Experimental Observation of Non-Linear Mode Conversion in Few-Mode Fiber

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Abstract: We show for the first time directly experimentally observed nonlinear spatial mode coupling in a 10 km long graded-index few-mode fiber.
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1. Introduction

Spatial mode-multiplexing in optical fibers has recently emerged as one of the leading technologies that could enable the capacity of optical fiber telecommunications links to increase beyond that of single-mode fibers(SMFs), which are fast approaching their theoretical capacity limits[1,2]. Few mode fibers (FMFs) are particularly well-suited for mode-multiplexing because precise mode-selective launch can be achieved using low-loss and low-cost techniques, such as photonic lanterns [3]. Nonlinear effects in FMFs present further difficulties since, in addition to the "classic" single-mode nonlinear interactions between channels encountered in SMFs, such as cross-phase modulation [4] and four-wave mixing [5], nonlinear coupling may also occur between the spatial modes [6]. These nonlinear effects limit the information capacity but could also potentially be exploited, for example to enable all-optical switching and mode-conversion in fibers, an effect that has been experimentally demonstrated using nonlinear chalcogenide glasses [7]. While some theoretical work has described nonlinear FMF mode-coupling [6], it is only very recently that experimental work has started examining these effects [4]. In this contribution, we report nonlinear mode rotation in a telecommunication-type FMF. To the best of our knowledge, this is the first time that such power-dependent nonlinear mode coupling over silica glass FMF has been observed experimentally.

2. Theory

The focus of this work is nonlinear mode rotation, proposed theoretically and analyzed numerically in [8]. Fig. 1 outlines the basic operation principle, while more details on the theory can be found in [8]. Probe light launched in the LP_{11a} mode of an FMF can be decomposed into its sum and differences with the LP_{11b} mode, termed modes A and B respectively. When pump light with high power is launched into the FMF with the same mode profile as that of mode A, the cross-phase modulation between the pump and mode A is three times larger than that between the pump and mode B due to the nonlinear Kerr effect, which results in mode rotation. This rotation can reach 90^{o} with sufficiently high pump power over a fixed fiber length, which has the effect of coupling all the probe light into the LP_{11b} mode. A typical power exchange curve between LP_{11a} and LP_{11b}as a function of total pump power is shown in Fig. 1b. It should be noted that the modes A and B shown in Fig. 1 are not eigenmodes of the FMF. Therefore, these modes may be unstable in the FMF due to differential mode-group delay and random mode coupling. The mode profile at the output of the FMF will be a mix of different modes in the first high-order mode group, rather than what was launched at the fiber input. However, in this work a coherent mode analyzer is used to decompose the output mode profile into a basis of linearly polarized (LP) modes. This enables, for the first time, measurement of the nonlinearity-induced change in the transmission matrix of the FMF.

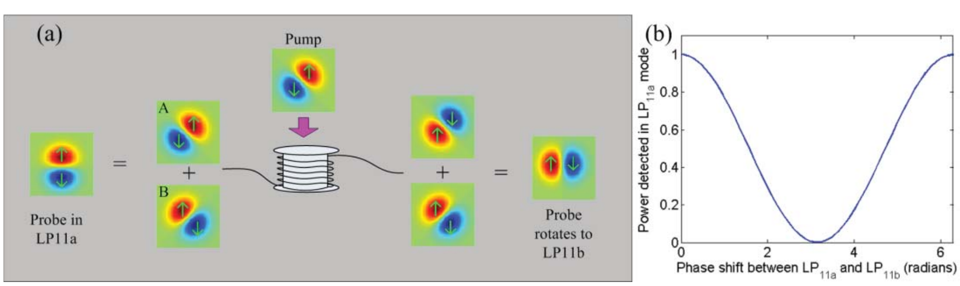

Fig. 1(a) Principle of nonlinear mode rotation (b) power exchange curve between LP_{11a} and LP_{11b} due to the Kerr effect.

3. Experimental Set-up and Results

The experimental setup is shown in Fig. 2. High-power CW pump light at 1550 nm and weak CW probe light at 1543 nm are injected into a 10 km spool of FMF. The FMF is a two-mode graded index fiber with insertion loss of

2.5dB. A mode-selective launch system constructed using phase plates is used to inject the pump light into both the $LP_{11a}$and LP_{11b} modes in the x polarization, termedLP_{11ax} and LP_{11bx} for short. The probe light is only injected into the LP_{11bx}mode. The polarization state is set using two polarization controllers and a polarizer at the input of the FMF. After the 10 km FMF, mode analysis is achieved using a spatial-light modulator (SLM) in a polarization diversity setup [9]. A free-space filter (Thorlabs FB1540-12) is used to remove the pump light, leaving only the probe light. Because the SLM is a phase modulation device, it can be used as a common-path interferometer to measure both the amplitude of and relative phase between modes. This means, for example, that the vorticity of the resultant output can also be measured as a function of pump power.

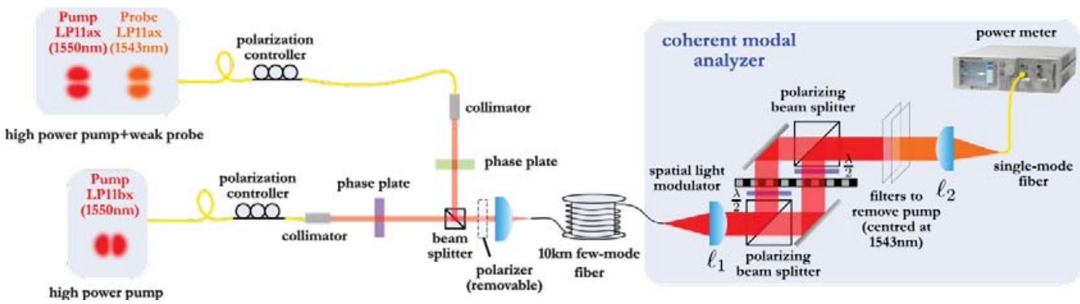

Fig. 2 Experimental setup for measuring nonlinear mode rotation showing the SLM-based modal analyzer.

Fig. 3 shows the measured modal power as a function of pump power. To isolate the impact of nonlinearity, a 10 m long piece of FMF is first tested as a control case and negligible mode conversion is observed, as shown in Fig. 3a. This short FMF is then replaced with the 10 km fiber spool and significant mode conversion is observed with increasing pump power, as shown in Fig. 3b. Fig. 3c shows how the total output power increases as a function of pump power. There is significant power leakage from pump to probe when the pump power is > 100 mW, therefore only powers below this value are considered here. Fig. 3b shows that conversion between the LP_{11a} and LP_{11b}modes is indeed observed, with the power of LP_{11a} decreasing and the power of LP_{11b} increasing in both polarizations. Neglecting linear mode coupling (including polarization coupling) and using the method described in [10] with measured $n_2=2.23\times10^{-20}m^2/W$ and A_{eff} of $LP_{11a}=125\mu m^2$, it is calculated that the pump power required to achieve full π rotation is ~400 mW. Mode rotation is observed here at a somewhat lower pump power and this discrepancy requires additional investigation.

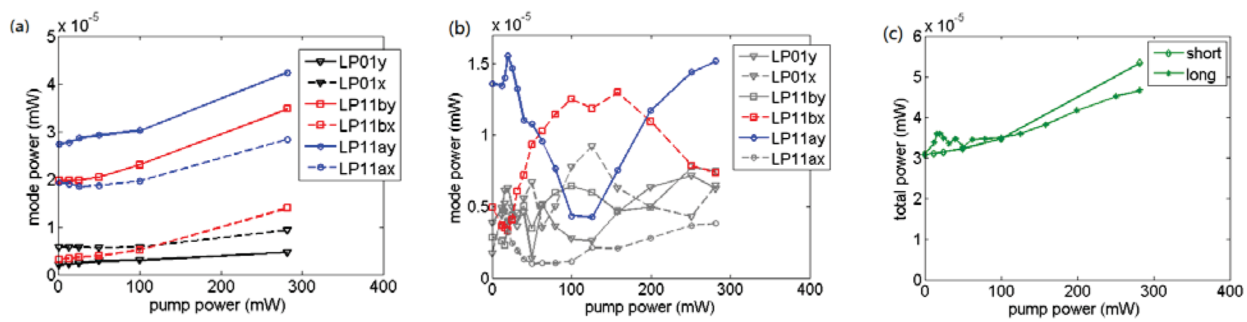

Fig. 3 Measured modal power as a function of pump power. (a) 10 m short fiber piece; (b) 10 km long fiber spool; (c) total power at the output of the short (diamond) and long (star) FMF versus pump power.

It is concluded that a pump-power dependent nonlinear conversion between probe spatial modes is observed over 10 km FMF. This is the first direct experimental observation of nonlinear mode conversion in such FMF.

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5. References

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