Project title: „On-chip Laser-written Photonic Circuits for Classical and Quantum Applications."

Project number: K266/2019

Executive Summary

The LAPTON project has been funded in the frame of the Leibniz Collaborative Excellence program. The main goal of the LAPTON research program is to manufacture optical chips with few-cycle laser pulses produced from an optical parametric amplifier. Such a class of laser source is, at the present time, essentially disseminated in the scientific community but rarely used in an industrial context. The optical chips envisioned in the frame of this research proposal are dedicated to enhance portable sensing capabilities, with a particular focus on refractive index domains relevant to biological applications, a field experiencing significant growth, accelerated by recent pandemic-related challenges.

The scientific and technical results of the project include the demonstration of direct photoinscription of low-loss, waveguiding structures at optical frequencies (ca. 0.15 dB/mm at 633 nm) and their applications to surface plasmon resonance sensing (SPR sensing). The platform achieves a sensitivity greater than 3000 nm/RIU in the 1.36–1.40 refractive index range, a domain of high relevance for biological sensing. On the theoretical aspects, this project has enabled the comprehensive understanding and the development of appropriate methodologies to analyze non-Hermitian systems. These theoretical efforts have allowed the design of integrated-optical devices with novel functionalities. Secondary outcomes achieved include the design and implementation of a method able to evaluate propagation losses in short waveguiding structures. The completion of the LAPTON project has been an invaluable opportunity to gain a precious experience in the domain of non-conventional microprocessing. In particular, controlling the three-dimensional sample trajectory over distances of several millimeters is more challenging than expected and requires an ongoing work with our industrial partners.

An aspect of the project which has not led to a solution is the fabrication of the electro-optic polymers. This topic has provided the opportunity to expand our collaborations with other institutes such as the IHP - Leibniz-Institute for High Performance Microelectronics Thanks to this collaboration we could design, fabricate (a first batch) and start to evaluate a low-index electro-optic polymer. Unfortunately, this activity had to be interrupted because of a long lasting rupture of a specific chemical agent. Moreover, the very late delivery of strategic components due to the global pandemic (in particular the difficulty to obtain quantum detectors) has prevented us to be conclusive on the non-classical applications of these chips.

Despite these peculiar conditions, we have adhered to the cost and time planing. In addition, the extra support of Max-Born-Institute has allowed to expand the scope of our work. For instance this support has enabled the direct photoinscription of surface waveguides of arbitrary lengths.

As a result of our research effort, several peer-reviewed articles have been published or are currently in production. Among these, we have published a paper illustrating how waveguide systems with tunable coupling constants such as the ones investigated in this proposal can be used for tayloring the nonclassical properties of light states https://doi.org/10.1364/JOSAB.521859. On the experimental achievements, we have published an important article demonstrated that the optical chips fabricated during the LAPTON project can serve as versatile microoptical sensing platform for direct refractive index as well as SPR sensing. A reproduction of this peer reviewed article (currently in press) can be found at https://doi.org/10.1364/opticaopen.28589771.v1 .

1. Achievement of objectives and milestones

This project is designed around three objectives. Objective 1 deals with the design and manufacturing of reconfigurable optical chips, Objective 2 deals with the demonstration of exceptional sensing in the classical regime and Objective 3 aims at studying high-order exceptional points.

Implementation of important objectives and milestones:
Objective 1: design and manufacturing of reconfigurable optical chips. Our efforts to complete Objective 1 resulted in the implementation of a few-cycle laser source able to deliver sub-10 fs, 10 µJ pulses at 800 nm, at a repetition rate of 400 kHz (with the help of Dr. Federico Furch, MBI). We have also demonstrated the direct laser writing of passive waveguide structures. To do so, we have designed, fabricated and tested a homemade focusing unit based on reflective optics. Our customized device includes a focal point located under the protective housing. This unique feature enables to process longitudinally samples of arbitrary lengths.

Objective 2: demonstration of exceptional sensing in the classical regime. The completion of Objectives 2 was hampered by the unpredictable breakdown of the supply chain after the global pandemic (see 2. 'Activities and Obstacles'). However, as an important milestone, we have demonstrated sensing with a dissipative micro-optical system based on surface plasmon resonances.

Objective 3: study of high-order exceptional points in the quantum regime. An analytical formalism for small numbers of waveguides (but arbitrary photon numbers) has been developed. Such a framework expands the current capabilities by enabling the analysis of (i) asymmetric microsystems and (ii) configurations involving more than two photons.

Most important points of the final financial plan compared to the original planning:
There are no major discrepancies between the original plan and the final financial plan.

2. Activities and obstacles

Activities The experimental aspects of the LAPTON project have included the realization of a workstation enabling the photoinscription of optical chips on the surface of fused silica. This workstation comprises an OPCPA system able to deliver sub-10 fs pulses, a homemade focusing unit (designed and fabricated at MBI), sample motion control and the possibility to monitor the photoinscription process in live phase-contrast microscopy. In addition to the microchip irradiation, MBI carried out the functionalization of these optical chips in view of their application to sensing. Finally, these chips were used for refractive index sensing as well as surface plasmon resonance sensing in refractive index ranges from 1.33-1.40, a highly relevant domain for bio-sensing.
Measurements on the surface waveguides were carried out at Fraunhofer IZM, where the equipment for insertion loss measurements was used. Additionally, measurements of the mode field diameters were performed to determine the wavelength at which the surface waveguides integrated into glass are single-mode and to calculate the coupling losses included in the insertion loss measurements. Due to the fact that the quality of the waveguide end-face has a major impact on the loss measurements, the glass chips were cut and polished at Fraunhofer IZM. These extensive measurements on numerous waveguides were necessary to gain a better understanding of laser writing and to adapt the writing parameters. There was also strong collaboration between Fraunhofer IZM and MBI to build a lens-based measuring setup for the waveguides at MBI.
The theoretical efforts within the LAPTON project have been aimed at obtaining a comprehensive understanding of the propagation of quantum light in waveguiding systems, notably regarding the potential of multi-photon integrated optical protocols. This includes the design of integrated-optical devices with novel functionalities and the development of appropriate methodologies to analyze non-Hermitian systems. In a first work [P1], the effect of different propagation constants in waveguide couplers (either as a result of fabrication tolerances or intentionally created) have been analyzed and the effect of detuning on the mean photon number and photon number distributions for experimentally feasible inputs, notably so-called photon catalysis schemes, has been determined. Subsequently, an advanced design based on a waveguide trimer has been proposed and analyzed [P2]. Owing to the highly interesting

characteristics of the (Hermitian) device proposed in [P2], the work has been extended to the non-Hermitian situation. Very loosely speaking, considering a lossy waveguide removes photons from the two-mode input state of the outer waveguides, similar to what a PNR-detector would do. In addition, the loss can be engineered, and this allows for the realization of a dissipation-engineered distillation of quantum coherence from incoherent sources via control of the resulting zero-eigenvalue modes [P3]. In addition, an analytical formalism for small numbers of waveguides (but arbitrary photon numbers) has been developed [P4]. When applied to a waveguide coupling system, this approach extends previous analytical works by other authors that have been limited to symmetric systems (Opt. Express 18, 6241 (2010)) or two photons (Opt. Lett. 48, 5435 (2023)).

Obstacles These obstacles were invoked to obtain a 6 Months prolongation of the project.
<u>Personal recruitment (Humboldt University)</u> The PhD student recruited by the HU could only start his position in August 2021 due to the international travel ban (student coming from India).
<u>Rupture in the supply chain industry (MBI)</u> The few-cycle laser source ceased to function in July 2021 (laser pump diode expired). The laser chain could only be brought back to full service by July 2022. Second, some chemical products could not be delivered. The synthesis of an electro-optic polymer relied on using disperse red 1. The purchase was initiated in 2021 and canceled near the end of 2022. The delivery of equipment has equally been impacted. For instance, the photon detectors could only be delivered in May 2023, one year after the order. Also, delivery times were systematically underestimated, which complicated the project's organization.
<u>Restricted premises access during the pandemic (MBI)</u> The number of MBI employees allowed to be simultaneously present in division A was reduced to about 50%. Home office was mandatory for the rest of the time, preventing experimental work.
Unfortunately, the impossibility to obtain the chemical supplies needed to produce our custom electro-optic polymer has persisted until the end of the project, because high volume customers were prioritized (private communication from supplier). As a consequence, we could not produce the electro-optic polymer, a crucial step on our way to tunable optical chips. Instead, we have adapted and pursued an approach based on passive losses (via surface plasmon resonance coupling).

3. Results and successes

At MBI, Laura Rammelt was appointed as a PhD candidate. She is currently finalizing her dissertation. Her personal investment enabled to publish one peer-reviewd journal article (in press) and one peer-reviewed book chapter. Moreover, she received the Young Researcher Award at the E-MRS Spring Meeting 2023 in Strasbourg, France.
At Humboldt University, Ananga Mohan Datta has joined the LAPTON team as a PhD student and successfully defended his dissertation in December 2024. From the research reported in this thesis, two publications have emerged [P1,P2] and a third publication [P3] is in preparation. In addition, a follow-up publicaiton is presently being conceived.
Similarly, Vinzenz Zimmermann has joined the LAPTON team and has complete his Master thesis on the theory of dissipation-assisted quantum state distillation in waveguiding systems. A corresponding publication is in preparation [P4].

Publications:
Book chapters (peer-reviewed): [P1] O. Ghafur, P. Jürgens, L. Rammelt, A. Mermillod-Blondin, *Ultrafast Meets Ultrasmall: Where Are the Limits of Ultrafast Waveguide Writing?*. In: Stoian, R., Bonse, J. (eds) Ultrafast Laser Nanostructuring. Springer Series in Optical Sciences, vol 239. Springer, (2023)
Articles (peer-reviewed): [P2] L. Rammelt, F.J. Furch, D. Engel, A. Mermillod-Blondin, *Refractive index sensing platform based on surface waveguides photoinscribed with few-cycle laser pulses, OMEX (2025) (in press)*

[P3] A.M. Datta, K. Busch, and A. Perez-Leija, *Tailoring the nonclassicality of light states via mode detuning in waveguide beam splitters*, J. Opt. Soc. Am. B **41**, 1557 (2024), https://doi.org/10.1364/JOSAB.521859
[P4] A.M. Datta, K. Busch, and A. Perez-Leija, *Odd and even photon-subtracted two-mode squeezed vacuum states*, arXiv:2412.07397, submitted to Phys. Rev. A, https://arxiv.org/abs/2412.07397
[P5] V. Zimmermann, A. Hashemi, A. Blanco-Redondo, K. Busch, and A. Perez-Leija, *Dissipation-assisted topological state distillation*, in preparation
[P6] A.M. Datta, A. Perez-Leija, F. Intravaia, R. El-Ganainy, and K. Busch, *Theoretical framework for the quantum dynamics in a non-Hermitian waveguide coupler*, in preparation

International conferences:
CLEO US 2023, San Jose, California, USA. Presenter: Laura Rammelt, PhD candidate.
E-MRS Spring Meeting 2023, Strasbourg, France. Presenter: Laura Rammelt, PhD candidate. Recipient of the Young Researcher Award.
Photonics West 2024, San-Francisco, USA. Presenter: Alexandre Mermillod-Blondin

Completed theses and dissertations:
[T1] V. Zimmermann, *Destillation of classical and quantum optical coherence using dissipative photonic lattices*, Master thesis, August 2023
[T2] A.M. Datta, *Tailoring non-classical light states via conditional measurements and integrated coupled photonics systems*, Dissertation, February 2025. https://doi.org/10.18452/32567

Dissertation in progress:
L. Rammelt, '*Towards fabrication of a non-Hermitian laser-written waveguide system exhibiting an exceptional point*', Defense date to be determined.

4. Equal opportunities, career development and internationalisation

At MBI, the recruitement is co-supervised by the Equal Opportunity Officer (formerly Fr. Rinck, replaced by Fr. Jeremias after her retirement). Three candidates were interviewed and we decided to offer the position to Fr. Rammelt. Fr. Rammelt decided to pursue her career in Aarhus, Denmark, where she is serving as the Center Manager at the Interdisciplinary Nanoscience Center at Aarhus University.
The PhD student position at Humboldt University has been advertised internationally and six candidates have been interviewed. Eventually, the position has been offered to Ananga Mohan Datta who completed his MSc degree at Banaras Hindu University, West Bengal, India. He has presented the results of the LAPTON project at several international conferences and workshops and successfully defended his PhD thesis in December 2024. Based on this, he has been offered and has started, effective May 1st, 2025, a postdoctoral research fellow position in the group of Prof. Kae Nemoto at the Center for Quantum Technologies, Okinawa Institute of Science and Technology, Japan.

5. Structures and collaboration

Structure of collaboration: The most notable deviation from our initial plan has been on the relationship MBI/IZM. Pigtailing of optical fibers proved challenging to carry out, because of technical reasons: the cross section of the laser-induced waveguides and optical fibers were too dissimilar to obtain relevant injection conditions. As a response, we have intensified the collaboration with IZM and decided to co-develop a method to characterize propagation losses directly at MBI, with the help of IZM expertize.
Changes in the governance of the project: During the funding period, Dr. Armando Perez-Leija has moved from the Max-Born-Institute to the University of Central Florida (Orlando, FL, U.S.A.).

Also, Dr. Gunnar Bötger (IZM) delegated the project to Dr. Julian Schwietering because of a professional evolution within IZM.
New partners: the synthesis of a new electro-optic polymer has motivated the initiation of an additional collaboration with Dr. P. Heise (Dr. Steglich at that time).

6. Quality assurance

At the Max Born Institute, the rules of good scientific practice are adhered to in the spirit of the recommendations of the Deutsche Forschungsgemeinschaft (see https://wissenschaftliche-integritaet.de/en/code-of-conduct/). Specifically, all employees of the MBI are obliged to act in accordance with the MBI Service Instructions for Good Scientific Practice (available at https://mbi-berlin.de/). Compliance with these rules is a contractual obligation at the Max Born Institute. For existing contracts, employees are obliged to do so by written declaration.
In the case of suspected violations of the rules of good scientific practice, the corresponding rules of procedure which apply are the rules in practice at Forschungsverbund Berlin e.V. (available at https://mbi-berlin.de/).
The policy at MBI is to favor open access publications. In the frame of the LAPTON project, we could publish all accepted articles in journals supporting open access.

7. Additional resources

At the center of this proposal, MBI has supported this project with additional resources.
Personal:

- Dr Federico Furch, senior scientist, to set-up the few-cycle laser pulse (3 PM.)
- Dr Dieter Engel, senior scientist, for the sample preparation (coating, polishing, profilometry). Commitment: 2 PM
- Akin Ünal, senior technician, maintenance of the few-cycle laser source (3 PM).
- Tobias Witting, senior scientist, pulse characterization and source engineering, (1 PM).

Equipment:

- Pump laser: MBI provided the main pump laser (used) for the few-cycle pulse source. Cost: ca. 120 000 € (price for an equivalent system, used, estimate obtained by comparison with comparable offers)
- Air-beared micro-positioner and controller: ca 16 000 €
- Consumables: ca 5000 €/year

8. Outlook

The completion of the LAPTON project has enabled to improve technical and technical know-how as well as our deep understanding of light propagation in coupled micro-optical systems. Experimentally, the research efforts generated by the LAPTON proposal have emphasized that the direct photoinscription of surface waveguides still needs improvements. First, a significant improvement would be the control of the waveguide's ellipticity, possibly by pre-shaping the spatial profile of the few-cycle pulse. A circular waveguide cross section would facilitate more efficient light injection into the structure and open up new fields of applications such as all-optical magnetic switching. Second, the production of curved structures is more complex than initially anticipated because of the irradiation scheme at grazing incidence. We are still in discussion with Physike Instrumente GmbH regarding a possible improvement of Hexapod to stage communication in the future. Finally, commercially available, low-index electro-optical polymers are sorely needed. These are usually available at refractive indices significantly higher than the refractive index of fused silica. On the theoretical side, ongoing work includes the application of the framework quantum-enhanced (developed in the frame of the present project) to exceptional-point sensors and the creation of specific non-Gaussian states (i.e. photon-added coherent states) for continuous-variable quantum technologies.