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# MFEs 2022-2023

# OPÉRA-photonique
# École polytechnique de Bruxelles

Les sujets de Mémoires de fin d'études suivants sont proposés, à titre principal, aux étudiants de 2e année du master Ingénieur civil physicien, Ingénieur civil électricien (spécialisation télécommunications) ou aux étudiants de 2$^{e}$ année du master en Sciences physiques.

Les thèmes proposés s'intègrent dans la palette des activités de recherche développées par le groupe **Photonique** du Service OPERA.

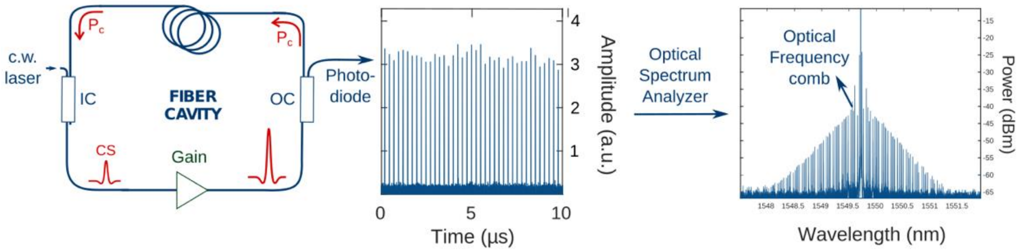
# Frequency comb sources in resonators with gain and external driving

Nature of work: experimental, numerical and theoretical.
Students: master in engineering physics, master in physics

Key words: optical cavities; nonlinear dynamics; frequency combs; dissipative structures; LIDAR.

## CONTEXT

Optical resonators allow for a strong increase of nonlinear interactions thanks to the build-up of an intra-cavity high-power beam. This can be harnessed for generating ultra-stable trains of ultra-short optical pulses, either in mode-locked lasers or in passive cavities with an injected signal. These stable optical pulse trains, also known as optical frequency combs, have found numerous applications in ultra-high precision optical metrology of time, frequencies or velocities to cite a few [1,2]. However, the difficulty to build low-loss fibre cavities makes optically driven fibre systems less competitive for applications than integrated passive resonators, or mode-locked lasers.
At OPERA-photonics, we have recently unlocked this limitation by demonstrating the existence of cavity solitons in resonators with a carefully designed gain section, allowing for the formation of frequency combs with unprecedented characteristics [3,4].



## GOAL

Various master theses (theoretical, experimental or both) subjects are possible on this topic, from applied to fundamental science. It includes:

- Absolute distance measurements, towards a new type of LiDAR system.
- Fundamental limitations of quantum noise on frequency comb stability in active cavities.
- Theoretical study of the dynamics of frequency comb generation in nonlinear active resonators based on semiconductor optical amplifiers.

More directions are possible depending on the student's interest. Feel free to contact us!

## REFERENCES

[1] *Optical frequency metrology*, T. Udem, R. Holzwarth, and T.W. Hänsch, Nature **416**, 233 (2002)
[2] 20 years of developments in optical frequency comb technology and applications, T. Fotier and E. Baumann, Communications Physics **2**, 153 (2019) https://doi.org/10.1038/s42005-019-0249-y
[3] *Temporal Solitons in a Coherently Driven Active Resonator*, N. Englebert, C. Mas-Arabi, P. Parra-Rivas, S.-P. Gorza and F. Leo, Nature Photonics **15**, 536 (2021) https://arxiv.org/abs/2007.15630
[4] Parametrically driven Kerr cavity solitons, N. Englebert *et al.*, Nature Photonics **15**, 857 (2021). https://arxiv.org/abs/2101.07784.

## CONTACT

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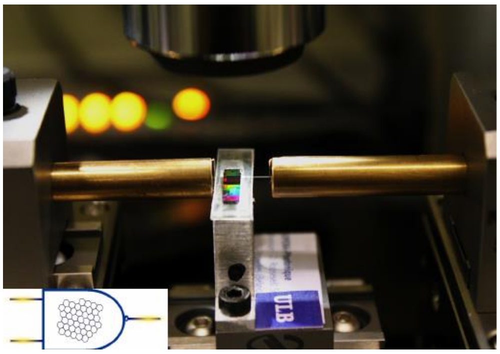
# Modelling and characterization of waveguides coated with graphene or other 2D materials

Information : Pascal Kockaert
Student background : engineering physics or physics
Type of work : theoretical (analytical and numerical), experimental (optional)
Keywords : integrated photonic circuits, graphene, 2D materials, numerical modelling

## MOTIVATION



2D materials, such as graphene, MoS2, BN, are extensively studied for their fascinating intrinsic properties, but also to modify (optical) waveguide properties. Different kinds of 2D materials can be stacked on top of a thicker waveguide, with almost no modification of its total thickness. Numerical tools used to simulate those structures are usually introducing an effective permittivity, which is not well defined for 2D material with a thickness lower than 1nm. Although this question is still controversial, most people agree that a better modelling should be based on surface currents.

## OBJECTIVES

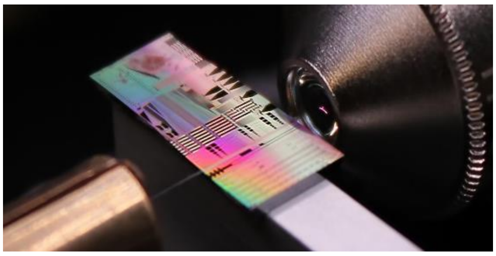
By means of a perturbative approach, it is possible to extract effective parameters describing the waveguide with a 2D material on top, from the exact modelling involving surface currents.

This approach has been implemented in the frame of a first master thesis on this topic. This allows to overcome a limitation of existing simulation tools that are based on meshes. Indeed, limiting the number of points in the mesh requires to model the 2D material as a thicker layer, which ensures that it contains more points from the mesh but also introduces a strong approximation through the use of an effective permittivity.

In this first approach, it was possible to include the (non isotropic) tensor nature of graphene (or 2D material), as well as dispersion (non instantaneity) and the exact mode profile including longitudinal components. The next step is to implement a nonlinear response, keeping the anisotropic and dispersive features.

The software will be preferably developed in the efficient and user-friendly language julia (https://julialang.org/), with possible parts written in python. Based on the existing code, that makes use of open source mode solvers, the student will develop a software allowing to model photonic integrated structures, with increasing complexity.

## NATURE OF THE WORK



As a first theoretical step, a simple waveguiding structure with a nonlinear 2D material on top will be modeled with the help of the perturbative approach. Simulation results will be compared to experimental results taken from the litterature. In a second time, it will be possible to either (i) take measurements on waveguides with graphene on top, available in our laboratory ; (ii) study the use of the previous method to more complex structures such as a nonlinear coupler or multiple layer structures ; (iii) optionally, compare numerical results to experimental ones obtained in step (ii).

## REFERENCES

- Opt. Lett. 41, 3281-3284 (2016) [https://arxiv.org/pdf/1607.00911]
- Phys. Rev. B 96, 235422 (2017) [https://arxiv.org/pdf/1707.09507]
- Adv. Mat. 29, 1606128 (2017) [https://doi.org/10.1002/adma.201606128]

## CONTACT

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## An instantly tunable pulsed-laser source

Nature du travail : travail de conception et expérimental
Étudiants concernés : ingénieur civil physicien, master en science physique
Mots clés :

### CONTEXT

Lasers sources are extremely diverse. Lasers can deliver radiation ranging from nW to TW power, CW to fs duration, UV to far-IR wavelengths, at costs ranging from c€ to B€. Optical parametric oscillators distinguish themselves by their typically high wavelength tuning range, modelocked lasers provide ultra short pulses and laser diodes are typically cheap. OPO are typically slow at changing the wavelength of the radiation they emit but laser diodes can do so at the sub-ns timescale [1]. This feature (changing the wavelength quickly) is becoming highly desirable for applications ranging from optical packet switching in data communication to all-optical control in quantum optics.

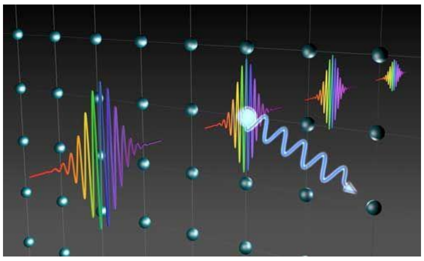
Illustration of a polychromatic light pulse

### GOAL

The goal of this project is to build a quickly (sub 100 ps) tunable source using a modelocked fiber laser and time to frequency mapping (similar to [2]) and to characterize it extensively.
This laser is eventually intended to be used in a quantum optics so that extra care will be given in order to have the output power of the laser fixed (within 1%) for any chosen wavelength of operation. This power balancing will be implemented using a spatial light modulator (SLM) acting in tandem with a diffraction grating to form an equalization filter (spectrally tunable attenuator). The work can possibly be split in two projects.

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### REFERENCES

[1] S. Dhoore, G. Roelkens, G. Morthier, Fast wavelength-tunable lasers on silicon, IEEE Journal on Selected Topics in Quantum Electronics (invited), 25(6), p.1500908
[2] Strickland, D., & Mourou, G. (1985). Compression of amplified chirped optical pulses. Optics communications, 56(3), 219-221.

## Generating photon triplets using Silicon nitride nanophotonics

Nature du travail : travail de conception
Étudiants concernés : ingénieur civil physicien, master en science physique
Mots clés :

### CONTEXT

Photon triplets[1] are very special states of light made of exactly 3 photons. They can serve as a resource in optical quantum computing. Unfortunately, those states are also very hard to generate. They require a nonlinear interaction that is extremely weak. In the simplest form, one photon has to spontaneously decay in 3 new photons having one third of the energy each. Unfortunately, the weak interaction is not even the biggest problem (it can partly be solved by increasing the number of initial photons). The biggest problems are twofold:
- For an efficient interaction, the phase matching (momentum conservation) condition has to be met which demands special efforts.
- Other more efficient nonlinear process might bury the few triplets generated under a wide photon noise.

### GOAL

The goals are multiple:
- Get familiar with the literature [1,2] around triplet generation as few attempts have been made in the past decade.
- Quantify the requirements for triplet generation in the case where phase matching is reaching
- Quantify the benefits of Bragg grating structures for reaching this phase matching

In the case of an exceptionally fast theoretical study, an experiment can possibly be realized to verify some of the obtained results.

### CONTACT

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### REFERENCES

[1] Bencheikh, K., Gravier, F., Douady, J., Levenson, A., & Boulanger, B. (2007). Triple photons: a challenge in nonlinear and quantum optics. Comptes Rendus Physique, 8(2), 206-220.
[2] Richard, S., Bencheikh, K., Boulanger, B., & Levenson, J. A. (2011). Semiclassical model of triple photons generation in optical fibers. Optics letters, 36(15), 3000-3002.

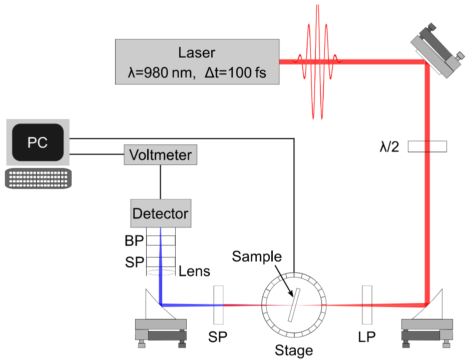
Related work:
https://mpl.mpg.de/research-at-mpl/independent-research-groups/joly/open-positions/generation-of-photon-triplets
https://mpl.mpg.de/research-at-mpl/independent-research-groups/joly/open-positions/generation-of-photon-triplets

# Hybrid nanophotonics waveguides based on organic crystal OH1

Nature du travail : travail de caractérisation expérimental
Étudiants concernés : ingénieur civil physicien, master en science physique
Mots clés:  cristaux organiques, optique non linéaire, optique quantique

## CONTEXT

With the progress of nanofabrication, new types of optical waveguides can be conceived that are expected to reach unprecedented properties. Especially, we are interested in developing waveguides with record high second order susceptibility allowing for efficient fusion of photons (sum frequency generation). In this master student, we will explore the use of an organic crystal known as OH1 [1, 2] as a monocrystalline layer on top of an existing nanophotonic waveguide. The resulting hybrid type of waveguide is expected to combine the excellent linear properties of the very mature Silicon nitride photonics with the exceptional nonlinear properties of OH1.



Optical setup for the nonlinear characterization of the OJH1 thin films

## GOAL

The goal of the project is to create and characterize optically those hybrid waveguides starting from the existing SiN chips and the OH1 raw material.
The fabrication implies depositing thin layers of OH1 that must be **monocrystalline**. This is performed in a two-step process involving first the deposition of amorphous (or polycrystalline) OH1 following by a recrystallization step using a thermal gradient technique.  The recrystallization itself requires a full knowledge of the thermal properties of the material that is acquired via calorimetry (standard DSC and fast scanning calorimetry) and broadband dielectric spectroscopy (BDS).
The characterization implies transmission measurement for the linear properties (absorption) and wave mixing experiment for the nonlinear properties [3].

## CONTACT

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Mr. Romain Morlegem (romain.morleghem@ulb.be)

## REFERENCES

[1] Hunziker, C., Kwon, S. J., Figi, H., Juvalta, F., Kwon, O. P., Jazbinsek, M., & Günter, P. (2008). Configurationally locked, phenolic polyene organic crystal 2-{3-(4-hydroxystyryl)-5, 5-dimethylcyclohex-2-enylidene} malononitrile: linear and nonlinear optical properties. JOSA B, 25(10), 1678-1683.
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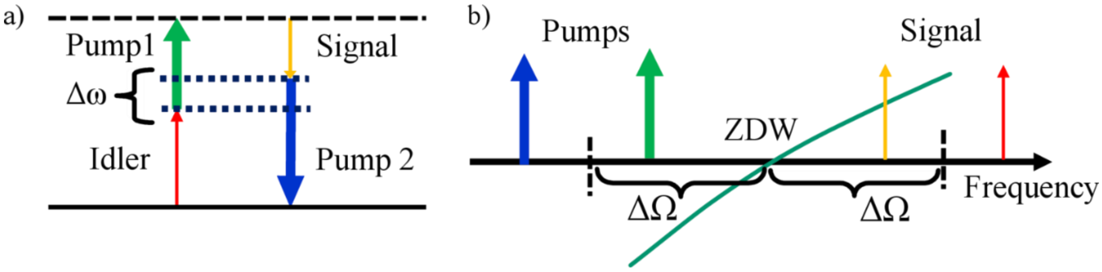
[3] Clemmen, S., Hermans, A., Solano, E., Dendooven, J., Koskinen, K., Kauranen, M., ... & Baets, R. (2015). Atomic layer deposited second-order nonlinear optical metamaterial for back-end integration with CMOS-compatible nanophotonic circuitry. Optics Letters, 40(22), 5371-5374.

# Color conversion of single photons via the process of Bragg grating four wave mixing

Nature du travail : travail de conception et expérimental
Étudiants concernés : ingénieur civil physicien, master en science physique
Mots clés :

## CONTEXT

Bragg scattering four wave mixing is a nonlinear process arising in optical fibers and nanophotonic waveguides. It can annihilate photons and recreate them at a different frequency[1]. Remarkably, the process can be noise free and reach near unity efficiency. Among a wide range of applications, our group is working on this phenomenon in order to create single photons deterministically[2]. This is achieved using optical fiber and powerful lasers on the short term but can be later be translated to integrated optics.



## GOAL

The goal is to setup and characterize a setup for the wavelength conversion of single photons via the Bragg scattering four wave mixing prcess. This implies acquiring a basic knowledge of the underlying theory and getting familiar with experimental nonlinear and quantum optics. An initial characterization can be performed in the classical domain to understand the possible limitations in term of efficiency and loss sources. Eventually, a quantum characterization is necessary in order to fully assess the noise properties of the process.

## CONTACT

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## REFERENCES

[1] Clemmen, S., Farsi, A., Ramelow, S., & Gaeta, A. L. (2016). Ramsey interference with single photons. Physical review letters, 117(22), 223601.
ISO 690
[2] Joshi, C., Farsi, A., Clemmen, S., Ramelow, S., & Gaeta, A. L. (2018). Frequency multiplexing for quasi-deterministic heralded single-photon sources, *Nature communications*, *9*(1), 1-8.

# A poor’s man Raman spectrometer

Nature du travail : travail expérimental
Étudiants concernés : ingénieur civil physicien, master en science physique
Mots clés: détection de photons uniques, spectroscopie

## CONTEXT

Spectroscopy allows to identify chemical compounds (drugs, biological samples), quantify composition, gather information about the crystallinity of solids, etc [1]. Direct absorption spectroscopy is extremely powerful but requires the use of high-end instrumentation. An alternative technique is Raman spectroscopy that rely on the inelastic scattering of light rather its absorption. The advantages brought by that technique are a greater spatial resolution, a better compatibility with biological samples and a simpler instrumentation. Raman spectroscopy has therefore found applications in many labs. A limitation preventing an even wider use outside of the lab is the cost of a deep cooled camera required in a Raman spectroscope.

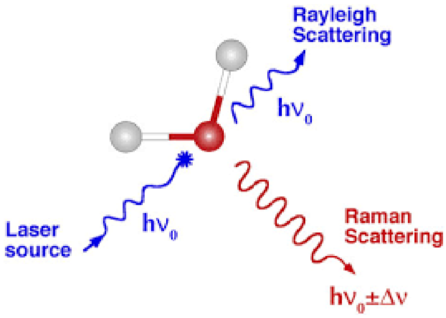

Illustration of the inelastic scattering of light known as Raman scattering

## GOAL

This project consists in using a temporal and quantum detection [2] rather than a spectral one. This change in architecture promises to make the best use of the detector and reduce simultaneously noise and cost by orders of magnitude. The project is experimental including lab work and extensive data analysis. The work aims at showing more precisely how strong the improvement over traditional Raman spectroscopy can be. Prior knowledge in optics is preferred but not required.

## CONTACT

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## REFERENCES

[1] Kneipp, K., Kneipp, H., Itzkan, I., Dasari, R. R., & Feld, M. S. (1999). Ultrasensitive chemical analysis by Raman spectroscopy. Chemical reviews, 99(10), 2957-2976.
[2] Yuan, Z. L., Kardynal, B. E., Sharpe, A. W., & Shields, A. J. (2007). High speed single photon detection in the near infrared. Applied Physics Letters, 91(4), 041114.

# Nonlinear multi-mode spectral broadening in graded-index fibers with spatio-temporally shaped input

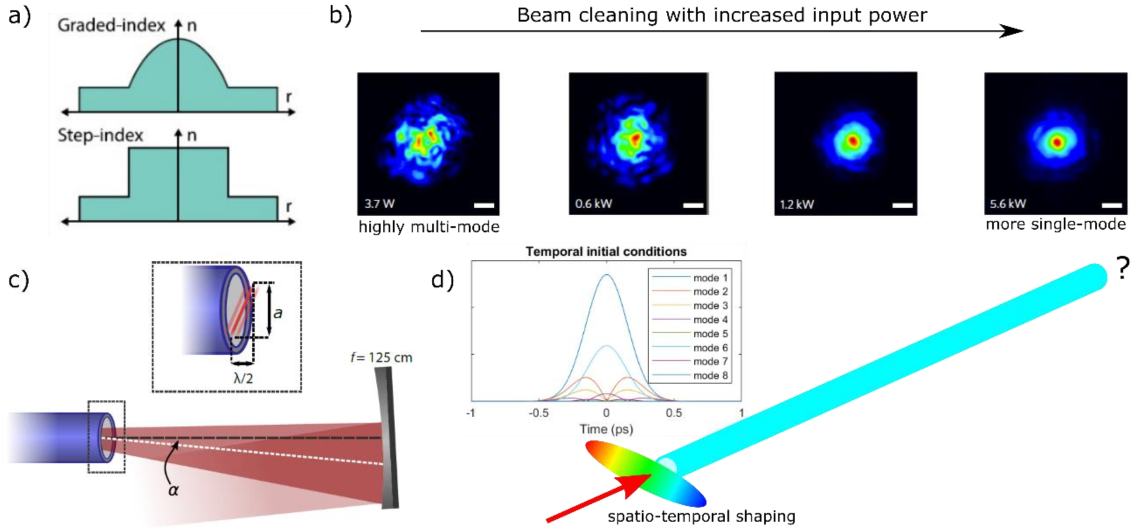
Nature of work: numerical simulations, data analysis
Students: master in engineering physics, master in physics
Key words: optical fibers; multi-mode fibers, nonlinear optics, supercontinuum generation, scientific computing

## Context

Nonlinear optics and nonlinear dynamics in optical fibers, optical resonators, and semiconductor nano-waveguides have been a specialty of the OPÉRA-photonique research team for decades, as mentioned in the introduction to this portfolio. These effects lead to soliton formation, soliton interactions, and spectral broadening (to name a few examples) within these structures, which are the building blocks of new optical technologies. Expanding upon these mature phenomena is the upcoming challenge in our field of research.

Multi-mode waveguides support the guiding of more than one transverse mode and are generally waveguides that have a larger core diameter. A single-mode waveguide for 1550 nm light (the standard in telecommunications) may have a 9-micrometer core diameter, and a fiber with a core diameter of 25 micrometers will support many modes. However, among many other reasons why multi-mode technology has lagged behind, the losses of the higher-order modes are much higher than the fundamental mode and the modes travel at different velocities, leading to little mode interaction. However, graded-index fibers (see panel (a) below) have lower losses and can be designed to have more advantageous dispersion such that rich multi-mode nonlinear optics occur. One such example is spatial beam cleaning in a multi-mode fiber with increasing beam power [1] (see panel (b) below). This has led to an explosion in the last 5-10 years in rich nonlinear physics being explored in multi-mode, primarily graded-index fibers [2].

The experiments and simulations so far have focused of course on many aspects of the various phenomenon, from understanding basic mechanisms to building new light sources. This has often involved directly exciting a higher-order mode at the input of the waveguide and observing the ensuing physics. One example of how to do this is by exciting the fiber at an angle (see panel (c) below) [3]. However, concretely this means that each mode is just excited with a different initial energy, but the temporal properties in each mode are the same (arrival time, temporal duration, etc.). We propose to study initial conditions where the different modes have different temporal properties, i.e. a spatio-temporally shaped input (see panel (d) below).



## Goal

The goal of this master's thesis is to implement spatio-temporal initial conditions within the existing simulation framework and to investigate interesting nonlinear optics when varying these inputs. This will start with relatively straight-forward examples of spatio-temporally shaped input, but should progress to arbitrary and potentially purposefully designed inputs. Spencer Jolly is an expert on spatio-temporal couplings and describing them theoretically and numerically, and will therefore guide this aspect. Prof. Kockaert will provide input and intuition on the nonlinear guided wave optics using his significant experience.

## Methodology

The work will be done within an existing simulation framework based on the Generalized Multi-Mode Nonlinear Schrödinger Equation (GMMNLSE), using the code written by Logan Wright of Cornell University for Matlab [4,5]. The scripts that generate the modes and define the initial conditions will be modified to allow for spatio-temporal inputs, while the multi-mode nonlinear propagation will be used as-is. This will allow the student to focus on the important aspects of the results rather than on the algorithms. The student should be able to write their own analysis and visualization scripts, although there are examples to start with. There are other codes written in Julia that are based on different models [6], which we are open to investigating if the student has the interest.

## References

[1] *Spatial beam self-cleaning in multimode fibres,* K. Krupa et al., Nature Photonics **11**, 237 (2017). https://doi.org/10.1038/nphoton.2017.32
[2] *Multimode nonlinear fiber optics, a spatiotemporal avenue*, K. Krupa et al., APL Photonics **4**, 110901 (2019). https://doi.org/10.1063/1.5119434
[3] *Soliton self-compression and resonant dispersive wave emission in higher-order modes of a hollow capillary fibre*, C. Brahms & J. C. Travers, https://arxiv.org/abs/2112.00369
[4] *Multimode Nonlinear Fiber Optics: Massively Parallel Numerical Solver, Tutorial, and Outlook*, L. G. Wright et al., IEEE Journal of Selected Topics in Quantum Electronics **24**, 5100516 (2018).
[5] https://github.com/WiseLabAEP/GMMNLSE-Solver-FINAL
[6] https://github.com/LupoLab/Luna.jl

## Contact

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