PhD proposal

Linear and nonlinear couplings
Analogies in the temporal, spectral and spatial propagation of light

Supervisors: Pierre COLMAN and Christophe FINOT

Context of the work :

The powerful analogy between the spatial and temporal evolutions of optical waves has stimulated a large number of recent researches. Indeed, the temporal consequences of dispersion are formally identical to the spatial evolution of a 1D beam affected by diffraction (see for example R. Salem, M.A. Foster, A.L. Gaeta, Adv. Opt. Photon. 2013, 5, 274-317 for a review of the basis of this analogy). The link between the various effects appears clearly when considering the problems in the Fourier space, emphasizing the essential heritage of Joseph Fourier, born in Burgundy 200 years ago. Given this powerful duality, numerous papers have reported the temporal analogs of well-known optical systems such as, to cite a few, lenses, Talbot effect, microscopes. In Dijon and through collaborations, we recently theoretically and experimentally explored the physics of lenticular lenses, dispersion gratings, interference devices and as well of the famous Arago spot formation.

That said, only the most basic aspects of this analogy have been discussed. The main contributions have therefore restricted their study to:

- Fully coherent waves
- The linear processes of diffraction/dispersion
- The study of plane waves or of Gaussian-like beams experiencing free-space propagation.
- Either spatial or temporal effects, with no connection between these two domains

Objectives of the work :

The goal of this three-year thesis is to extend the aforementioned works in several new fundamental directions.

First of all, only fully coherent waves have been investigated in details, leaving the field of partially coherent optics aside. By using statistical optics tools, we plan to investigate the shaping and evolution of the properties of a random optical wave with temporal content experiencing nonlinear self-coupling. The challenge will be to develop a solid theoretical background that could be compared with exhaustive numerical simulations of the temporal propagation. The results of these predictions will also be evaluated against experimental results.

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The second objective of the thesis is to apply the temporal/spatial analogy to the spectral domain. Indeed, we have already demonstrated in the past in collaboration with the Fresnel Institute that the concept of spectral lens could be obtained by using self-phase modulation induced by a parabolic waveform. The key to this spectral tailoring is nonlinearity; so we expect that pushing this analogy further may cast a new light to the interpretation well-known nonlinear effects such as modulation instability or the propagation of rogue waves; thematic where our team has developed a widely recognized knowledge. Once again, the student is expected to develop a solid theoretical and numerical framework to understand and predict the coupling that may occur between an arbitrary number of waves with amplitudes and phases that may vary over a large range. Optimization technics of the full numerical simulations will be explored and approximate analytical models will be tested. Experiments will validate the efficiency of the proposed approach.

Finally, we would like to stress that the analogy has been largely restricted to the study of plane waves or of Gaussian-like beams experiencing free-space propagation. This description assumes implicitly that the medium is infinite and that there is no discretization effect that could impact considerably diffraction phenomena, or prevent the creation of a given frequency (band gap effect). In this prospect understanding the mechanisms underlying the evolution of several optical modes in interaction will also be an exciting theoretical challenge. Instead of relying on commercial software that are costly and are a closed box providing little understanding on the phenomena, we plan to develop a reduced model able to catch the full physics and the analogies that can be drawn between the different spaces. If spatial optics have inspired new control techniques in the temporal/spectral domain, it will be also equally important to also see how the news concept developed in the spectral/temporal control could be applied back to spatial optics, hence closing the loop between spatial and temporal analogies.

All those targets are part of the research project of Pr. FINOT, junior member of the Institut Universitaire de France (a highly selective institution promoting research excellence). They are also perfectly in line with P. COLMAN research project that focuses on few modes optics and spatial control.

Expected results :

We expect this ambitious project to lead to results publishable in the top academic journals of physics (Physical Review Letters, Physical Review X, Communication Physics, New Journal of Physics) or in high-impact journals dedicated to optics (Optica, Optics Letters, and other journal of the Optical Society of America). Given the scope of this largely under-explored subject, our ambition is to complete at least one article per year. Communications in international conferences given by the student will also be planned (one per year). Long term applications of the resulting are foreseen in the field of ultrashort pulse sculpturing and characterization. Given the fundamental nature of the present subject, patenting our new concepts will not be our primary goal.

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Skills of the candidate :

We are looking for highly motivated students that are willing to explore new fundamental subjects connected to experimental work. The candidate should have a Master specialized in Physics and Optics. The candidate must ideally be already familiar with the following fields:

- Characterization of the temporal, spectral and spatial aspects of a continuous or pulsed optical wave.
- Nonlinear waves such as solitons or breather pulses.
- Fiber optics and optical waveguides
- Signal processing
- Programming in Matlab language
- English writing and oral communication.

We aim at all times to recruit the person who is most suited to the job and welcome applications from people of all backgrounds – men and women, people of all ages, nationalities, religions and beliefs.

Place of work :

The thesis will take place at the Laboratoire Interdisciplinaire CARNOT de Bourgogne (UMR 6303 CNRS-Université de Bourgogne, http://icb.u-bourgogne.fr), in the Photonic Department. The successful candidate will benefit from the very stimulating research environment of a world-leading research team in nonlinear fibers optics, i.e. the Soliton, Lasers and Optical Communications team (Dijon). It will benefit from the experimental skills developed in the team and the candidate will have access to the state-of-the-art testbeds of the PICASSO platform.

Collaborators :

This thesis will benefit from a high number of well-established collaborations with members of the ICB laboratory or with French or European leading research institutions:

- **Dr Kamal Hammani**, OSNC and SLCO team, will provide feedback on the temporal / spatial aspects.
- **Dr Bertrand Kibler**, SLCO team, will be an expert involved in the discussions regarding the optical synthesis of extreme events and nonlinear coupling between an arbitrary number of modes.
- **Pr. John Dudley**, University of Franche-Comté, will be involved in modulation unstable processes.
- **Dr. Sonia Boscolo,** Aston University, will share her expertise regarding the advanced mathematical description of wave evolution.
- **Dr. Hervé Rigneault**, Institute Fresnel (Marseille), will be involved in discussions regarding the temporal/spatial/spectral analogies that can be drawn in the various systems.

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References :

The candidate could find here a few and non-exhaustive examples of published related works we achieved in the recent years :

E. R. Andresen, C. Finot, D. Oron, and H. Rigneault, "Spectral Analog of the Gouy Phase Shift," Phys. Rev. Lett. 110, 143902 (2013).

P. Colman, C. Husko, S. Combrie, I. Sagnes, C. W. Wong, and A. De Rossi, "Temporal solitons and pulse compression in photonic crystal waveguides," Nat Photon 4, 862-868 (2010).

C. Finot and H. Rigneault, "Arago spot formation in the time domain," J. Opt 21, 105504 (2019).

S. Boscolo and C. Finot, *Shaping Light in Nonlinear Optical Fibers* (2017), Wiley

G. Xu, K. Hammani, A. Chabchoub, J. M. Dudley, B. Kibler, and C. Finot, "Phase evolution of Peregrine-like breathers in optics and hydrodynamics," Phys. Rev. E 99, 012207 (2019).

M. Erkintalo, K. Hammani, B. Kibler, C. Finot, N. Akhmediev, J. M. Dudley, and G. Genty, "Higher-Order Modulation Instability in Nonlinear Fiber Optics," Phys. Rev. Lett. **107**, 253901 (2011).

Contact :

To discuss any details of the project informally, please contact Pr. Christophe Finot (christophe.finot@u-bourgogne.fr) or Dr. Pierre Colman (pierre.colman@u-bourgogne.fr).

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