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# Experimental observation of discretized conical wave in a multimode fiber

Karolina Stefańska<sup>1,2,\*</sup>, Pierre Béjot<sup>1</sup>, Karol Tarnowski<sup>2</sup>, and Bertrand Kibler<sup>1,\*\*</sup>

<sup>1</sup>Laboratoire Interdisciplinaire Carnot de Bourgogne, UMR6303 CNRS-Université de Bourgogne, Dijon, France

<sup>2</sup>Department of Optics and Photonics, Wrocław University of Science and Technology, Wrocław, Poland

**Abstract.** We demonstrate spontaneous emission of discretized conical wave when an ultrashort pulse propagates nonlinearly in a multimode fiber. Our theoretical predictions are experimentally and numerically confirmed, providing a general understanding of phase-matched radiations emitted by nonlinear waves in multidimensional dispersive optical system.

## 1 Introduction

Conical wave formation is one of the striking spatiotemporal phenomena in nonlinear optics observed during the last decades but limited to bulk samples or condensed media [1]. Corresponding optical wavepackets are propagation-invariant due to their intrinsic coupled spatiotemporal properties driven by a phase-matching condition mainly defined by the dispersion of the material. Some recent works have generalized the theoretical concept of conical waves towards structured media and even space-time wave packets carrying orbital angular momentum [2], by considering a linear superposition of fiber modes with an engineered spatiotemporal spectrum. Besides, numerical investigations have also reported that such conical waves can spontaneously emerge during nonlinear propagation of ultrashort pulses in multimode optical fibers (MMF) similarly to bulk conical emission [3]. As MMFs support the propagation of a discrete and finite number of guided modes, the modal distribution then provides a discretization of conical waves. Our study demonstrates both numerical and experimental evidence of the conical wave formation when an intense ultrashort pulse propagates nonlinearly in the normal dispersion of a commercial step-index MMF (more specifically in the case of femtosecond pulse pumping and input peak powers around the critical self-focusing threshold of silica glass) [4].

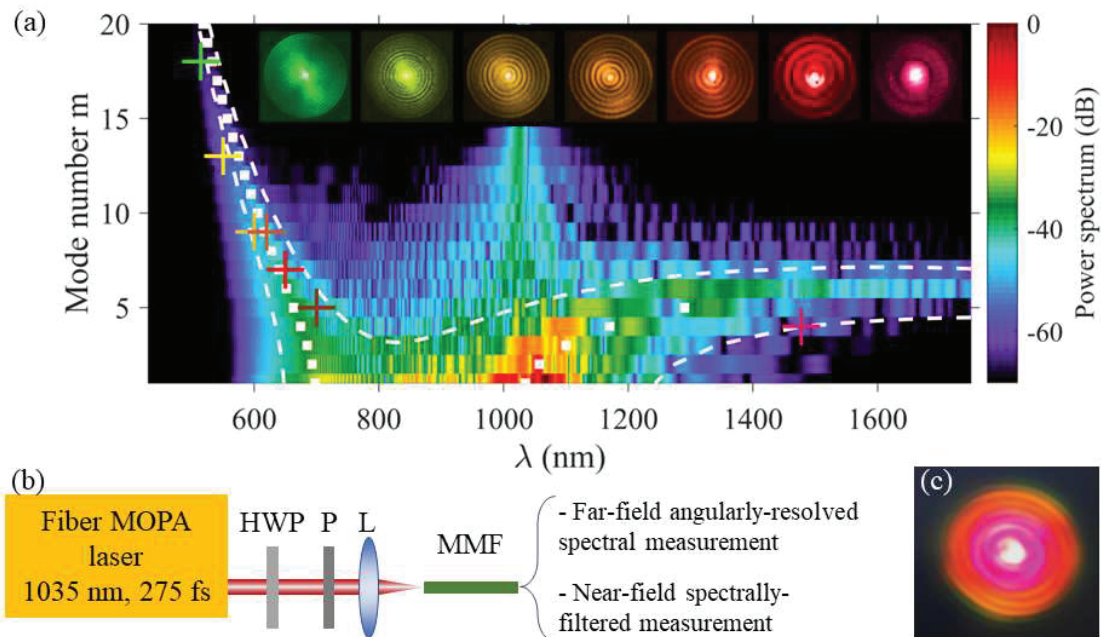
## 2 Numerical simulations and theoretical predictions

Our numerical approach is based on the multimode unidirectional pulse propagation equation [5], which describes the evolution of the complex electric field in the scalar approximation. We consider the nonlinear propagation of 275-fs pulse injected into a 5.8-cm-long segment of step-index MMF. The central wavelength of the pump pulse

is 1035 nm, in the normal dispersion regime of the fiber. The fiber under study is a commercially available MMF (pure silica core with 105- $\mu\text{m}$  diameter, and numerical aperture equal to 0.22). We limit our studies to the linearly polarized modes of  $\text{LP}_{0,m}$  class. Our pumping configuration is a Gaussian beam coupling into the fundamental mode of the fiber (namely,  $\text{LP}_{0,1}$  mode). Figure 1(a) shows the distribution of the full optical spectrum (power in log scale) over the different fiber modes after propagation for an input pulse energy of 1.2  $\mu\text{J}$ . We observe here an evident X-shaped pattern of the field distribution that is very similar to typical conical wave (i.e., X-wave) studied in the Fourier domain for bulk media [1]. The detailed evolution for power spectrum, time and space profiles as a function of propagation distance are not shown here, it reveals that the spectral dynamics reaches a stationary state after 2 cm, just past pulse-splitting phenomena observed in the time domain, i.e. a typical scenario already analyzed in normal dispersion of bulk media [1]. The pulse splitting occurring at the nonlinear spatial focus produces sub-pulses and a strong and rapid spectral broadening induced by the self-steepening effect (formation of an optical shock at the trailing edge). This spectral broadening seeds linear waves, in higher-order modes according to the velocity of the shock front. Indeed, the spontaneous formation of this energy spreading in higher-order modes from the fundamental mode can be retrieved by using the three-wave mixing picture, previously developed for describing the generation of conical waves in bulk media [6]. One can find that the energy of the spectral broadening will concentrate in fiber modes  $\text{LP}_{0,m}$  when fulfilling the following phase matching condition [3]:  $\beta(m, \omega_c) - \beta_0(1, \omega_s) - \beta_1(1, \omega_s) \times [\omega_c - \omega_0] \leq 2\pi/d_r$ , where  $\beta(m, \omega)$  are the frequency dependent propagation constants,  $\beta_0(1, \omega_s)$  and  $\beta_1(1, \omega_s)$  are the propagation constant and the inverse of group velocity of the most intense pulse (the shock front) that is triggered during the nonlinear propagation, and it then seeds a superposition of linear waves centered at  $\omega_c$ , thus forming the discretized conical wave.

\* e-mail: karolina.stefanska@pwr.edu.pl

\*\* e-mail: bertrand.kibler@u-bourgogne.fr



**Figure 1.** (a) Mode-resolved power spectrum numerically obtained after propagation in our MMF. Inset shows spatial intensity profiles recorded experimentally by means of a CMOS camera using narrowband spectral filters. Colored crosses indicate corresponding spectral positions of the experimentally observed  $LP_{0,m}$  modes in both visible and infrared. White squares show the theoretical phase-matching condition of the discretized X-wave. (b) Experimental setup. HWP: half-wave plate, P: polarizer, L: lens. (c) Far-field image of discretized conical emission.

cal wave. Since the nonlinear process takes place over a finite length  $d_r = 1.4$  mm, the phase-matching relation exhibits a certain tolerance (marked with white dashed line in Fig. 1(a)). White squares in Fig. 1(a) show the theoretical predictions, and this confirms the formation of a discretized conical wave for which the shortest (visible) and longest (infrared beyond the pump) wavelengths are continuously contained in higher-order modes.

### 3 Experimental results

Figure 1(b) depicts the experimental setup dedicated to conical wave generation and its characterization. Pumping and fiber parameters are given in the previous section. We simply optimized the Gaussian beam coupling into the fundamental mode by means of a single lens with a focal length of 12.5 cm. The output light from the fiber is collected and characterized in both spectral and spatial domains by combining bandpass spectral filters with near-field imaging or far-field measurement with optical spectral analysis. In the inset of Fig. 1(a), we show the spatial intensity patterns measured by near-field imaging the fiber output face, with simultaneous narrowband spectral filtering at various wavelengths located in the two branches of the expected discretized X-wave. We clearly reveal that such selected spectral bands are assigned to almost single circularly symmetric  $LP_{0,m}$  modes. Corresponding spectral positions of the experimentally observed  $LP_{0,m}$  modes are plotted with colored crosses onto the mode-resolved power spectrum numerically obtained. Our measurements are in excellent agreement with our previous

simulations and theoretical phase-matching of discretized X-wave. The far-field characterization that allows to reconstruct an angularly-resolved power spectrum [4] also confirms this agreement. Fig. 1(c) shows the far-field image of discretized conical wave emitted from the MMF output (i.e., distinct colored rings are seen on the white screen).

In conclusion, we have unveiled the possible emergence of discretized conical waves in MMFs, resulting from a linear superposition of fiber modes with an engineered spatiotemporal spectrum and seeded by an intense ultrashort pulse injected into the fundamental mode of the fiber. We expect that next experiments in multimode fibers could reveal different forms of dispersion engineered conical emission, in particular orbital angular momentum-carrying space-time wavepackets [7].

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