Mode-Dependent Gain Characterization of Erbium-Doped Multimode Fiber Using C^2 Imaging

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Abstract: We characterize the mode profiles, delays and mode-dependent gains of an erbium-doped step-index multimode fiber using C^2 imaging based on a swept-wavelength interferometer. Space-to-time mapping is used to reduce measurement time.

OCIS codes: (060.2270) Fiber characterization; (060.2410) Fibers, Erbium.

1. Introduction

The spatially and spectrally resolved imaging method, known as S^2 imaging, has been applied for modal content analysis for a variety of optical fibers, i.e., large-mode area fibers applied for high-power fiber lasers [1] and few-mode or multimode fibers focused recently for space division multiplexing (SDM) [2]. A dominant power mode, usually the fundamental mode, is required in S^2 imaging to generate spectral interference between the dominant power mode and the other modes. Compared to S^2 imaging, the cross-correlation (C^2) imaging method, which applies an external reference arm to create the spectral interference is more flexible, e.g., no constraint on mode excitation at the input, and has larger dynamic range. Moreover, the C^2 imaging method provides more information about the fiber [3, 4]. Chromatic dispersion and modal delay characteristics for each mode can be acquired without any prior knowledge of the fiber under test. By employing a tunable laser, C^2 imaging in frequency domain can significantly reduce measurement time [5, 6].

In this paper, we develop a frequency-domain C^2 imaging method based on a swept-wavelength interferometer (SWI) with a wavelength scanning range of 100 nm (from 1520 nm to 1620 nm). A cladding-pumped erbium-doped step-index multimode fiber (MMF) is fully characterized including modal delays, modal contents and mode-dependent gains.

2. The C^2 Imaging Method Using A Swept-Wavelength Interferometer

Figure 1(a) shows the C^2 imaging setup based on a swept-wavelength interferometer (SWI) [7] for characterizing the erbium-doped fiber (EDF). The schematic of the SWI is illustrated in Figure 1(b), which uses a polarization-diversified

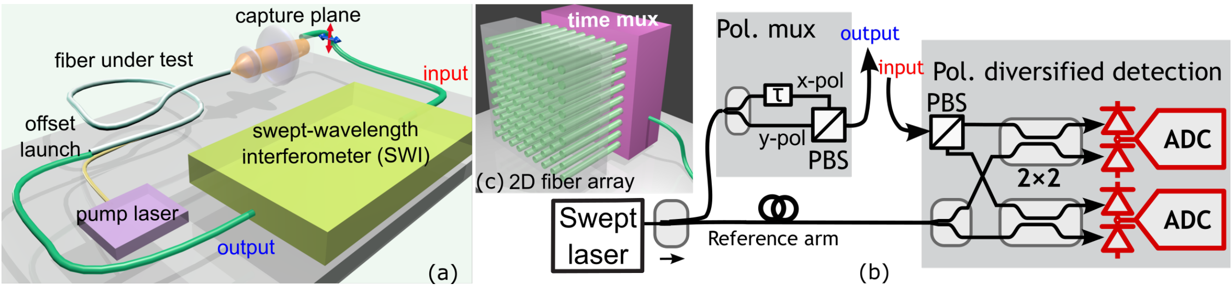
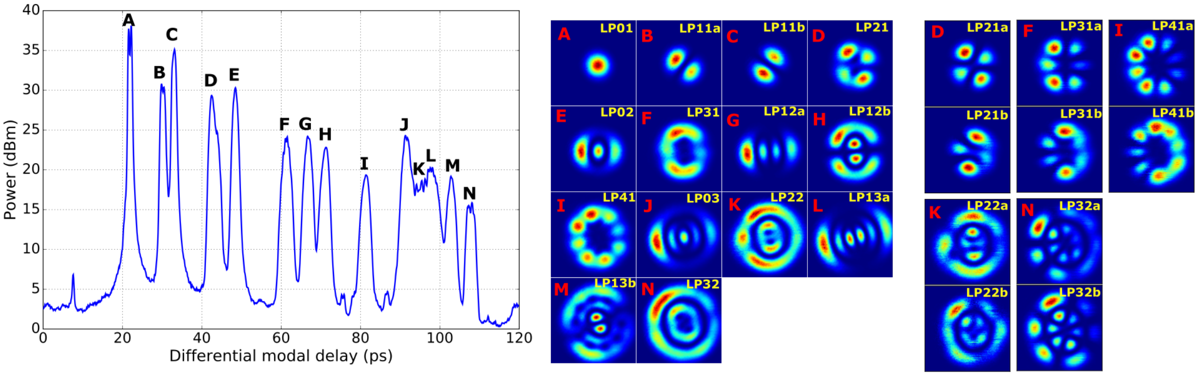


Fig. 1: Schematic of (a) the C^2 imaging setup, (b) a swept-wavelength interferometer with polarization diversified detection, and (c) using a 2D fiber array and a time-multiplexing block based on fiber delay lines to realize space-to-time mapping for reducing measurement time.



(a) (b) (c)

Fig. 2: (a) Cross-correlation trace summed over all scanning pixels, (b) mode profiles using a Fourier filter to select each cross-correlation peak, and (c) separated degenerate modes using multivariate analysis.

receiver to detect both states of polarization simultaneously and a polarization multiplexer with a time delay to launch both states of polarization simultaneously. A large measurement time window around 163 ns and finest temporal resolution of 0.08 ps can be offered by the SWI, operated with a wavelength-sweeping rate of 1300 nm/s and an analog-to-digital converter (ADC) sampling rate of 50 Mb/s. Either applying a reference fiber with a same chromatic dispersion (CD) characteristic to the mode of interest or using digital signal processing to compensate the unbalanced CD can enable the finest temporal resolution.

Offset launch was applied at the input to excite all modes. A free space telescope was used to achieve a magnified beam at the capture plane where a single-mode fiber (SMF) scans in 2 dimensions for mode spatial reconstruction. 2-dimension (2D) mechanical scanning is a time-consuming process, which can be avoided through space-to-time mapping using a 2D fiber array and a time-multiplexing block, as illustrated in Figure 1(c). Related demonstration will be present in next section.

We characterized a 4-meter long EDF [8] with a diameter of 22-24 μm and a core-cladding refractive index difference of 2.3×10^{-3}. Figure 2(a) shows the cross-correlation trace summed over all scanning pixels, where different beat peaks representing the interference between the reference arm and all 19 spatial modes. Each has two polarizations. After selecting each cross-correlation peak through a Fourier filter, mode profiles can be reconstructed by integrating the spectrum over all scanning pixels. Due to the slightly elliptical core of the EDF, non-degeneracy for some usually degenerate modes in a circular core such as LP11 modes can be observed, see Figure 2(b). It becomes difficult to separate higher-order degenerate modes. Due to fiber imperfection, both spectral and spatial degeneracies are unlikely to be fully maintained as in the ideal case [9]. Multivariate analysis based on non-negative matrix factorization (NMF) [10] was applied to the datasets. It can be seen in Figure 2(c) that all degenerate modes can be isolated.

3. Amplifier Gain Characterization Using Space-to-Time Mapping

We applied a 1-dimension fiber array with 7 SMF ports, spaced at 381 μm as a proof-of-concept demonstration for space-to-time mapping due to the unavailability of a closely-packaged 2D fiber array. The fiber array only needs to be scanned within a 381-μm range along the array direction along with a full 2.7-mm scan in the other direction to cover a capture plane with a size of 2.7×2.7 mm^2, which reduces the total measurement time by 7 times. By employing a closely-packaged 2D fiber array covering the whole capture plane,the measurement can be finished in a single scan.

To avoid the lasing effect, the 4-m EDF was operated under 0.15-W pump power through side pumping [8]. Figure 3(a) shows the time-multiplexed data sequence for 7 spatial ports at one scanning position, where two peak groups for each port representing two launch polarization states, i.e., x and y polarization. Figure 3(b) shows the cross-correlation results with and without pumping, summed over all scanning positions. The mode-dependent gain difference for the first 10 spatial modes is around 3 dB, see Figure 3(b), which is comparable to the measured results in [8]. Since the SWI is based on heterodyne detection, this method is insensitive to the amplified spontaneous emission (ASE), which does not preserve the mode content as observed in [11] and will disturb the measurement for modal content with direct detection, e.g., using a single camera. In our measurement, the input SMF was spliced to the EDF with an offset that induced weak mode excitation for LP12a, LP03 and LP13a modes, corresponding to the cross-

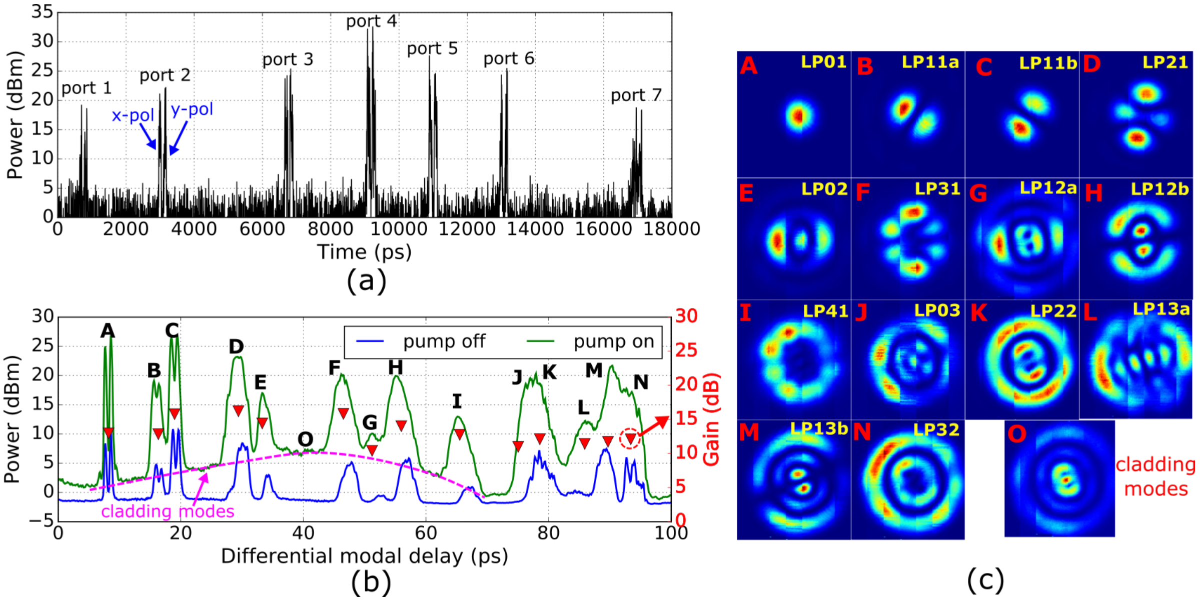


Fig. 3: (a) Time-multiplexed data sequence for 7 spatial ports, (b) cross-correlation results with and without pumping summed over all scanning pixels and calculated mode-dependent gains for different modes, and (c) mode profiles for each cross-correlation peak selected by a Fourier filter.

correlation peaks at G, J and L. Mode profiles for different cross-correlation peaks are illustrated in Figure 3(c). The noise floor (the pink curve in Figure 3(b)) from 10- to 70-ps delay was built up due to the cladding modes, which were below the system noise floor without amplification. The cladding modes propagated faster than all the core modes. It caused the cladding modes of the y polarization intrude in the capture window of the x polarization, see Figure 3(a)). Increasing the polarization delay at the polarization-multiplexing stage can eliminate this effect. The amplified power for the LP12a mode was comparable to that of the cladding modes, which induced a superimposed mode profile at G in Figure 3(c)).

4. Conclusion

We demonstrated C^2 imaging with 163-ns measurement time window and 0.08-ps temporal resolution by employing a swept-wavelength interferometer. Using space-to-time mapping, measurement time can be significantly reduced. A cladding-pumped erbium-doped multimode fiber was fully characterized by the C^2 imaging method. Mode-dependent gain characterization of 14 spatial-modes was measured simultaneously.

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