Investigation of Wideband Distributed Raman Amplification in a Few-Mode Fiber Link

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Abstract: We experimentally investigate distributed Raman amplification in a graded-index three-mode fiber over more than 80 nm signal bandwidth. We measured gain of up to 6 dB with 0.3 dB mode-dependence when pumping only the highest-order modes.

1. Introduction

Space-division Multiplexing (SDM) is a promising technology to increase the capacity in optical fiber communications by utilizing multiple parallel spatial channels of an optical fiber to transmit independent data signals [1]. Among various demonstrated fibers suitable for SDM transmission, few-mode fibers (FMFs) are a particularly interesting fiber type, as FMFs can guide multiple spatial channels within a common fiber core, leading to a high spatial channel density [2]. Additionally, FMFs and relevant devices such as mode-multiplexers are compatible with wideband transmission, and more than 80 nm transmission has been demonstrated over short- [3] and long-haul distances [4]. For long-distance FMF transmission, it is desirable to use FMFs with low differential-mode delay (DMD), typicality achieved by employing graded-index core designs.

Distributed Raman amplification can reduce the apparent loss of a transmission link and hence increase the signal quality at the receiver. In FMFs, two different types of Raman gain can be achieved: intramodal Raman gain, where signal and pump propagate in the same fiber mode and intermodal Raman gain, when signal and pump propagate in different fiber modes. Raman amplification in FMF transmission has been theoretically investigated [5,6] and experimentally demonstrated over short- [7,8] and long-haul distances [9,10], however so far only using signals with up to 15 nm total optical bandwidth within the C-band [10], with a single Raman pump wavelength [7–10] and mostly using step-index fiber FMF designs [7–9].

In this paper, we experimentally investigate distributed, backwards-pumped Raman amplification in a 54.4 km, graded-index FMF link, using 12 Raman pump wavelengths between 1410 nm and 1502 nm and a wideband signal spanning the C- and L-bands between 1527 nm and 1608 nm. We find that the wavelength-averaged Raman On-Off gain can reach up to 6 dB while only a small mode-dependent gain was observed. Spectral gain varied by up to 2 dB between peak gain at 1550 nm and lowest gain at 1608 nm. We confirm theoretical predictions [5] that due to the graded-index core design, the gain in the fundamental mode, due to cross-modal Raman amplification from pumps, propagating in the higher-order modes, is similar to the intra-modal Raman gain within the higher-order modes. This shows that distributed Raman amplification can be used without significantly increasing the mode-dependent loss of the transmission link, highlighting the potential of combining distributed Raman amplification with wideband transmission in FMF-based SDM transmission.

2. Experimental Setup

The experimental setup to analyze wideband distributed Raman amplification in a FMF link is shown in Fig. 1. To emulate a wideband signal, two C- and L-band erbium-doped fiber amplifiers (EDFAs) were used in combination with two optical processors (OPs) to generate spectrally flat amplified spontaneous emission noise (ASE) spanning a wavelength from 1527 nm to 1608 nm with a 3 nm guard-band from 1567 nm to 1570 nm. A variable optical attenuator (VOA) was used to control the output power of the ASE source. The signal was split into three paths, each decorrelated by 1 m SMF before a mode-selective, fused-fiber photonic lantern mode-multiplexer (MUX) was used to launch the signals into the three fiber modes of a FMF link. Both used MUXs had insertion loss of 0.5 dB in the LP_{01} modes and 0.8 dB in the LP_{11} modes. The 54.4 km FMF link consisted of three spans for almost ideal compensation of the differential mode delay (DMD). The LP_{01} and LP_{11} modes had attenuation

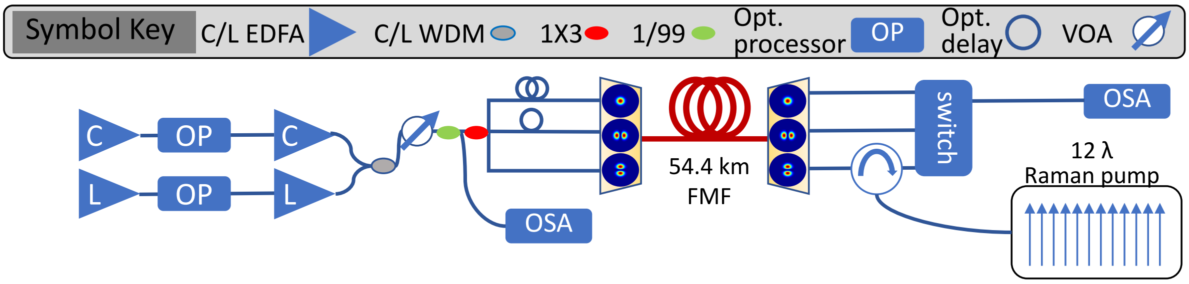

Fig. 1. Experimental setup for the investigation of wideband, backwards-pumped, distributed Raman amplification in a 54.3 km few-mode fiber link, using shaped amplified spontaneous noise between 1527 nm and 1608 nm as a signal and 12 pump lasers between 1410.8 nm and 1502.7 nm wavelength as Raman pump lasers. Due to strong coupling within the LP_{11} mode-group, pump light was only coupled into one of the mode-demultiplexers.

below 0.2 dB/km and 0.22 dB/km, respectively, at 1550 nm wavelength. The effective area of the fundamental mode was measured at 125 μm^2. After mode demultiplexing (DE-MUX) in a similar device as the mode-MUX, an optical switch enabled the measurement of the optical spectra at the three output ports with an optical spectrum analyzer (OSA). The 12 lasers for backwards-Raman pumping were coupled through an optical circulator into one of the LP_{11} mode ports of the DE-MUX. Due to strong coupling within the LP_{11} mode-group, pump light rapidly spread to all modes within this mode-group. The Raman pumps were distributed feedback (DFB) lasers with wavelengths between 1410.8 nm and 1502.7 nm with up to 160 mW for the two lowest wavelengths pumps and 80 mW for the remaining 10 pump lasers for a total maximum pump power of approximately 1120 mW. Equal pump powers were used on all but the two lowest wavelength pumps to asses Raman gain in the FMF, while we leave an individual pump power optimization for spectral gain equalization for future investigations.

3. Results and Discussion

Initially, the loss- and crosstalk characteristics of the FMF link were investigated by launching the light from a broadband super continuum light source sequentially into the three input ports of the MUX, while measuring the output spectrum at the three ports of the DE-MUX in sequence with an OSA. From these measurements, we calculated the loss, including MUX, FMF and DE-MUX, as well as the crosstalk between the LP_{01} and LP_{11} mode-groups. Figure 2(a) shows the loss for the two mode-groups, indicating a strong increase of loss below 1450 nm wavelength and an increase of the loss difference between the two mode-groups with increasing wavelength, reaching up to 3 dB at 1620 nm. Figure 2(b) shows moderate crosstalk levels between the two mode-groups, ranging between 8 dB and 13 dB, indicating high mode-purity at both, signal and pump wavelengths.

In FMFs, Raman amplification can be achieved due to the interaction of signal and pump light propagating in the same fiber mode (intramodal gain) or due to pump light that propagates in a different fiber mode than the signal light (intermodal gain). The relative strength of intra- and intermodal gain can be determined by the intensity overlap integrals f_{ij} between modes i and j, shown in Fig. 2(c), normalized to the value of the LP_{01} mode for a step-index and a graded (parabolic)-index FMF, calculated as described in [5]. Unlike in step-index FMFs, the intermodal gain in graded-index FMFs between pumps in the LP_{11} modes and signals in the LP_{01} modes is equal to the intramodal gain that signals experience in the LP_{11} modes due to pumping of the LP_{11} modes. While this implies that exclusively pumping the LP_{11} modes does not increase MDL, it also shows that it is not possible to partially or fully compensate any already existing MDL by achieving higher gain in the LP_{11} modes, compared to the LP_{01} mode.

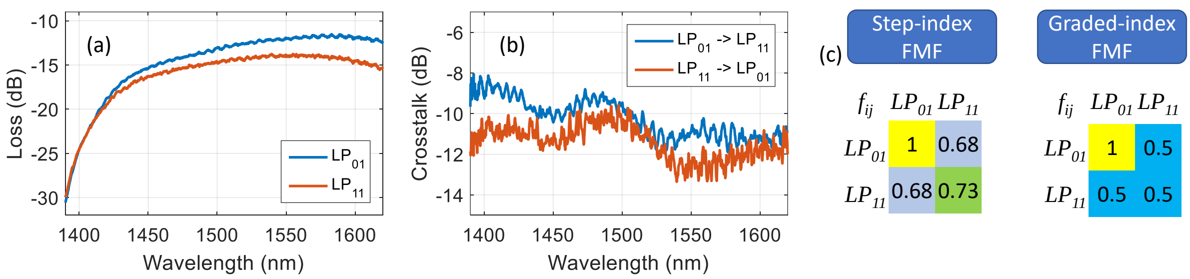

Fig. 2. (a) Wideband loss and (b) crosstalk measurements for the 54.3 km FMF link, including mode-multiplexers. (c) Normalized intensity overlap integrals f_{ij} for a step-index and a graded-index FMF.

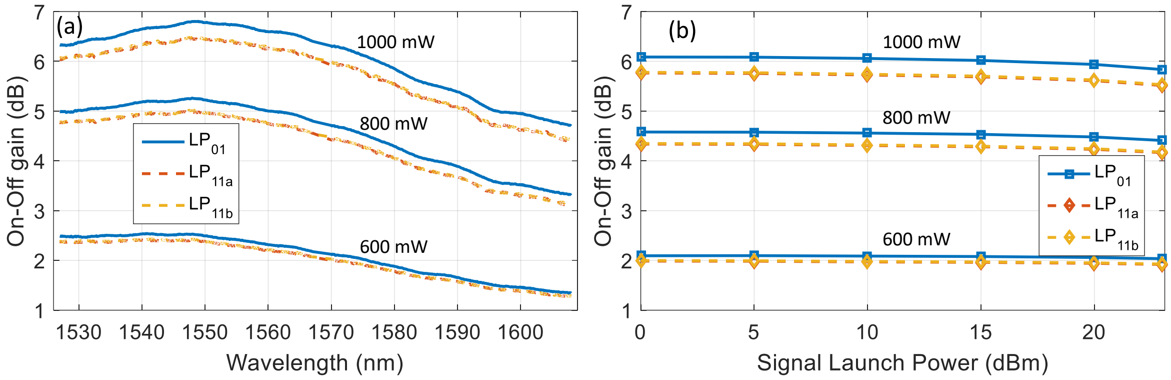

Fig. 3. (a) Wideband On-Off gain for three different pump powers, while launching the signal at a total power of 0 dBm per mode. (b) Wavelength-averaged On-Off gain as a function of the total signal launch power per mode for different total pump powers.

Figure 3 shows the wideband On-Off gain, defined as the difference of the measured output spectra at 0 mw pump power and with the pump lasers turned on, for three different pump power levels. The total signal power per mode was 0 dBm for all graphs to remove the influence of stimulated Raman scattering (SRS) between spectral components within the signal bandwidth. At maximum pump power of 1000 mW, the gain reaches 6.7 dB at 1550 nm and 4.7 dB at 1608 nm wavelength in the LP_{01} mode. The gain is equal in both LP_{11} modes and 0.3 dB lower across the entire bandwidth compared to the LP_{01} mode. We attribute the spectral gain shape to a combination of available pump wavelengths and selected powers and the spectral attenuation of the FMF. Figure 3(b) shows the On-Off gain as a function of the total signal launch power, and thus incorporating SRS within the signal bandwidth at higher launch powers, as expected in a transmission system with optimum launch power per wavelength channel. At 23 dBm launch power per mode, the average gain reduces by 0.2 dB compared to 0 dBm, presumably due to pump depletion. The gain difference between the LP_{11} and LP_{01} modes is independent of the signal launch power. Despite the simple pumping scheme, only injecting pump light into one of the three ports of the DE-MUX, this experiment has demonstrated broadband, mode-independent gain within the two LP_{11} modes and low mode-dependent gain of 0.3 dB between the LP_{01} and the LP_{11} modes.

4. Conclusion

We have experimentally analyzed backwards-pumped distributed Raman amplification in a three-mode few-mode fiber for wideband signals, spanning more than 80 nm wavelength in C- and L-bands. Gain of more than 6 dB was shown with 0.3 dB mode-dependent gain variation. This demonstration shows the potential of distributed Raman amplification in wideband few-mode fiber-based space-division multiplexed transmission systems.

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