Observation of Light Self-Organization and Mode Attraction in a Multimode Optical Fiber

Saurabh Jain[1], Kunhao Ji[1], Martin Miguel Angel Núñez-Velázquez[1], Ian Davidson[1], Jayanta Sahu[1], Julien Fatome[2], David.J.Richardson[1], Stefan Wabnitz[3], Massimiliano Guasoni[1]

1. Optoelectronics Research Centre, University of Southampton, Southampton SO17 1BJ, United Kingdom
2. Laboratoire Interdisciplinaire Carnot de Bourgogne, CNRS, University of Bourgogne-Franche-Comte, 21078 Dijon, France
3. Department of Information Engineering, Electronics and Telecommunications (DIET), Sapienza University, 00184 Rome, Italy

Abstract: We present the first-ever quantitative analysis of mode attraction in a multimode fiber with a counter-propagative setup, as well as an overview of novel self-organization processes.

1. Introduction

Multimode (MM) fibers exhibit a complex nonlinear spatiotemporal dynamics that has been the subject of intense theoretical and experimental research in the last decade [1,2]. However, while most of the studies so far have focused on a co-propagative setup, only a very few have addressed the problem of counter-propagative beams coupled via Kerr-nonlinearity. Nonlinear counter-propagating systems may exhibit robust modal attraction, such that any arbitrary input modal state of the forward beam is attracted towards a stable attractor state that is fixed by the backward beam [3]. In other words, light self-organizes due to the nonlinear interaction among the beams in play. In this framework, promising results have been achieved in single-mode fibers, where all-optical polarization control have been demonstrated via self-organization of orthogonally polarised LP01 modes [4]. Recently, we have generalised the idea of light self-organization to MM optical fibers supporting any number *N* of co-polarised modes [5]. In this contribution we extend our investigation to the most general case in which the modes have arbitrary polarization, which enriches the diversity of modal attraction processes. Moreover, to the best of our knowledge we provide the first ever systematic and quantitative experimental measurement of modal attraction in a MM fiber.

2. Theoretical framework

We consider a MM optical fiber where a forward signal and a backward control beam (CB) are counter-propagating (see Fig.1a) and coupled to several and different spatial modes. Starting from the Maxwell equations, we derive a set of coupled Schrödinger equations for the forward and backward modal amplitudes:

$$\partial_z F_n + v_n^{-1}\,\partial_t F_n = -i\gamma_{nn}|F_n|^2 F_n + iF_n\sum\gamma_{nm}(k|B_m|^2 + 2|F_m|^2) + ikB_n^{*}\sum_{m\neq n}\gamma_{nm}B_m F_m \qquad (1)$$

$F_n(z,t)$ and $B_n(z,t)$ being the amplitude of the forward and backward mode *n*, v_n the related group velocity, γ_{nm} the Kerr nonlinear coefficient for modes *n* and *m*. A similar equation holds true for B_n. For simplicity, here we focus on the case where the signal and CB are either linearly co-polarized (k=2 in Eq.1) or orthogonally polarized (k=2/3). In order to illustrate the mode attraction process, we consider an example where at one fiber side the input forward signal is coupled to three fiber modes (LP01, LP11e and LP11o) having random and varying relative power R in time. Here, $R = (P_{11}-P_{01})/(P_{11}+P_{01})$ where P_{01} is the power coupled to LP01, whereas P_{11} the power coupled to LP11 (Lp11e +LP11o). At the opposite fiber end, the CB is coupled to the LP01 mode only. When the CB is off, the output forward signal exhibits a random relative power characterised by a uniform probability distribution (similar to the input signal). However, when the CB is on and its power large enough, the nonlinear coupling among counter-propagative modes triggers an efficient self-organization process such that the forward signal condensates towards the LP11 modes at the output. The attraction towards the LP11 modes is maximized in the co-polarised case (fig.1b). It is still present-but weaker- in the opposite case of orthogonal polarization (Fig.1c). It is worth noting that while in this specific example the LP11 modes play the role of modal attractor, however several different self-organization scenarios can be achieved when the CB is coupled to different modes or when the fiber supports more than 3 modes.

3. Experimental setup and results

The schematic experimental setup is shown in Fig.1a. An in-house built linearly polarized source (1040 nm, 500ps with max peak power of 50kW) is split into two beams (forward signal and the backward CB) using a combination of HWP and PBS, which are injected at the opposite ends of a standard 1m-long SMF28 fiber supporting modes LP01,LP11e,o at 1040nm. A combination of half-wave-plates (HWPs) and polarization beam splitters (PBS) is used to control the power of the input forward signal and the backward CB, as well as their relative polarization. A phase-plate (PP) in the forward signal path is used to launch the combination of LP11 and LP01 modes. Signal output power is sampled using optical wedges and camera and observed at different polarization using a polarizer. The camera-based M^2 measurement system represents the core of our setup to retrieve the intensity and phase of the output signal using an iterative phase retrieval method [6]. This is followed up by an off-line mode decomposition scheme based on the correlation with the fiber modes, which allow estimating the power and phase carried by the guided modes LP01, LP11e,o(fig.2b,c). In Fig.2a we observe the typical evolution of the output signal modal distribution versus the CB power. In this example, the input signal is mainly coupled to the LP01 mode with a fixed peak power of 17.5kW. When CB is off, the output signal mode content reflects the input one (only ~ 25% power coupled to LP11 modes, see point A in Fig.2). However, when CB is on, the induced nonlinear coupling among backward and forward beams modifies the modal content of the latter and leads to an effective modal attraction towards LP11 modes (up to ~ 80% power coupled to LP11 modes, see point B in Fig.2). As predicted by our numerical simulations (Fig.1), the strength of the attraction depends on the relative signal-to-CB polarization. Moreover, similar results to those displayed in Fig.2 are obtained for different input signal mode distributions.

4. Conclusions

Counter-propagative systems exhibit robust self-organization of light. This work generalizes previous studies involving 2 modes to the general case of *N* interacting modes with arbitrary polarization in MM fibers. Besides disclosing a rich variety of novel self-organization processes, these outcomes may find application in a diversity of both optical (e.g. on-chip waveguides) or non-optical (hydrodynamics, BECs) nonlinear discrete physical systems. Moreover, these results pave the way to all-optical coherent combination of multiple modes for novel high-power, high-brightness fiber lasers. Our experimental setup implements mode decomposition of the output field, which provides clear evidence of mode attraction when an intense backward CB is injected.

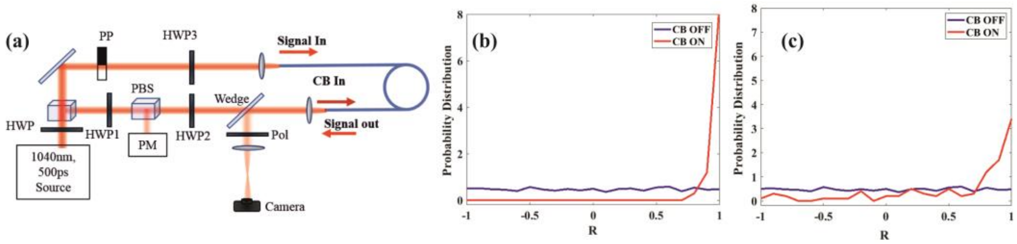

Fig.1 (a) Experimental setup. (b) Numerical simulation of Eq.1 in the co-polarised case: probability distribution function of R (300 temporal samples) with CB OFF/ON. (c) Same as panel b in the orthogonal polarization case.

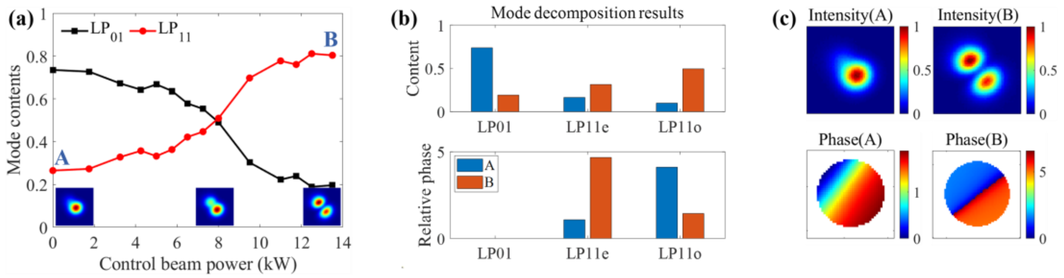

Fig.2 Experimental results. (a,b) Mode decomposition of the output signal computed through our off-line algorithm. Despite the input signal is mainly coupled to LP01, however the output signal undergoes growing attraction towards LP11 (Lp11e+LP11o) when increasing the CB power. (c) Spatial intensity and phase profiles of the output signal measured through our M2 setup when CB is OFF (A) and ON with 14KW power (B).

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