Coupled-Core Optical Amplifier

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Abstract: We demonstrate a 4-core fiber amplifier that has strongly coupled cores at both the pump and signal wavelengths. Strong mode-coupling minimizes the mode dependent loss and simplifies requirements on the spatial uniformity of the pump.

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1. Introduction

Coupled-core transmission fiber has been shown to outperform equivalent single-mode fiber (SMF) [1] because the strong random mixing between cores reduces the buildup of nonlinear interactions [1–4]. Linear impairments are also reduced as the mixing ensures that every input signal propagates nearly equally on all cores which homogenizes any loss or delay differences between cores. In particular, the mode-dependent loss and the differential group delay between cores grows proportional to the square root of the length rather than linearly [5]. We extend these strong mixing concepts studied in transmission fibers to amplifying fibers to solve two problems: 1) reducing mode-dependent gain (MDG) by scrambling the signal modes across all cores and 2) distributing the pump more evenly to all modes. We fabricated and tested a 4-core coupled-core amplifier and are showing below that the strong mixing reduces the amplifiers MDG.

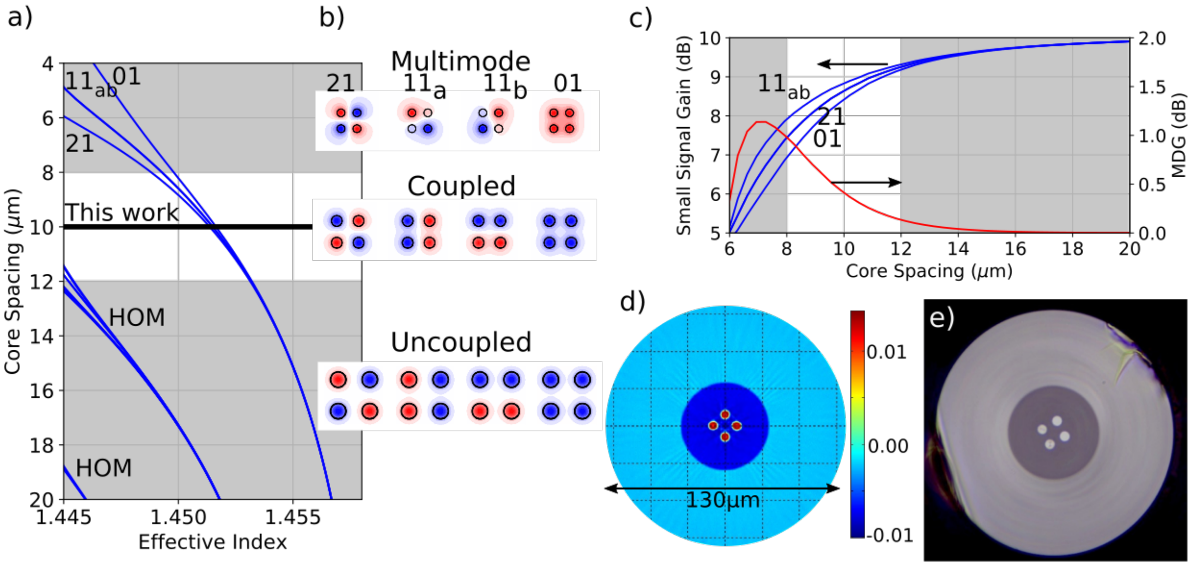

Fig. 1: a) Mode effective indexes and b) propagation constants versus pitch. c) Small signal gain and MDG vs. core spacing and d) Refractive index with respect to silica and e) fiber facet image. HOM: Higher Order Modes of each core.

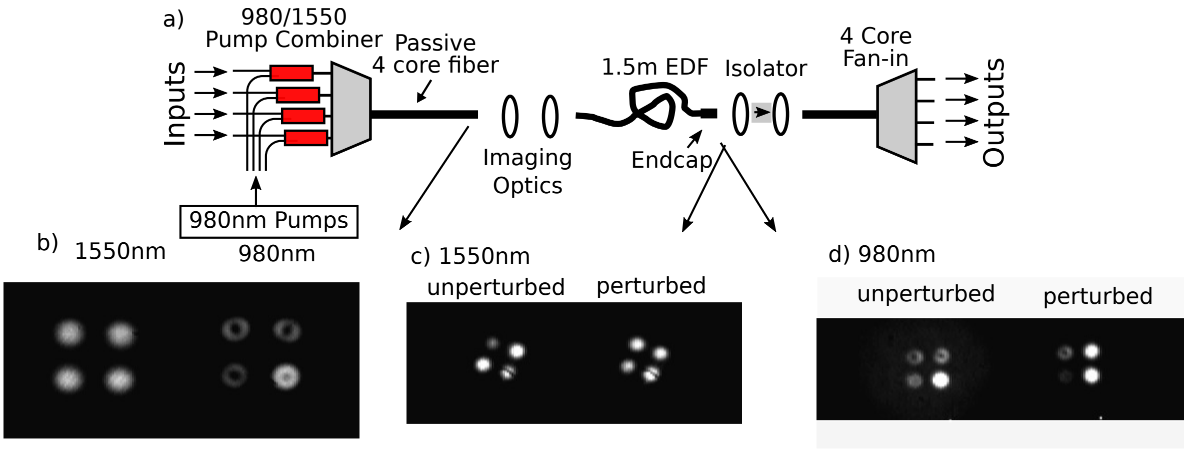

Fig. 2: a) Amplifier characterization setup. b) Output of fan-in. c,d) Output of 2-m EDF without and with fiber pertubation.

2. Coupled Core Amplifying Fiber Design

Figure 1d) shows the refractive index profile of the 4-core erbium-doped fiber (EDF) amplifier under test. It was fabricated by placing four etched erbium core rods into a fluorinated preform with 4 drilled holes. The core Δn is 0.015, core spacing is 9.4 μm and core diameter is 6 μm. The cores are doped with an erbium density of 1.5×10^{25} m^{-3}, and the peak loss at 1530 nm is 20 dB/m. It is designed to have the same core spacing to pitch ratio as the 4-core transmission fiber [6] which has a pitch of 20 μm and mode-field diameter of 12 μm such that imaging optics can efficiently magnify the amplifier outputs to match the transmission fiber. Future fibers can use a lower Δn to obtain strong coupling at the 20 μm pitch.

To obtain strong random mixing in a coupled-core fiber, the cores cannot be placed too close together or too far apart. Figure 1a) shows the mode propagation constants and Fig. 1b) shows the mode profiles for different core spacings. Note, the displayed supermodes and propagation constants are for the entire 4-core structure; individual core modes can be calculated as a superposition of the 4 supermodes, and the beat lengths of these core modes are inversely proportional to the difference of the supermode propagation constants.

There are three different regimes: 1) multi-mode, 2) coupled-core and 3) uncoupled. In the multimode and uncoupled regimes the supermodes do not couple, and in the coupled-core regime, the supermodes strongly couple. In the multimode regime (core spacings $<$8 μm) the 4 cores behave like a single core with four separate modes. Each of the modes has a very different overlap with the doped core which induces MDG [Fig. 1c)] and the large splitting of the propagation constants inhibits random mode coupling between the cores. In the uncoupled regime (core spacings $>$12 μm), the supermodes are degenerate, and the mode profiles have the same intensity (but different phases) and there is very small mode coupling because the supermodes do not beat. In the coupled-core regime, the 4 cores start to behave like a single multi-moded core, but the propagations are slightly different which cause the cores to be susceptible to pertubative mode coupling which can be induced by environmental fluctuations such as bends, twists, temperature, squeezing, or fabrication defects such as microbends, diameter fluctuations, and refractive index inhomogeneity. Thus, the coupling can be enhanced by intentionally twisting and bending the fiber.

Figure 1c) shows the small signal gain assuming an amplifier length that provides peak gain of 10 dB computed from the mode overlap integrals which shows the MDG increasing as the cores get closer together. In the coupled-core regime, the MDG is around 0.5 dB, however, the strong mode-mixing is expected to mitigate the MDG. The measured mode-mixing at 1550 nm is 100% after a few cm and at 980 nm is around -7 dB/m. Fig. 2c,d) shows how twisting and bending the fiber can enhance the pump scrambling at 980 nm.

3. Experimental Setup

Figure 2a) shows the setup for measuring the amplifier. The amplifier was intentionally twisted and bent to enhance the random mode coupling. Note, that commercial amplifiers could use spooling and twisting to achieve the desired level of repeatable mixing. 4-f imaging optics with a magnification of 2.2× are used to couple light from the 4-core fiber into 2-m of 4-core transmission fiber pigtails. Fiber fan-in devices with 0.5 dB loss demultiplex the signals from the transmission fiber into separate SMFs. The pumps were coupled into the SMFs using 980/1550nm fiber combiners. At 980 nm the fan-in is core selective with some higher-order mode (HOM) crosstalk into the adjacent cores, and at 1550 nm the fan-in is fully scrambled [Fig. 2b)].

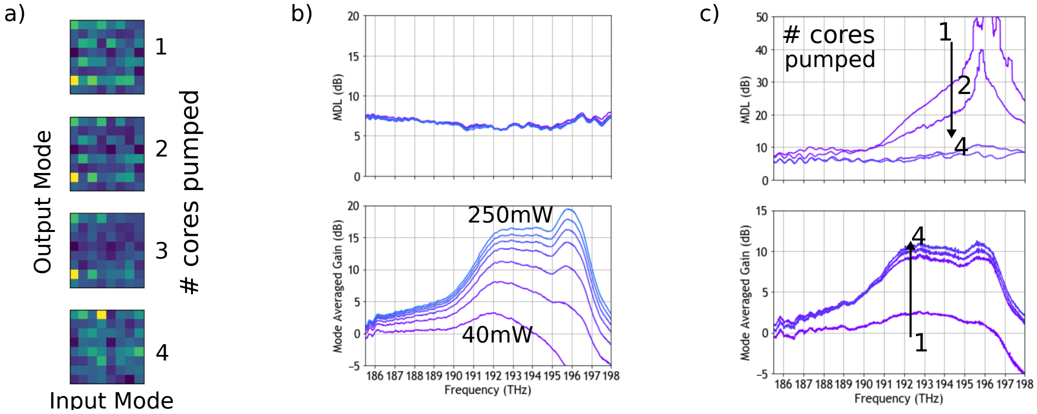

Fig. 3: Mode-dependent gain measurements of a 1.5-m and 2-m EDF. a) Transfer matrix summed across all wavelengths with brighter color indicating larger coupling versus number of pumped cores. MDL and mode averaged gain vs total launched pump power of b) a 2-m piece and c) a 1.5-m sample that is intentionally perturbed versus number of pumped cores.

4. Mode Dependent Gain Measurements from Transfer Matrix Measurements

In an uncoupled core amplifier with N cores (without mode-mixing) MDG can be measured by launching and receiving each mode one-by-one and calculating the ratio of minimum and maximum value. However, in fully coupled systems mode-selective excitation and reception is erroneous because each input evenly excites all outputs. The most accurate way to measure MDG is to characterize the amplitude and phase transfer matrices (TM) of the amplifier between each input and output pair across all wavelengths. The TM captures all possible paths (N^2) through the multimode system. From this TM, the MDL/MDG and mode averaged insertion loss/gain (IL/IG) can be computed by a Eigen-analysis of the TM similarly to how polarization dependent loss can be calculated from the 2×2 Jones matrix [7]. We measure the TM using swept-wavelength interferometer with spatial-diversity [7].

To study the benefits of mode-mixing to mitigate amplifier impairments, we measure the TM with a subset of pumped cores. This is an extreme example, because an unpumped core would have high loss and effectively reduces the number of cores, unless strong mixing at the pump wavelength distributed the pump to all cores. Fig. 3a) shows the intensity of the 8×8 TM (4 cores and 2 polarizations) measured across the entire C-band. We show the matrix to illustrate that the system is fully coupled and to highlight the importance of TM measurements to characterize the MDG. Fig. 3b) shows the mode averaged gain for even pump illumination for different pump powers which shows the MDL does not change under uniform pump illumination. The 6-dB to 7-dB floor is due to imperfections in coupling into the amplifier such as rotational misalignment. Fig. 3c) shows the mode-averaged gain and the MDL as the # of pumped cores (each at 60 mW) is varied from 1 to 4 on a shorter, but more perturbed sample. As soon as 2 cores are pumped the gain is within 3-dB of its maximum value, however the mode-dependent loss at the short wavelengths is >30-dB. With 3 and 4 cores pumped the MDG across the whole band has reduced to approximately 7 dB. Without pump scrambling, pumping only 3 cores would result in nearly infinite MDL because the EDF would lose a core. Here, the MDG performance is only slightly worse for 3 pumped cores compared to 4 pumped cores which indicates that the random mode scrambling can lessen the effects of a lost pump and possibly other core dependent effects.

In conclusion, we have demonstrated a coupled-core amplifier supporting 4 modes. Strong coupling minimizes the effect of MDG variations between cores and can be extended to multimode amplifiers.

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