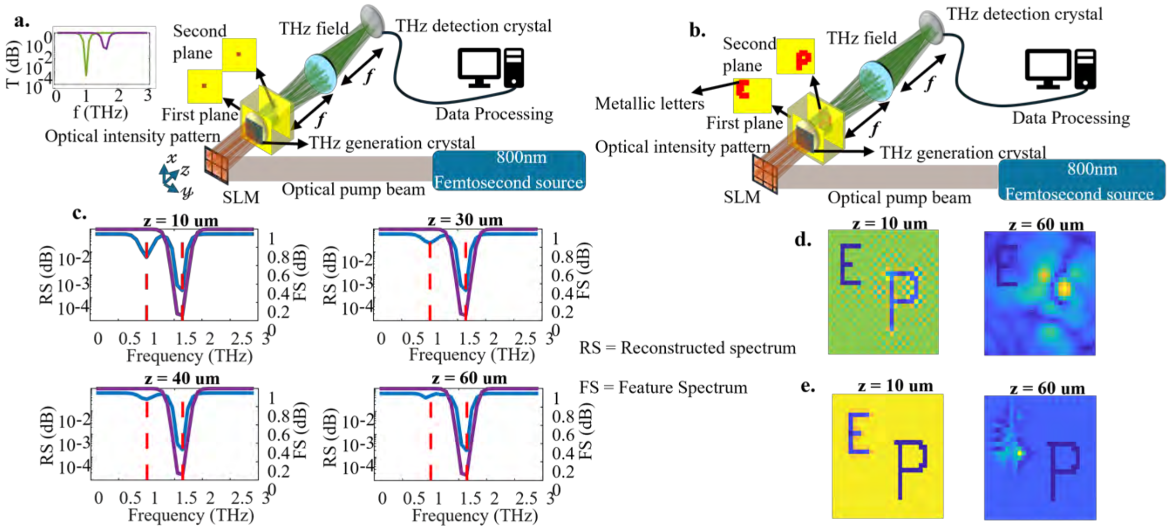


Fig. 1. (a), (b) Simulation models of our experimental setup. (c) Spectral reconstruction of subwavelength features embedded inside 3D volume. (d), (e) Spatial reconstruction of metallic masks inside 3D volume

References

[1] L. Olivieri, J. S. Totero Gongora, A. Pasquazi, M. Peccianti, *ACS Photonics* **2018**, *5*, 3379.
[2] L. Olivieri, J. S. Totero Gongora, L. Peters, V. Cecconi, A. Cutrona, J. Tunesi, R. Tucker, A. Pasquazi, M. Peccianti, *Optica* **2020**, *7*, 186.
[3] L. Olivieri, L. Peters, V. Cecconi, A. Cutrona, M. Rowley, J. S. Totero Gongora, A. Pasquazi, M. Peccianti, *ACS Photonics* **2023**, *10*, 1726.

Noise induced modulations in the pulse arrival times of passively mode-locked semiconductor lasers with optical feedback

L. Jaurigue [1,*], K. Lüdge [1],

[1] *Institut für Physik, Technische Universität Ilmenau, Ilmenau,Germany*
lina.jaurigue@tu-ilmenau.de

Optical feedback can be used to reduce the timing jitter of passively mode-locked lasers. However, long feedback delay times can lead to additional noise-induced modulation of the pulse arrival times, meaning that the typical methods of estimating the timing jitter are not applicable. These modulations can be suppressed with an appropriately chosen second feedback delay-line.

Introduction

For passively mode-locked semiconductor lasers to be useful as pulsed light sources, it is necessary to overcome the issue of their large timing-jitter. One approach is to use optical self-feedback [1, 2, 3]. The advantage of this technique is that it is passive. It has been shown that long feedback delay times that are resonant with the pulse period are ideal for timing-jitter reduction [2, 3]. However, noise-induced modulations of the pulse period become increasingly undamped for longer feedback delay-lines. We investigate how these modulations influence the timing-jitter and show that they can effectively be suppressed with the addition of an appropriately chosen second delay-line.

Results

Figure 1a shows the power spectrum of a simulated passively mode-locked semiconductor laser with resonant optical self-feedback (dark blue), using the model described in [3]. The feedback stabilisation of the fundamental frequency is evidenced by the narrow main peak, however the pronounced supermodes arise due to the weakly damped eigenmodes corresponding to the feedback delay time. The supermodes indicate noise-induced modulations of the pulse arrival times, which means that the common methods of estimating the timing-jitter can not be applied. This can be seen in Fig. 1b where the variance of the fluctuations of the pulse arrival times [3] is shown. In the absence of noise-induced modulations the long-term timing-jitter is given by the limit of this quantity for large roundtrip numbers. Adding a second feedback delay-line can suppress the supermodes [4] and the modulation of the timing fluctuations (Fig. 1a-b orange). Thereby the timing-jitter can be calulated and is closer to the limit in absence of the noise-induced modulations (Fig. 1b grey dash-dotted line).

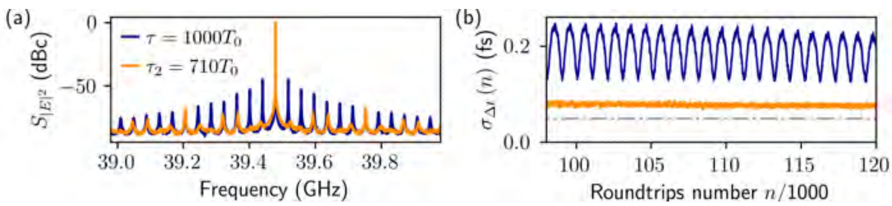


Fig. 1. (a) Power spectrum of a simulated passively mode-locked laser with optical self-feedback. (b) Variance of the pulse timing fluctuations as a function of the number of laser cavity roundtrips.

Conclusion

Ignoring the influence of noise-induced modulations, or supermodes, can lead to an incorrect esmitation of the timing-jitter of mode-locked lasers with self-feedback. Adding a second delay-line can alleviate this problem and improve the timing-jitter.

References

[1] O. Solgaard and K. Y. Lau. Optical feedback stabilization of the intensity oscillations in ultrahigh-frequency passively modelocked monolithic quantum-well lasers. *IEEE Photon. Technol. Lett.*, 5(11):1264, 1993.

[2] C. Otto, L. C. Jaurigue, E. Schöll, and K. Lüdge. Optimization of timing jitter reduction by optical feedback for a passively mode-locked laser. *IEEE Photonics J.*, 6(5):1501814, 2014.

[3] L. C. Jaurigue, A. S. Pimenov, D. Rachinskii, E. Schöll, K. Lüdge, and A. G. Vladimirov. Timing jitter of passively mode-locked semiconductor lasers subject to optical feedback; a semi-analytic approach. *Phys. Rev. A*, 92(5):053807, 2015.

[4] L. C. Jaurigue, E. Schöll, and K. Lüdge. Suppression of noise-induced modulations in multidelay systems. *Phys. Rev. Lett.*, 117:154101, October 2016.

Optimizing Illumination for Precise Multi-Parameter Estimation in Coherent Diffractive Imaging

D. Bouchet[1,2], J. Seifert[1,*], A. P. Mosk[1]

[1] *Nanophotonics, Debye Institute for Nanomaterials Science, Utrecht University, Netherlands*
[2] *Université Grenoble Alpes, CNRS, LIPhy, 38000 Grenoble, France*
j.seifert@uu.nl

We present a Fisher-information-based approach to optimize illumination in CDI, enabling subwavelength multi-parameter retrieval from intensity-only data. By controlling the incident field, we optimize the estimation precision for geometric parameters of a sparse object, even in single-shot acquisitions.

Introduction

Coherent diffractive imaging (CDI) measures diffraction intensities to characterize objects. With a sparse representation, one estimates only a few parameters, but shot noise sets fundamental precision limits. We use the Cramér-Rao lower bound to adapt the illumination fields for enhanced sensitivity.

Results

We form the Fisher information matrix and minimize the largest eigenvalue of its inverse, balancing photon flux across critical sample areas. By inverse-designing a zone plate (Fig. 1a), we amplify subtle intensity changes in the camera plane (Fig. 1c) relevant for high-accuracy parameter estimation.

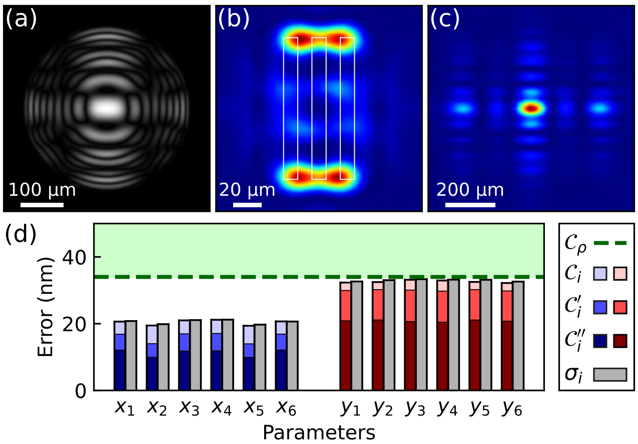


Fig. 1. Zone plate for CDI which distributes intensity to maximize parameter sensitivity. [1]

Conclusion

Shaping illumination in CDI reduces the error floor for multi-parameter retrieval. Our approach is straightforward to implement numerically and may advance the design of next-gen metrology tools.

References

[1] D. Bouchet, J. Seifert, and A. P. Mosk, "Optimizing illumination for precise multi-parameter estimations in coherent diffractive imaging," Opt. Lett. 46, 254–257 (2021).

Recovering Optical Fibre Transmission Matrices from Partial Measurements

C. Wilson (callum.wilson@nottingham.ac.uk), Y. Zheng, G. S. D. Gordon
Optics and Photonics Research Group, University of Nottingham, Nottingham NG7 2RD, UK

We present a physics-informed AI model that reconstructs the transmission matrix (TM) of bent multimode optical fibre from partial measurements. By learning an inverse mapping between the TM and bend radius from simulations, our model is robust enough to reduce measurements by 50% with TM error of only 5%.

Multimode optical fibres have been proposed for use as ultrathin (<0.1 mm diameter) endoscopes but suffer from image distortion due to unpredictable bending [1]. If the fibre's transmission matrix (TM) is known, these distortions can be removed to produce clear images [2]. However, measuring the full TM can be too time-consuming. Previous work has suggested that the effect of bending on the TM is predictable and could be used to infer the TM, but this is limited by the experimental lack of precise refractive index profile knowledge [3]. This insight has enabled, for example, fibre shape sensors that rely solely on MMF and speckle measurements [4]. We propose combining these two approaches by using a subset of rows of a TM (analogous to speckle measurements) to estimate the bending and then applying a forward physical model to estimate the full TM for imaging.

Our data consisted of 8000 training and 2000 test TMs, covering single bend radii from -0.85m to 0.85m. The TMs were generated using the transfer matrix method (TMM), which includes modelling the fibre as a sequence of infinitesimally small segments, and using spatial translation between segments to simulate the mode coupling induced by bending [5]. Partial input TMs were created by removing either 33.3% or 50% of the TM rows. The AI model we developed includes 7 layers such as patch splitting, dimensionality reduction, self-attention, and global pooling.

The mean absolute errors in predicting the radii were 0.26% and 0.65% for the 33.3% and 50% reduction scenarios respectively. The predicted radii were then passed to the TMM simulation to recover the full TM. The "TM error" (the difference between the predicted and actual TMs after compensating for global phase) was within 5% for bending radii larger than -0.2m and 0.17m when only 50% of the TM was available, and within 1% for radii larger than -0.33m and 0.24m.

Our model successfully recovers TMs for bend radii > 0.17m, however this is larger than the bend limits of some commercially available fibres [6], so more work is required. Future work will focus on enhancing accuracy for smaller bend radii, developing a model that can operate with further reduced input TMs, and incorporating data with multiple bends to enable complex TM recovery.

[1] Zheng, Y., Wright, T., Wen, Z., Yang, Q., & Gordon, G. S. D. (2023) 'Single-ended recovery of optical fiber transmission matrices using neural networks', Communications Physics, 6(306), p. 2.

[2] Kim, M., Choi, W., Choi, Y., Yoon, C., & Choi, W. (2015) 'Transmission matrix of a scattering medium and its applications in biophotonics', Optics Express, 23(10), pp. 12648 – 12668.

[3] Boonzajer Flaes, D. E., Stopka, J., Turtaev, S., de Boer, J. F., Tyc, T., Čižmár, T. (2018) 'Robustness of Light-Transport Processes to Bending Deformations in Graded-Index Multimode Waveguides', Physical Review Letters 120(233901), p. 3.

[4] Cao, C. G. L., Javot, B., Bhattarai, S., Bierig, K., Oreshnikov, I., Volchkov, V. V. (2024) 'Fiber-Optic Shape Sensing Using Neural Networks Operating on Multispecklegrams', IEEE Sensors Journal 24(17), pp. 27532 – 27540.

[5] Argyros, A., Lwin, R., Large, M. C. J. (2008) 'Bend loss in highly multimode fibres', Optics Express 16(23).

[6] Sumitomo Electric Lightwave (2024) *OM1 Multi-Mode 62.5µm Fiber Bundles*. Available at: https://sumitomoelectriclightwave.com/product/om1-multi-mode-62-5um-fiber-bundles/ (Accessed: 4 February 2025).

Photonic Reservoir Computing: From Principles to Neuromorphic Sensing

G. Anufriev[1], S.Phang[1], D.Furniss[1], A. Seddon[1], and M.Farries[1]

[1]*Midinfrared Photonics Group and George Green Institute for Electromagnetics Research, University of Nottingham, UK, NG7 2RD.*

* gleb.anufriev@nottingham.ac.uk

This presentation will describe the fundamental working principles of Photonic Reservoir Computing (PhRC). The simulation and experimental implementation of a neuromorphic chemical sensing system based on electro-optical reservoir computing (EORC) will be described.

Photonic Reservoir Computing as an approach to Artificial Intelligence

Recent developments in Artificial Intelligence (AI) have redefined the way humans work and live in the modern day. In many cases, AI is an integral part of recent innovations such as self-driving cars, virtual assistants and smart devices. Currently, all AI processing is done on cloud-servers. This is because AI algorithms and models require large amounts of computational power due to working on large datasets. This is something traditional microelectronic processors are unable to provide. Photonic Reservoir Computing is a unique approach, which combines an existing machine learning architecture and combines it with various advantages of optical systems – such as high speed, parallel processing and non-linear high-dimensional dynamics.

The neuromorphic sensing system

Recent advancements in computing and AI have also enabled advancements in the sensing and medical fields, where miniaturization is a common goal. This creates a demand for smaller, more portable devices. An example of this are smartwatches capable of recording heart rate, pulse and even blood oxygen levels. Inspired by this success, a novel application of PhRC to sensing applications is presented – the neuromorphic sensing system. This is based on combining the EORC approach with a cheap, commercially available pyroelectric sensor (Fig. 1) [1, 2]. Additionally, a chaotic stochastic cavity system approach will be presented as an approach to miniaturization of the neuromorphic sensing approach.

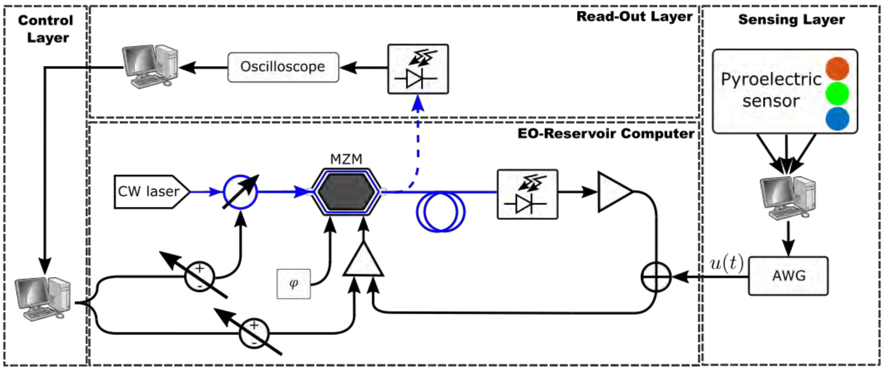


Fig. 1. Schematic illustration of the neuromorphic sensing system.

References

[1] G. Anufriev, D. Furniss, M.C. Farries, and S. Phang. *Non-spectroscopic sensing enabled by an electro-optical reservoir computer,* Optical Materials Express, 12(5), pp.1767-1783, 2022.

[2] G. Anufriev, D. Furniss, M.C. Farries, A.B. Seddon, and S. Phang. *An experimental demonstration of neuromorphic sensing of chemical species using electro-optical reservoir computing*, Scientific Reports, 14, 27915, 2024.

Adaptive wavelength sampling and machine learning in nanophotonics

F. Ferranti[1,*]

[1]*Brussels Photonics (B-PHOT), Department of Applied Physics and Photonics*
Vrije Universiteit Brussel and Flanders Make
Pleinlaan 2, 1050 Brussels, Belgium

*francesco.ferranti@vub.be

Using frequency-domain electromagnetic solvers to collect data samples requires a suitable sampling of the frequency (wavelength) variable to avoid undersampling and oversampling phenomena. An adaptive wavelength sampling approach will be presented.

Summary

Machine learning techniques [1-3] have been explored in the literature for modeling photonic devices, offering a means to accelerate the design process. These models rely on data samples obtained from electromagnetic simulations, which can be computationally expensive. Therefore, reducing the computational cost of data collection is a crucial consideration. When using frequency-domain electromagnetic solvers, a proper frequency (wavelength) sampling is essential to prevent undersampling or oversampling. An adaptive wavelength sampling technique to cope with this challenge will be presented.

Adaptive wavelength (frequency) sampling techniques [4-5] enable automatic sampling of the wavelength variable while also generating a model of the wavelength-domain system response across the entire wavelength range of interest. The proposed adaptive wavelength sampling technique can be applied to nanophotonic applications and responses as scattering parameters. Using local rational models, local refinement of sub-intervals within the wavelength range and suitability for parallel computing can be exploited. This approach samples the wavelength variable while maintaining a target error threshold for the final model obtained after the procedure. As a result, it significantly reduces the computational effort required when using frequency-domain electromagnetic solvers to collect data samples for building machine learning models.

References

[1] J. Peurifoy, et al., "Nanophotonic particle simulation and inverse design using artificial neural networks,", Science Advance, vol. 4, no. 6, eaar4206, June 2018.
[2] C. Zhang, et al., "Broadband achromatic metalens design based on predictive neural network and particle swarm optimization-genetic algorithm", New Journal of Physics, vol. 25, Oct. 2023.
[3] F. Ferranti, "Feature-based machine learning for the efficient design of nanophotonic structures," Photonics and Nanostructures - Fundamentals and Applications, vol 52, Dec. 2022.
[4] D. Peumans, S. De Keersmaeker, C. Busschots, Y. Rolain, F. Ferranti, "Adaptive frequency sampling based on local rational modeling for microwave electromagnetic simulations", IEEE Trans. on Microwave Theory and Techniques, vol. 72, no. 8, pp. 4568-4578, 2024.
[5] F. Ferranti, "Wavelength-dependent responses and machine learning in nanophotonics modeling", SPIE Photonics Europe 2024, Strasbourg, France, April 2024.

Multi-objective optimization of a large-area silicon grating coupler

Gervasio Adriano D'ANZIERI*, Daniele MELATI

Centre de Nanosciences et de Nanotechnologies, Université Paris-Saclay, CNRS, 91120 Palaiseau, France

*gervasio-adriano.danzieri@universite-paris-saclay.fr

Introduction

Grating couplers are fundamental devices in silicon photonics used to couple light form optical waveguides to fibers and the free space. Several figures of merit must be considered at the same time [1]. We present a computational approach based on a multi-objective genetic algorithm for the design of a large-area silicon grating coupler for free space optical communications.

Results

We optimized a grating coupler with 5 design parameters as shown in Fig.1.a. Each period is composed of 4 lateral features with lengths L_1 - L_4: this structure allows vertical light scattering while reducing back-reflections [2]. Etch depth is the fifth design parameter. Shallow etching allows designing a weak grating that scatters light over a length of 50 µm. Such a large size allows to obtain small angular dispersion in the far field, which is fundamental for large optical phased array with increased directionality. Four objectives have been optimized simultaneously: we aimed at maximizing the upward scattered power Tup while minimizing the scattering angle Θ, the angular dispersion δΘ and the back-propagating power Tb. A non-dominated sorting genetic algorithm (NSGA II) [3] was employed to solve this multi-objective optimization problem. Genetic algorithms minimize multiple objectives and overcome the difficulty of finding global minima.

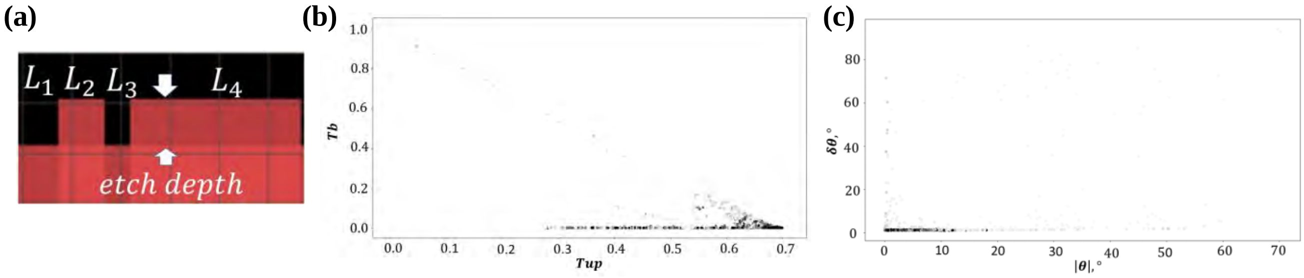


Fig. 1.(a) Representation of the grating period **.** Evolution of the **(b)** Tup –Tb space and **(c)** the Θ – δΘ space during optimization

2D cuts of the 4-dimensional Pareto–front, i.e. the group of best devices obtained at the end of the optimization, are shown in Fig.1.b and Fig.1.c. The evolution of the algorithm is tracked generation by generation through a grey scale: one can notice that starting from the earlier generations, represented with lighter dots, the optimization converges toward high Tup, small Tb, small Θ and small δΘ values. As an example, the selected final device shows Tup = 65.82%, Tb = 2.48%, Θ = -4.44° and δΘ = 1.26°**,** demonstrating the effectiveness of genetic algorithms for the multi-objective design of highly – performing grating couplers.

References

[1] Lirong Cheng et al.,*"Grating Couplers on Silicon Photonics: Design Principles, Emerging Trends and Practical Issues"*. In: *Micromachines* 11.7 (2020)

[2] T. Watanabe et al.,*"Perpendicular Grating Coupler Based on Blazed Antiback-Reflection Structure"* in *Journal of LightWave Technology,* vol.35, no.21

[3] N. Srinivas and Kalyanmoy Deb. "*Multiobjective Function Optimization Using Nondominated Sorting Genetic Algorithms*". In: 2 (June 2000)

Inverse metalens design and simulation

D. Huynh[1*], J. Niegemann[2], H.-H. Cheng[3], T. Leportier[2], F. Duque-Gomez[2], A. Reid[2]
[1]ANSYS Germany GmbH, Germany
[2]ANSYS Canada Ltd., Canada
[3]ANSYS Japan K.K., Japan
*dan-nha.huynh@ansys.com

Recent years have seen increased interest in metalenses, as they facilitate the tailoring of the light response at the nanoscale. As a result, they allow for the creation of imaging systems that are not only more compact but also lighter than their diffractive counterparts. A prime example where this is highly desired is in augmented reality (AR) and virtual reality (VR) headsets. Here, we present the inverse design of metalenses via adjoint optimization.

Method

We pre-calculate a database of the individual meta-atom's near-field response based on their geometry and excitation using rigorous coupled-wave analysis (RCWA). The individual responses are then assembled to form the overall metalens response. Through several iterations, we obtain the metalens design which best matches our desired target. Depending on the desired length scale, computational effort, and accuracy, the design can then be combined with different solvers. For the most accurate results, we use FDTD. A combination of near-field assembly with local periodic approximation and near-to-farfield transformation is used for mid-range applications. For macroscopic distances, propagating the metasurface response via ray-tracing proves to be the fastest method.

Design results

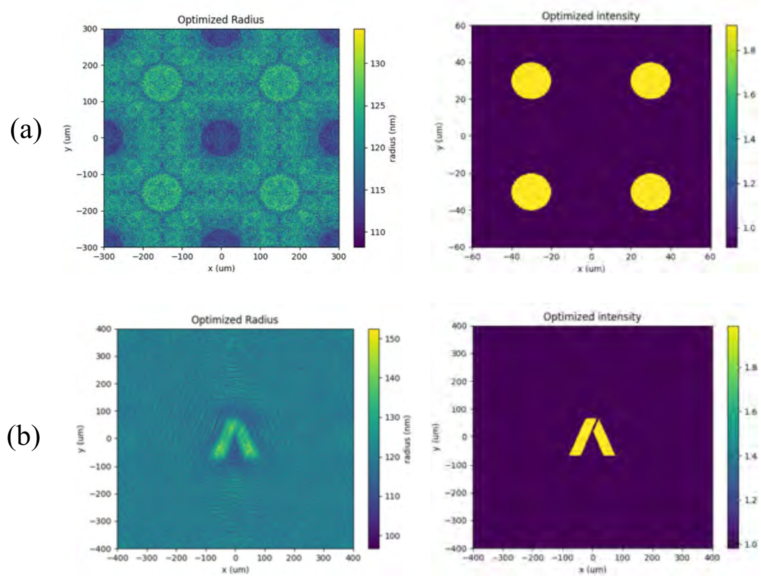


Fig. 1. Optimization results for pillar shaped meta-atoms: The optimized radius distribution and intensity is given for (a) a periodic dot-array target and (b) the stylized letter "A".

Inverse Design of 3D Nanophotonic Devices feasible for Additive Manufacturing

O. Kuster [1,*], Y. Augenstein [2], R. Narváez Hernández [1], C. Rockstuhl [1,3], T. J. Sturges [1]

[1] *Institute of Theoretical Solid State Physics, Karlsruhe Institute of Technology, Karlsruhe , Germany*
[2] *Flexcompute Inc., Belmont MA, USA*
[3] *Institute of Nanotechnology, Karlsruhe Institute of Technology, Karlsruhe, Germany*
oliver.kuster@kit.edu

We present a method to design nanophotonic structures which adhere to the fabrication constraints of 3D additive manufacturing. By using an auxiliary heat solver, we can enforce structural integrity in the design process. Topology optimization then enables the free form design of fabricable nanophotonic structures.

Introduction

3D additive manufacturing allows for the design of intricate nanophotonic devices with sub-wavelength feature sizes. With every voxel being a degree of freedom, complex and highly efficient designs can be realized. Gradient-based optimization in particular offers an efficient free form design approach to these strucutres. However, free form design in 3D introduces additional complexities to the design process. Not only do the usual fabrication constraints such as minimum feature size have to be considered, but also the structural integrity of the final designs. We need to make sure, that no free-floating parts appear, that the structure does not collapse on itself and that no cavities are formed which might trap the photoresist. To do so, we combine our electromagnetic simulations with an auxiliary heat diffusion solver to ensure the connectivity of material and void. By using the material (or the void) as heat sources and boundaries as heat sinks, we are able to penalize non-connected parts in our optimization process. This leads to a multi-objective optimization problem, in which we maximize the optical performance while simultaneously minimizing the total temperature in our structure, which leads to structural connectivity.

Results

We use our method to design two different devices. First, we present a focusing device. Without an auxiliary heat solver, the optimization will result in a free floating design with cavities. By enforcing the structural integrity in the design process, we not only find a device which is suitable for fabrication, but also a device which performs almost as well as a free floating one.
Our second device is a waveguide junction. We want to connect two incoming waveguides to two outgoing waveguides, which are rotated by $90°$ to the incoming waveguides. Without the heat solver, free floating artifacts will appear in the final design. By using an auxiliary heat solver, we not only remove these artifacts, we also significantly reduce the required material, with minimal loss in the optical performance.

Conclusion

In our work, we present a robust multi-objective optimization method to ensure structural integrity in the design process of nanophotonic devices. Using an auxiliary heat solver not only ensures the structural connectivity of the material and the void, but also preserves the optical functionalities with minimal trade-offs. The resulting designs serve as digital blueprints for fabrication using 3D additive manufacturing, paving the way for enabling practical and efficient devices for real-world applications.

OWTNM

31st International Workshop on Optical Wave & Waveguide Theory and Numerical Modelling

8–10 April 2025

Nottingham Trent University, Nottingham, UK

IOP Institute of Physics