Multi-scale fibre-based optical frequency combs: science, technology and applications (MEFISTA)

Deliverables D2.1 (D8) MEFISTA

Theory and experimental demonstration of active PT-modelocking

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Consortium

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Contents

List of Figures

EXECUTIVE SUMMARY

The Deliverable D.2.1. was supposed to be provided 18 months after the project start, and approximately around 18 months after the start of the WP2's ESR2. However, due to extraordinary situation with Covid-19 the engagement of the ESR2 occurred with a substantial delay. Nevertheless, the UPC team started preparatory research on the non-Hermitian turbulence control, without the ESR2 (more precisely with the "distant" participation) of the accepted candidate for ESR2, Nayeem Akhter. Nayeem physically joined the UPC team in May 2021, and continued the work started. Presently, we have a proof of concept on non-Hermitian turbulence management (article submitted, however without the ESR2). The ESR2, since his incorporation in UPC, started developing the software package for the study of nonlinear multimode fiber, repeating the turbulence study, repeating the proof of nonlinear self-cleaning concept, and presently is at the stage of delivering result for active (non-Hermitian) self-cleaning. This should result in the first article of ESR2 within MEFISTA.

Introduction

The basic idea of the WP2 is to apply the newly proposed ideas of non-Hermitian field management to control the nonlinear light behaviour in multimode fibers. Typically the non-Hermitian potentials in space (index and gain/loss) modulation can provide the unidirectional currents in space. The WP2 presents a twist on the idea, i.e. the application of non-Hermitian potentials for the control of the stationary flows in space, however for the flows of excitation through the transverse modes. The non-Hermitian potentials introduce unidirectional coupling towards higher or lower transverse modes (depending on the parity of the potential) therefore the coherence of multimode dynamics can be potentially controlled. The control of coherence properties in multimode fibers is crucial for the application of multimode fibers for frequency combs.

The concept has been proved in our UPC team in [1] (see description below). The proof has been performed on the basis of Complex Ginzburg-Landau Equation, a paradigmatic model for optical turbulence in spatially extended nonlinear optical systems. The principal proof in [1] has been performed in a somewhat simplified model, not containing the trapping potential (not in a fiber). The idea should work also in nonlinear fiber, with (parabolic) confining potentials. The ESR2, during his first 3 months within MEFISTA received the necessary training and gained experience to prove that concept for the specific system of GRIN fibers with parabolic, or nearly parabolic potential. This work within approximately 6 months should provide results for the first paper in WP2.

Here we provide the description of the idea of non-Hermitian turbulence control [1], and the sketch of the initial working plan of ESR2 within the MEFISTA.

Non-Hermitian Turbulence Control

Abstract: We propose a method for smart control of turbulence by modifying the excitation cascade of turbulence. The method is based on the asymmetric coupling between the spatial excitation modes induced by non-Hermitian potentials. The non-Hermitian potentials are known, since recently, to introduce unidirectional coupling between modes. We demonstrate that such unidirectional coupling towards larger (smaller) wavenumbers can increase (reduce) the energy flow to turbulent states, and therefore influence the character of turbulence. The study is based on the Complex Ginzburg-Landau Equation (CGLE) which is known as a universal model for pattern formation and turbulence in a wide range of systems. We show that enhancement or reduction of turbulence is indeed governed by the

introduced direction of the energy flow, controlled by the phase shift between the real and imaginary parts of the temporal oscillation of the non-Hermitian potential.

The idea of non-Hermitian turbulence control is provided in Fig.1. The (spatio-temporal) turbulence spectra are shown in Fig.1.a of 1D system, representing a fuzzed parabola, which corresponds to the dispersion curve of the CGLE. Dashed lines show the unstable spatial modes range. Solid lines correspond to integrals of the spectrum intensity over w and kx respectively. The arrows indicate the intermodal coupling for usual, Hermitian potentials. Fig.1.b) and c) show spectral intensity of the system with an inward and outward non-Hermitian coupling. The arrows in a) indicate all possible mode couplings, while in b) and c) correspond to the efficient unidirectional mode couplings.

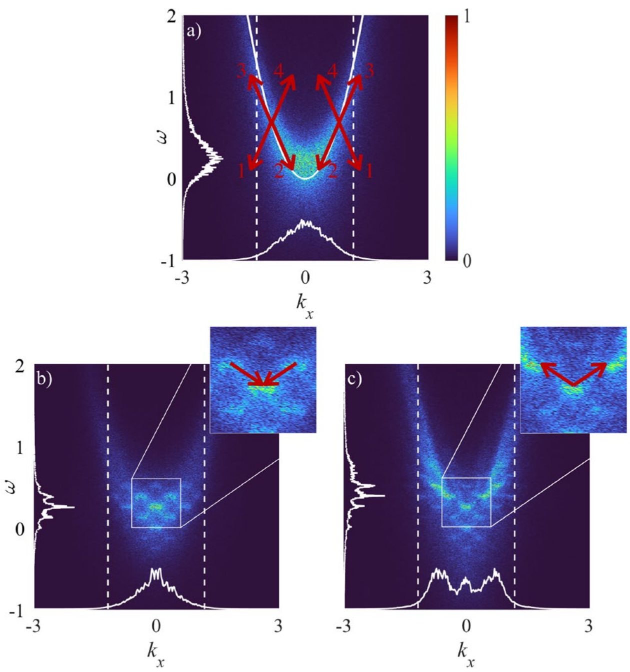

Figure *1. The idea of the non-Hermitian turbulence control*.

In this way the proper non-Hermitian coupling can provide the mode coupling directed inwards (suppression of turbulence) or outwards (increase of the turbulence. This is the main physical idea upon WP2 in MEFISTA.

The spectacular proof of the idea is summarized in Fig.2. The uncontrolled 2D turbulence is shown in Fig.2.a.b – the spatial snapshot of the computed CGLE together with time averaged turbulent spectrum intensity for the 2D CGLE. This represents the broadened spatial spectrum. The dashed white circle corresponds to the range of unstable spatial modes. Lattices of the non-Hermitian potential are shown in the insets. Left column corresponds to non-Hermitian potentials with the optimal phase shift to suppress the turbulence, whereas the right column – to phase shift to maximally enhance the turbulence. Solid white plots correspond to maximum cross-sections at kx = 0 and ky = 0.

Depending on the geometry of the potentials the turbulence has been suppressed/enhanced in one quadrature (to demonstrate the effect), or in both quadratures (to demonstrate the full turbulence control).

In this way the effect of unconventional control of optical turbulence has been provided for somewhat idealized conditions [1]. This could be considered as a proof of concept. The submitted work [1] is the first work towards the goals of the WP2 of MEFISTA, although completed without the ESR2.

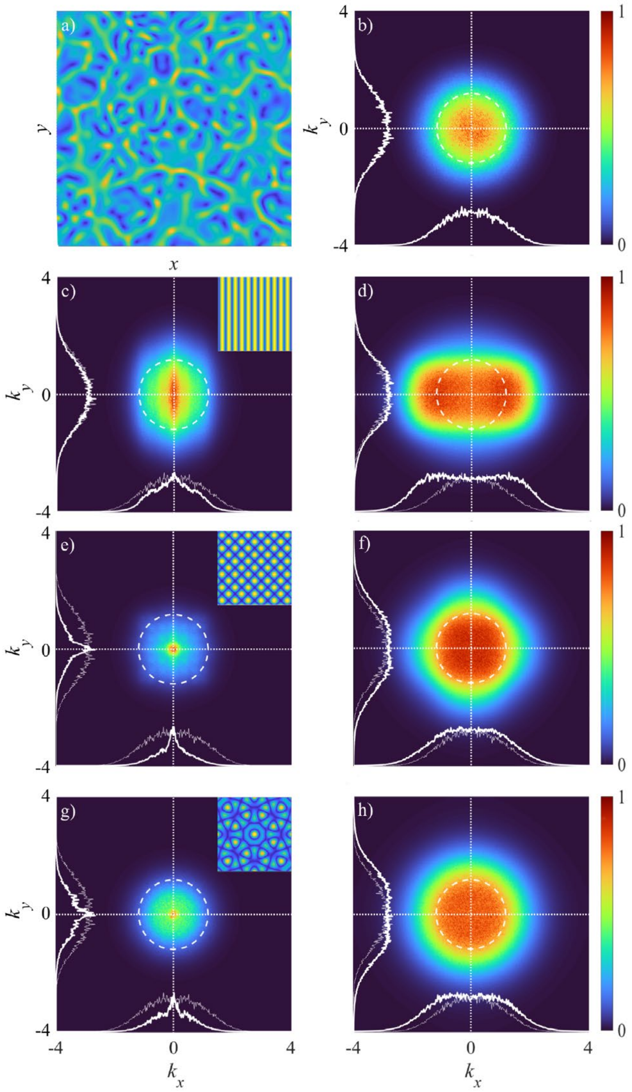

Figure 2. The non-Hermitian control of the 2D turbulence.

Non-Hermitian transverse mode control in multimode fibers

The idea proved in [1] under idealized condition is now being explored for the multimode fibers. Different transverse modes have different propagation constants. In case of the parabolic potential the modes are equidistant, therefore the periodic modulation (with the periodicity corresponding to separation of the mode propagation constants) couple the transverse modes. Application of the idea elaborated in [1] will allow to achieve directional coupling – towards lower or higher order transverse modes. The idea is sketched in Fig.3.

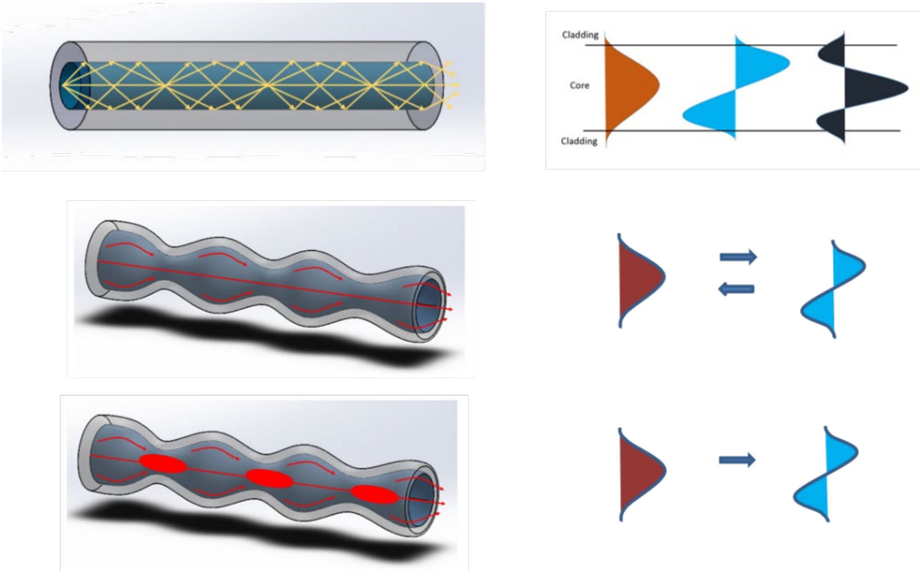

Figure 3. *Non-Hermitian mode coupling in multimode fibers*.

Conclusions and perspectives

In this report, we study the non-Hermitian field management to control the nonlinear light behaviour in multimode fibers in analogy to the non-Hermitian turbulence control. This method is based on the asymmetric couplings between the spatial excitation modes induced by non-Hermitian potentials. The non-Hermitian modulations of the multimode fibers arising from the simultaneous refractive index and gain-loss modulations introduce unidirectional coupling towards lower or higher order transverse modes.

References

[1] Salim B. Ivars, Muriel Botey, Ramon Herrero, and Kestutis Staliunas, Turbulence control by non-Hermitian potentials, Phys.Rev.Letters, submitted 2021.

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