Assembly and Characterization of a Multimode EDFA Using Digital Holography

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Abstract: We present the assembly and characterization of a multimode EDFA supporting up to 45 modes using digital holography to measure the transfer matrix of the system at each step to obtain mode dependent loss and crosstalk characteristics of the amplifier.

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1. Introduction

The capacity limit of single mode fibers (SMFs) has led to the development of new technologies, such as space division multiplexing (SDM), where multiple spatial modes can be used for future data transmission, including few-mode fibers (FMFs) [1], coupled-core multicore fibers (CC-MCFs) [2] and uncoupled multicore fibers (MCFs) [3]. These new fibers increase the transmission capacity relative to SMFs by using the spatial degree of freedom, where each fiber contains multiple modes or cores. A key component for such systems to become feasible and possibly deployed, is the design and fabrication of amplifiers compatible with each of the different types of fibers used for SDM. Of particular interest in this work are multimode amplifiers which support more than 10 spatial modes [4].

The challenge with building a multimode amplifier is achieving equal gain across the fiber waveguide. In other words, all modes need to have exactly the same gain. Additionally, there are several critical parts to a multimode amplifier including the input and output splices through which the transmission fiber modes are amplified, and each part contributes to the overall mode dependent loss and mode scrambling.

In an ideal amplifier without mode mixing, each input mode couples to exactly the same output mode. Characterizing such an amplifier with N modes would require exactly N measurements. However, in the presence of mode mixing, each input mode can couple to every single output mode and the entire complex transfer matrix must be measured (i.e., $N \times N$ measurements) and analysis of this matrix can determine the linear properties of the fiber such as mode dependent loss (MDL), crosstalk (XT), and gain. Proposed methods such as swept wavelength interferometry for measuring the transfer matrix of an amplifier requires the use of a pair of mode multiplexers which themselves can introduce MDL and XT and no direct feedback can be inferred in the intermediate assembly steps of the amplifier. The issue becomes more pronounced when the number of modes is increased as the mode multiplexer will typically have more parasitic effects [4].

Digital holography is a powerful technique that does not require a mode demux, and therefore can be used to measure the transfer matrix at each section of a device [8]. In this work we present the detailed assembly and characterization of a multimode amplifier supporting up to 45 spatial modes an its characterization using digital holography to measure the transfer matrix and obtain the MDL and XT of the amplifier at each step during the assembly from the MMF input through the mode matched splices and all the way to the multimode output.

2. Experimental setup

The step index erbium-doped fiber (EDF) used for this amplifier was made in house having core/cladding diameters of 30/83 µm with an erbium ion concentration of 4.5×10^{-3} and low refractive index coating with 0.46 NA as shown in Fig. 1 (b) , this fiber supports around 60 modes at 1550nm. The passive multimode fiber has a graded index profile and is described in [5] supporting 45 spatial modes, with a maximum index difference between core center and cladding of $\Delta n=15\times10^{-3}$ at 1550 nm. The modes of the EDF are different than the HG modes in the graded index multimode fiber leading to an increase in MDL. To better match the EDF and graded index multimode fiber we use an intermediate fiber, an 80 µm core diameter graded index fiber having the same mode sizes as that of the 50 µm fiber, which is tapered down to 80 µm cladding diameter to reduce the MDL when splicing to the EDF. This amplifier was designed and used for pre-amplified detection after going through a turbulent free space link as reported in [6].

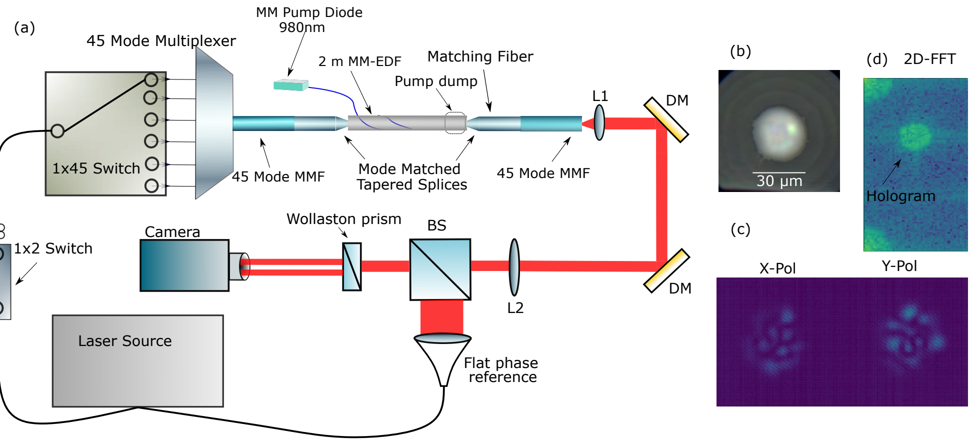

Fig. 1. (a)Digital holography setup used for the characterization of the MM-EDF amplifier, L1, L2: Lens 1 and 2 respectively, DM: Dichroic mirror, BS: Beam splitter, (b) cross section of the EDF, (c) Captured images on the camera for X and Y polarizations, and (d) resulting hologram

The digital holography setup is depicted in Fig. 1 (a), light from a tunable laser is split into 2 paths, the first is send to the reference arm and the second is sent into a 1x2 switch for each polarization, and subsequently into a 1x45 switch, which is connected to each of the inputs of a 45-mode multiplexer based on multi-plane light conversion (MPLC) [7]. The output multimode fiber from the MUX is spliced to the 80 µm graded index fiber and subsequently spliced to the EDF after tapering as previously mentioned. The 980-nm pump light from a multimode laser is injected into 2m of EDF by tapering down to 15 µm a section of coreless fiber and wrapping it around the EDF, at the end of the 2m section of EDF we have a pump dump to prevent most of the the unabsorbed pump light to couple into the following passive fiber. To further reduce the unabsorbed pump light we also use 2 dichroic mirrors, whereas a beam splitter is used to combine the signal and reference beams, and a 4F imaging system is used to record the modes using a InGas camera after passing through a Wollaston prism that allows for simultaneous detection of both polarizations. The recorded image shows the interference pattern between the signal and the reference as shown in Fig. 1 (c) , after taking the Fourier transform of the recorded image we obtain the hologram as seen in Fig. 1 (d). To characterize the whole transfer matrix of the amplifier, we switch over each input mode per polarization and record the amplified mode with the camera.

The holograms are then processed by overlapping with a set of desired modes, for this specific amplifier we use the first 45 Hermite-Gaussian modes, matching closely the eigenmodes of graded-index multimode fiber. Digital holography allows for measuring the whole transfer matrix of the system at each step of the assembly process of the amplifier: the initial transfer matrix is shown in Fig. 2 which is the output of the multimode fiber after the MUX, we obtain two per polarization transfer matrices that combined form the complete transfer matrix, we typically observe strong mode coupling within the mode groups, when we add all modes for each mode group we obtain the diagonal transfer matrix per mode group, where the measured XT from the obtained transfer matrix is around 11dB. The XT is calculated as the ratio between the total power in the diagonal respect to the power in the non-diagonal area of the transfer matrix.

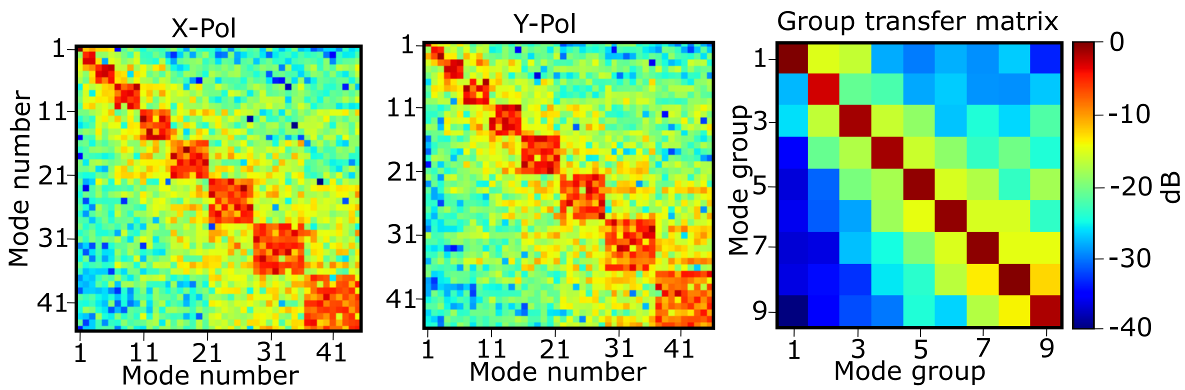

Fig. 2. Transfer matrices for X and Y polarizations, and summed group transfer matrix after the multimode graded index fiber coupled from the MUX

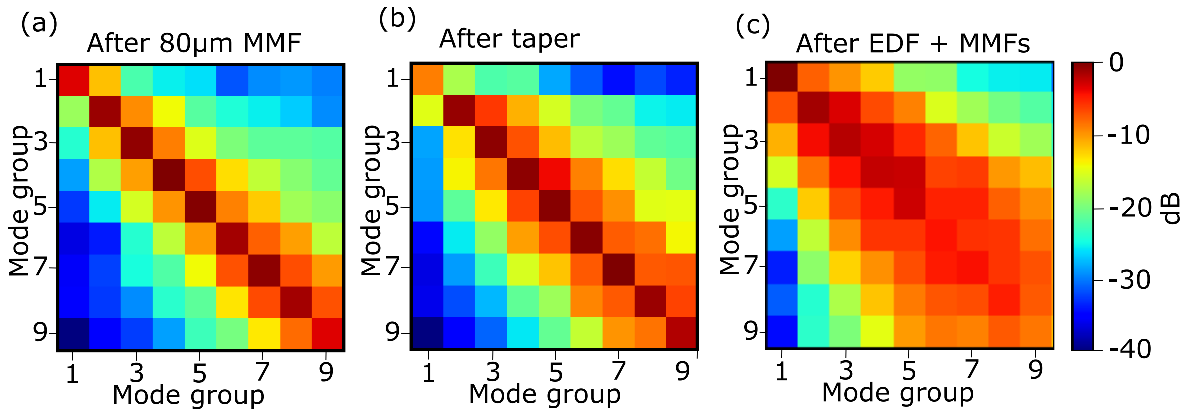

Fig. 3. Transfer matrices during the assembly process (a) after splicing 80 μm matching fiber, (b) after tapering mode matching fiber(c) after the final multimode fiber spliced to the amplifier

3. Results

With the use of digital holography we can measure the transfer matrix at each step during the assembly of the amplifier, we use the transfer matrix after the multimode graded index fiber as a reference for the performance of the amplifier when adding/splicing each passive and active fiber. First when splicing the 80 μm fiber we measure the transfer matrix as shown in Fig. 3 (a), we observe from this a degradation of the XT to 3.3 dB after the splice due to the mode overlap during the splice,Fig. 3 (b) shows the transfer matrix after tapering which is almost the same as before tapering with little degradation in XT to 1.75 dB, this process continues and for each splice point we can measure the transfer matrix, after having the whole transfer matrix of the system we can quantify the final MDL and XT of this amplifier, Fig. 3 (c) shows the final transfer matrix after the final splice to the multimode fiber in which we observe that due to the mode mismatch we obtain a XT value of -3.2 dB, where the XT for higher order modes is stronger than that of the first mode groups, however, we still observe that most of the power is confined within the diagonal of the transfer matrix.

From the transfer matrix we can obtain the MDL at each step of the assembly, in our reference transfer matrix we measured 9.5 dB MDL, and as we continue adding each fiber the MDL is degraded, when adding the 80 μm fiber the MDL is 11.1 dB, whereas, after tapering the MDL increases to 13.4 dB, at the final transfer matrix the MDL has a value of 16.8 dB. It is important to notice that this technique allows for an active alignment by monitoring MDL without needing a second MUX.

4. Conclusions

We have shown a detailed assembly and characterization of a multimode EDFA using digital holography, this technique allows for a step by step characterization of the amplifier by measuring the transfer matrix of the system, and obtaining important parameters such as MDL and XT at each splice point while requiring only one single multiplexer, and can be applied regardless of the number of modes.

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