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Investigation of Nonlinear Coupling and Parametric Interactions in Coupled Multi-Core Fibers

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Abstract *We studied linear and nonlinear coupling in coupled multicore fiber (MCF) experimentally and numerically. We investigated wavelength and polarization-dependent coupling and effects of coupling strength on parametric interactions. Results show that nonlinear responses depend sensitively on the longitudinally varying coupling coefficient in real MCF. ©2025 The Author(s)*

Introduction

The growing demand for data throughput has led to significant interest in spatial multiplexing using multi-core fibers, which show promise for both transmission[1] and parametric interactions. It has been shown in[2]–[4] that the coupling plays a significant role in the phase matching condition, enabling wavelength-independent exponential gain[2], which is not possible in single-core fibers. Coupling between cores has been studied analytically for decades, including nonlinear coupling[5], solitons[6], and parametric amplification[2],[3], though experimental verifications of these models are fewer.

Experiments show that the ideal model, assuming constant coupling between cores, is incomplete, with significant random fluctuations in coupling being observed[1],[7]. Macho et al.[7] proposed a unified model for linear and nonlinear crosstalk. Random polarization effects, bending, and twisting also affect crosstalk in coupled MCF[8],[9]. While most studies are theoretical, experimental measurements of nonlinear coupling and the wavelength and polarization dependence remain limited.

In this paper, we present a comparative study of linear and nonlinear coupling in an ideal (simulated) MCF with constant coupling and a real MCF. Unlike the ideal case, the real MCF exhibits random coupling in both frequency and time, caused by environmental perturbations (e.g., temperature, strain, bending, and twisting) and fabrication imperfections (e.g., variations in core radius and separation). We have also investigated the wavelength and polarization dependence of coupling and its impact on parametric processes, particularly wavelength conversion[4].

Theory and Simulation

We assume two identical cores in a coupled dual-core fiber (DCF), where u_1 and u_2 are the wave amplitudes described by coupled nonlinear Schrödinger equations (NLSEs). The cores have identical dispersion and nonlinearity, with a constant coupling coefficient C. The parameters β_n, γ, and C represent the nth-order dispersion, nonlinearity, and coupling strength, respectively. The coupled NLSEs are given by

$$\frac{\partial u_1}{\partial z} = i\sum_{n=2}^{\infty} i^n \frac{\beta_n}{n!}\frac{\partial^n u_1}{\partial t^n} + i\gamma u_1|u_1|^2 + iCu_2 \quad (1)$$

$$\frac{\partial u_2}{\partial z} = i\sum_{n=2}^{\infty} i^n \frac{\beta_n}{n!}\frac{\partial^n u_2}{\partial t^n} + i\gamma u_2|u_2|^2 + iCu_1. \quad (2)$$

We numerically solved the coupled NLSEs using the split-step Fourier method (SSFM)[10]. Defining the dispersion and nonlinear operators as

$$D_k = i\sum_{n=2}^{\infty} i^n \frac{\beta_n}{n!}\frac{\partial^n}{\partial t^n}, \quad N_k = i\gamma u_k|u_k|^2.$$

Where, k denotes the core index. The SSFM independently solves Eqs. (1) and (2) at each step dz, after which the solutions u_1 and u_2 are coupled using a 2×2 transfer matrix R of the coupler, given by:

$$R = \begin{pmatrix} \cos(Cdz) & i\sin(Cdz) \\ i\sin(Cdz) & \cos(Cdz) \end{pmatrix}. \quad (3)$$

The numerical step of Eqn. (1) and (2) becomes

$$\begin{pmatrix} u_1(z+dz) \\ u_2(z+dz) \end{pmatrix} \approx R \begin{pmatrix} e^{D_1 dz/2} e^{N_1 dz} e^{D_1 dz/2} u_1(z) \\ e^{D_2 dz/2} e^{N_2 dz} e^{D_2 dz/2} u_2(z) \end{pmatrix}. \quad (4)$$

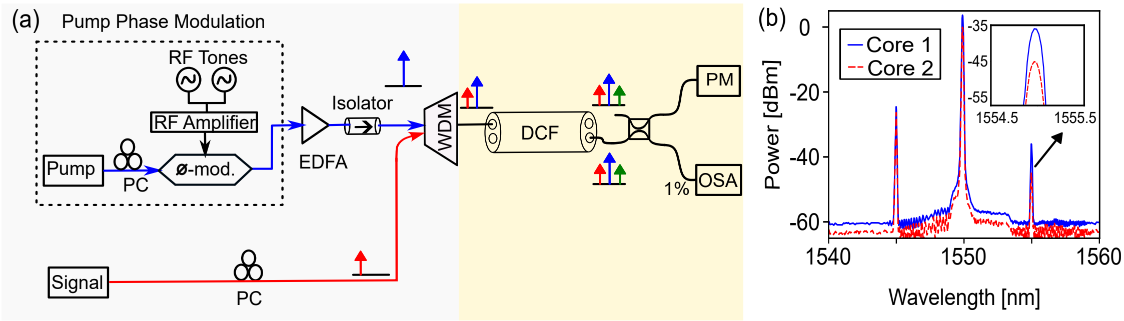

Fig. 1: (a) The experimental setup for measurement of crosstalk and wavelength conversion in coupled DCF. (b) Spectrum showing idler generation based on four wave mixing experiment.

The solution remains valid as long as the step size dz is much smaller than the coupling, nonlinear, and dispersion lengths of the coupled dual-core fiber. The measured value of C is 2.5 $\times 10^{-4}\,\mathrm{m}^{-1}$ at 1550 nm with β_3 and γ being $0.07\,\mathrm{ps}^3/\mathrm{km}$ and $7.1\,\mathrm{W}^{-1}\mathrm{km}^{-1}$, respectively, for both cores. The zero-dispersion wavelengths are measured to be 1543.5 nm and 1544.5 nm in core 1 and core 2, respectively, with an error of about 0.5 nm. The DCF is 350 m long, with a core diameter of 4.77 μm and a core-to-core separation of 17.4 μm, within a 125 μm cladding diameter.

Experimental setup

The experimental setup, shown in Fig 1 (a), consists of a tunable pump laser and a high-power EDFA with a maximum output power of 34 dBm. When working with high power pump, we need to suppress the Stimulated Brillouin Scattering threshold, which is about 20 dBm. The pump is phase modulated before sending it to the DCF. The RF input for the phase modulator is generated by an RF tone generator, which is amplified and fed to the modulator. We used two RF tones (100 MHz and 300 MHz) to modulate the pump phase. The modulated pump is amplified and passed through an isolator. A WDM coupler is used to filter pump ASE noise and combine the signal and pump before sending them to the DCF. The output of the DCF is recorded on an optical spectrum analyzer (OSA). The same setup measures power-dependent crosstalk in adjacent cores by turning off the signal and sweeping pump power from 0 dBm to 32 dBm. Wavelength-dependent coupling in the linear regime is measured using the EDFA as an ASE source, and polarization dependence with a tunable laser in the same setup.

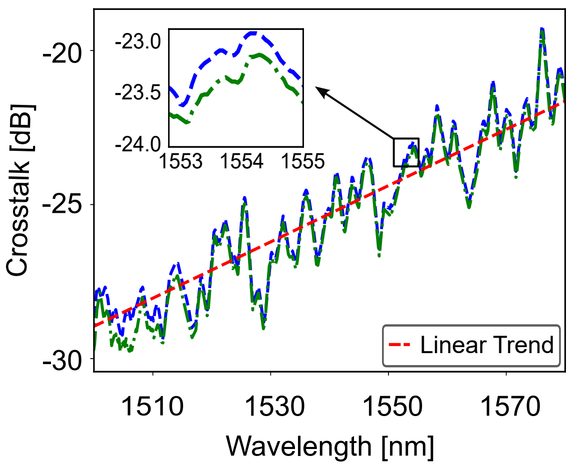

Fig. 2: Measurement of wavelength-dependent coupling in the linear regime of coupled MCF, showing two data sets taken 10 minutes apart.

Results and Discussion

The wavelength-dependent coupling in the linear regime is shown in Fig (2). This coupling in MCF arises from random perturbations such as core radius fluctuations, varying core separation, random birefringence, and micro-bending along the fiber. At longer wavelengths, the mode area increases, leading to higher mode overlap integrals and stronger coupling. Our experimental observations show that in the linear regime, changing the SOP of the launched signal causes significant crosstalk variation, as shown in Fig (3). The effect of polarization on nonlinear coupling is shown in Fig (4). In SMF, polarization mode disper-

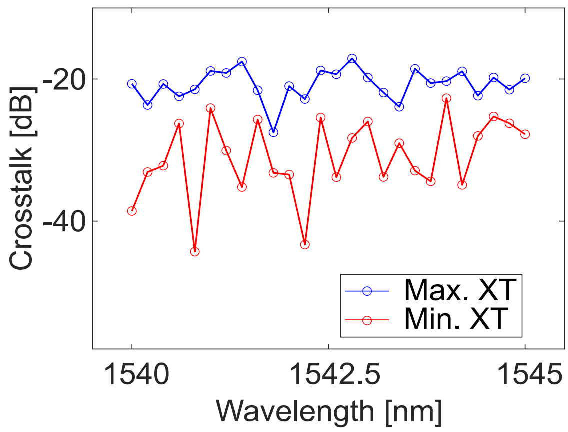

Fig. 3: Measured crosstalk variation with (max./min.) state of polarization (SOP) and wavelength.

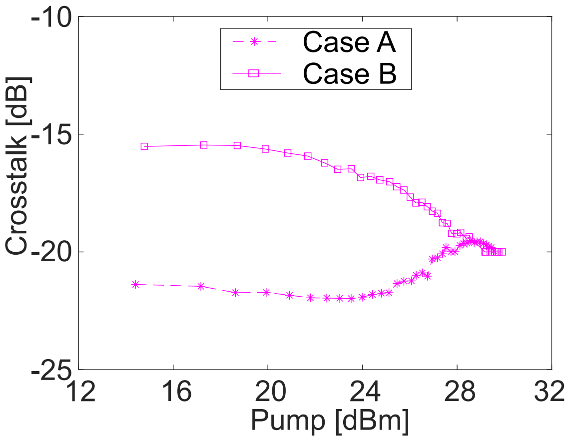

Fig. 4: Power-dependent crosstalk at 1554 nm. Case A (Case B) corresponds to the SOP being set for min (max) crosstalk in the linear regime.

sion (PMD) and nonlinearity compete for control of polarization of the wave[11]. However, in coupled MCFs, another interacting phenomenon is linear coupling. In the nonlinear regime, as pump power increases, the influence of PMD, which primarily affects case A, diminishes due to the enhanced self-polarization effect of the pump. When pump power exceeds a certain threshold, cross-polarization terms, sensitive to phase mismatch caused by birefringence, become comparatively negligible. Consequently, case A and case B are influenced identically by linear and nonlinear coupling effects.

A measurement of nonlinear coupling at two wavelengths is shown in Fig (5). Efficient power transfer occurs only when phase matching is satisfied. At high power, the nonlinear phase shift affects phase matching[5],[12]. As a result, optical power remains in the same core, leading to nonlinear power suppression in the adjacent core[13]. However, at sufficiently high power, the phase-matching condition is disrupted, changing the power transfer trend. Phase matching can be disrupted by the interplay between linear coupling and nonlinearity, as discussed in[5], and by inherent random wavelength-dependent coupling. Crosstalk depends sensitively on the coupling coefficients, and differences between ideal and measured fiber can be partly understood by longitudinally varying random coupling coefficients; an example is shown in Fig 5 (solid lines).

Parametric effects and idler conversion efficiency are measured in both cores, as shown in Fig (6). Wavelength conversion in coupled MCF is investigated using a 24 dBm pump and a weak signal launched into the same core. The idler spectrum is shown in Fig 1(b). The wavelength dependence of the coupling causes fluctuations in the idler conversion. The bandwidth reduction compared to simulations in core 1 may be due to PMD and zero-dispersion wavelength fluctuations along the fiber[14],[15]. Simulations show that stronger coupling (dashed lines in Fig 6) enhances phase matching and reduces the phase mismatch dip in both cores, thereby improving conversion efficiency. Experimental results are in good agreement with the simulations.

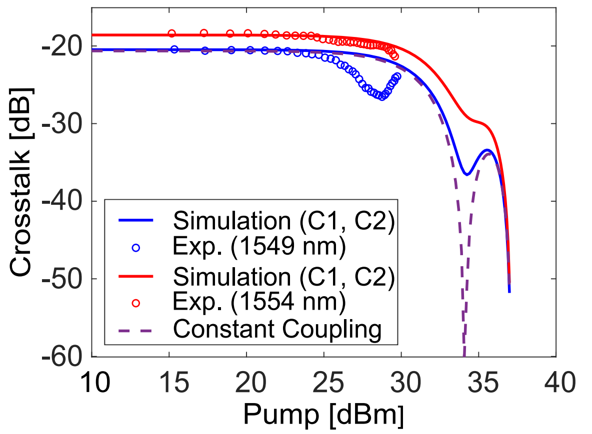

Fig. 5: Power-dependent crosstalk measured at different wavelengths. Simulations using coupling coefficients C_1/C_2 in the first/second half of the fiber show improved agreement with experiments.

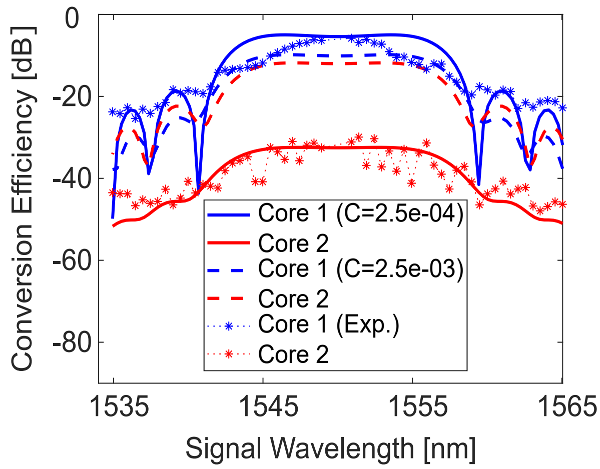

Fig. 6: Wavelength conversion in coupled MCF when only one core contain both pump and signal.

Conclusions

We have studied linear and nonlinear coupling in an MCF experimentally and numerically. Our results show that nonlinear responses are highly sensitive to the longitudinally varying coupling coefficient in real MCF fiber. We have also investigated wavelength and polarization dependent coupling, showing that wavelength-dependent coupling causes idler conversion fluctuations, and stronger coupling reduces the phase mismatch dip in both cores.

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