Time-Domain Interference of Nonlinearly Interacting Spatial Modes in a Multimode Fiber

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Abstract: The study of nonlinear optics in multimode fibers has gathered considerable interest recently. We report experimental observation of time-domain interference between nonlinearly interacting co-polarized spatial modes of a graded-index multimode fiber at 1550nm.

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1. Introduction

Multimode fibers (MMFs) have gathered a lot of interest in the recent past in many areas in optics. In telecommunication systems, space-division multiplexing using MMFs offers an increased bandwidth by providing an extra dimension to exploit, in order to meet the ever increasing demands of data transfer capabilities [1]. Spatiotemporal dynamics due to optical nonlinearity in MMFs are being studied by various groups around the world in order to better understand the complex interactions between the spatial modes [2,3]. Supercontinuum generation based on spatiotemporal effects in MMFs has also been demonstrated recently [4], and nonlinear propagation of optical pulses through MMFs has come to receive much attention [4–6] recently. Even though linear modal coupling in MMFs is negligible, nonlinear intermodal coupling is significant and leads to a rich variety of spatiotemporal nonlinear effects. In this paper, we report experimental detection of time-domain interference between nonlinearly interacting co-polarized spatial modes in a graded-index multimode fiber at 1550nm.

2. Theory and Modeling

The Multimode Generalized Nonlinear Schrödinger Equation (MM-GNLSE) was introduced in [5, 7] as a multimode generalization of the well known single mode nonlinear Schrödinger equation. The MM-GNLSE is a set of N nonlinearly coupled first order differential equations that describes the evolution of the N allowed transverse modes as they propagate through the fiber. In our work, we work with a single polarization of the electric field, and a gaussian pulse in time. The x-polarized electric field can be decomposed in terms of the transverse modes of the fiber as:

$$E_x(r,\phi,z,t) = \sum_p A_p(z,t)\psi_p(r,\phi)\exp\left[j\left(\omega_0 t - \beta_0^{(p)} z\right)\right] \tag{1}$$

where $\psi_p(r,\phi)$ is the field distribution of mode p, and $A_p(z,t)$ is the corresponding slowly-varying amplitude.

For the fiber length and pulsewidths considered here, the differential group delay among the excited modes is negligible, and the intramodal and intermodal Kerr terms are the most significant significant nonlinear interactions. Considering just the two lowest order radially symmetric spatial modes LP_{01} and LP_{02} for simplicity, the MM-GNLSE reduces to:

$$\frac{\partial A_1}{\partial z} = j\left(\gamma_{1111}|A_1|^2 + 2\gamma_{1122}|A_2|^2\right)A_1 \quad \text{and} \quad \frac{\partial A_2}{\partial z} = j\delta A_2 + j\left(\gamma_{2222}|A_2|^2 + 2\gamma_{2211}|A_1|^2\right)A_2 \tag{2}$$

where the indices on the nonlinear coefficients γ_{pqrs} correspond to the mode numbers p, q, r and s following the notation in [5, 7], and $\delta \equiv \beta_0^{(2)} - \beta_0^{(1)}$ is the difference in propagation constants between the two modes. These equations can be solved analytically to obtain

$$A_1(z,t) = A_1(0,t)e^{j(\gamma_{1111}+2\gamma_{1122}\Gamma)|A_1|^2 z} \quad \text{and} \quad A_2(z,t) = A_2(0,t)e^{j\delta z}e^{j(\gamma_{2222}\Gamma+2\gamma_{2211})|A_1|^2 z} \tag{3}$$

where $\Gamma \equiv |A_2|^2/|A_1|^2$ describes the power ratio in which the two modes are excited at the input facet, and from equation (2), $|A_1|^2$ and $|A_2|^2$ are constant in z. Because of the three different nonlinear coefficients (γ_{1111}, γ_{2222}, and

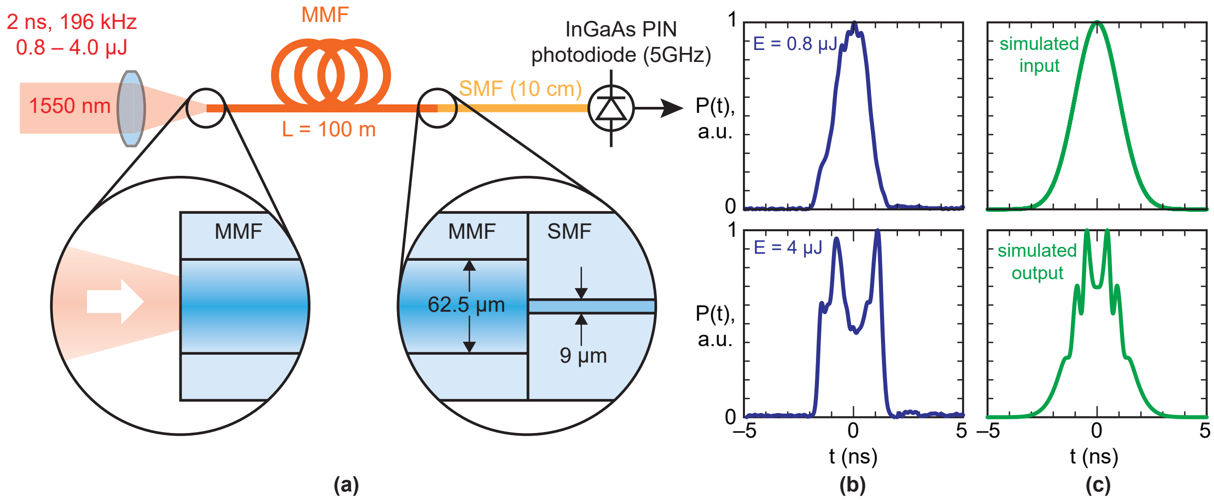

Fig. 1. (a) Experimental setup to observe time-domain interference between nonlinearly interacting spatial modes in a multimode fiber, (b) Experimental results, (c) Numerical simulation results

γ_{1122}), when a gaussian pulse is launched into the fiber, each of the transverse modes acquires different nonlinear chirp according to (3). If the resulting fields are spatially sampled at a specific transverse location of the output facet, they will therefore produce intensity-dependent interference fringes in the time domain. The nonlinear phase difference changes in direct proportional to the pulse intensity $|A_p(z,t)|^2$, which produces temporal interference fringes that are symmetric about the pulse peak. This simple result can be extended to any number of modes. We numerically simulate the more general and realistic case with 8 excited modes.

3. Results and Discussion

Fig. 1a depicts the experimental setup used to observe the nonlinear mode interaction. A pulsed 1550 nm fiber laser generates 2 ns pulses at a repetition rate of 196 kHz, which were focused through a f = 20 mm lens onto the center of the input facet of a 100 m long conventional 62.5 μm-core graded-index multimode fiber. The size of the focused beam was measured to be 25 μm, which was chosen to excite a superposition of the radially symmetric LP modes of the fiber. A conventional single-mode fiber was fusion-spliced to the end of the MMF to sample the near-axis field intensity. This is directed to a 5 GHz InGaAs photodiode, which records the transmitted pulse shape.

Fig. 1b shows the transmitted optical pulse shape, measured for low input power (0.8 μJ, upper plot) and for higher input power (4.0 μJ, lower plot). The appearance of temporal fringes at higher intensity is a direct consequence of interference between spatial modes, which experience different nonlinear phase shifts by virtue of their different mode areas. To confirm this effect, we conducted numerical simulations using the coupled nonlinear Schrödinger equation, incorporating the nonlinear coupling of the lowest 8 radially symmetric LP modes. Fig. 1c shows the input (upper) and calculated output (lower) curves, which exhibit a temporal fringe pattern that is symmetric about the pulse peak, which qualitatively resembles that observed in the experiments.

In single-mode fiber, the nonlinear chirp produced by the optical Kerr effect is most commonly observed as intensity-dependent broadening of the optical spectrum. In multimode fiber, because there are many co-polarized propagating modes with dissimilar nonlinear coefficients, it is possible to directly observe the nonlinear chirp through a temporal interference pattern produced when the field is spatially resolved. This is a simple yet powerful demonstration of the spatiotemporal nature of the complex nonlinear interaction between the spatial modes of a multimode fiber, and is to our knowledge the first experimental demonstration of this phenomenon in the telecom band.

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