Light control by Non-Hermitian modulation in multimode fiber

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Abstract : We show that a non-Hermitian modulation of the potential along the nonlinear multimode fibers controls dynamics of propagating radiation. Specifically we consider simultaneous modulation of the refraction index and gain/loss profile. We observe that the non-Hermitian modulation introduces a unidirectional and controllable coupling towards the lower/higher order transverse modes, depending on the potential parameters. Such effect may enhance the beam self-cleaning phenomena. On the contrary, coupling towards higher order modes may enhance pulsing, turbulence and, eventually help in super-continuum generation.

Recently, there has been a resurgence of interest in multimode fibers (MMFs) for being an attractive playground to unveil new exciting phenomena in multimode complex nonlinear optics. Particularly, the propagation of intense beams in graded index (GRIN) MMFs unveiled the Kerr effect as the mechanism leading to the emergence of high order fiber modes and speckle patterns on one hand, but also to a cleaning of the transverse beam profiles, the so called self-cleaning effect [1] on the other hand.

We here propose a new light management mechanism in MMFs through longitudinal non-Hermitian modulations of the complex refractive index, i.e. the refraction index and the gain/loss (Fig. 1). Such non-Hermitian modulation, with the spatial frequencies near to the intermodal beat frequencies, are shown to strongly influence the transverse mode dynamics. In particular this allows to enhance/reduce the self-cleaning effects, which is very promising result from the technological view-point.

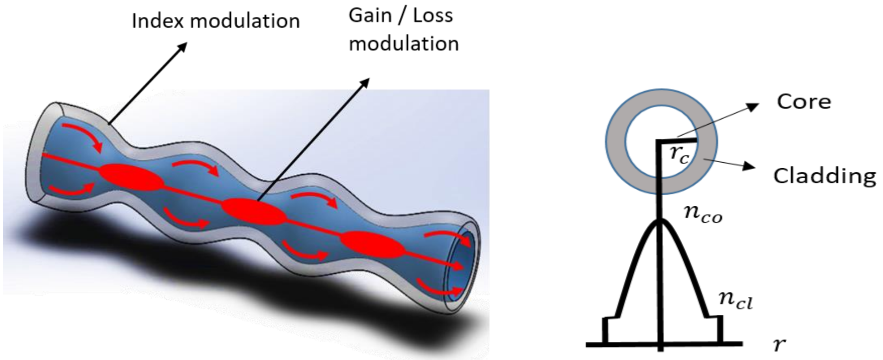

Fig. 1: Modulated GRIN MMF

Specifically, a harmonic non-Hermitian modulation is applied in the longitudinal direction in a multimode graded index fiber with a parabolic refractive index transverse profile. The applied potential corresponds to a simultaneous refractive index and gain/loss modulation and may be controlled by its characteristic parameters, namely the spatial periodicity, relative phase between the real and imaginary components of the modulation and the amplitudes.

In the absence of longitudinal modulations, the propagation of a radiation in such multimode nonlinear fibers typically shows a multimode and turbulent behaviour. The non-Hermitian potential introduces a unidirectional and controllable coupling between the transverse modes [2]. The coupling is directed either from higher to lower order modes or reversed. The coupling sense is controlled by the relative phase of the refraction index and gain/loss modulation component. The effect is numerically demonstrated by solving a (2+1) D Nonlinear Schrodinger Equation (Eq. 1), as well as by simplified system of ordinary differential equations for an oscillating Gaussian beam.

$$\frac{\partial A}{\partial z} = i\frac{1}{2k_0}\nabla^2 A - \frac{ik_0\Delta}{r_c^2}r^2 A + i\left[\boldsymbol{m_1\,cos(qz) + i\,m_2 sin\left(qz + \frac{\pi}{2} + \phi\right)}\right]\boldsymbol{e}^{-\frac{r^2}{r_0^2}}A + ik_0\frac{n_2}{n_{co}}|A|^2 \quad (1)$$

To see the unidirectional coupling due to this non-Hermitian modulation, we calculate the dependency of the intensity drift and amplitude of oscillation on modulation amplitude (m_1, m_2) and relative phase (ϕ) (Fig. 2) with a modulation period nearly equal to the self-imaging period.

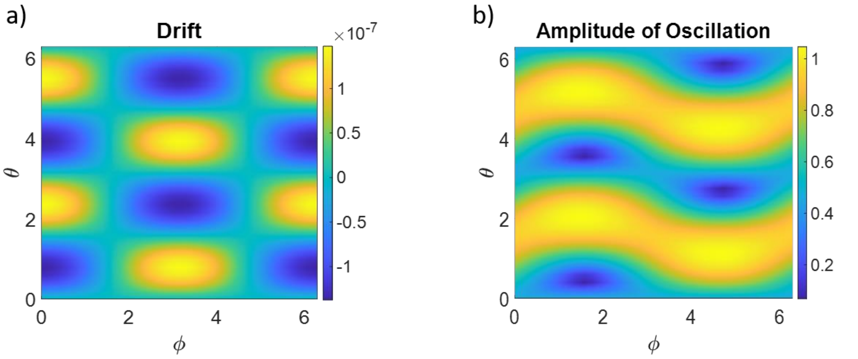

Fig. 2: Drift and Amplitude of oscillations in (ϕ,θ) space, $m_1 = m\,cos(\theta)$, $m2 = m\,sin(\theta)$.

The reported effect may enhance the beam self-cleaning phenomena, i.e. the improving of the spatial structure of light in its propagation along the modulated MMFs. On the contrary, coupling towards higher order modes enhances pulsing, turbulence and, eventually, may help in super-continuum generation.

References

1. K. Krupa, A. Tonello, B. M. Shalaby, M. Fabert, A. Barthélémy, G. Millot, S. Wabnitz, and V. Couderc, “Spatial beam self-cleaning in multimode fibres,” Nat. Photonics **11**(4), 237–241 (2017).

2. J. M. Pardell, R. Herrero, M. Botey, and K. Staliunas, “Non-Hermitian arrangement for stable semiconductor laser arrays,” Opt. Express 29, 23997-24009 (2021).