Mode-Equalized Distributed Raman Amplification in 137-km Few-Mode Fiber

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Abstract: We experimentally demonstrate 8 dB of mode-equalized distributed Raman gain using a backward pumping scheme. The equivalent noise figure of the amplifier is -1.5 dB, and the amplifier was successfully employed to demonstrate 6-channel mode-multiplexed MIMO transmission over 137-km few-mode fiber.

OCIS codes: 060.4510, 060.1660, 060.2280, 040.1880, 060.4230.

1. Introduction

Mode-multiplexed transmission over few-mode fibers (FMFs) has recently been garnered considerable attention for its potential to dramatically increase the capacity of a single fiber [1–4]. However, in order to repeat the success story of wavelength-division multiplexing in single-mode fibers (SMFs), optical amplification in mode-multiplexed fibers is a key requirement. In this work we present, to the best of our knowledge, the first experimental demonstration of mode-equalized optical amplification in FMFs. We use stimulated Raman scattering as the amplification effect in a back-propagating-pump configuration. Gain equalization is obtained by selectively coupling the depolarized pump laser into a linearly polarized LP_{11} mode of the FMF. We demonstrate a gain of 8 dB for both LP_{01} and LP_{11} modes, for a pump power of 1.25 W, and an equivalent noise figure of -1.5 dB at 1550 nm. The multimode amplifier was tested in a record 137-km mode-multiplexed single-span transmission, where 6×20-Gbaud-QPSK signals were successfully recovered using 6×6 multiple-input multiple-output (MIMO) digital signal processing (DSP).

2. Raman amplification in few-mode fiber

The FMF used in this work supports a total of 6 spatial- and polarization modes. The fiber design is based on a depressed cladding index profile with normalized frequency of $V \approx 5$ [4]. The fiber loss coefficient is 0.205 dB/km at 1550 nm and 0.26 dB/km at 1455 nm, and no significant mode-dependent loss is observed. The effective areas of the LP_{01} and LP_{11} modes are approximately 155 and 159 $\mu\mathrm{m}^2$, respectively, and the chromatic dispersion is around 18 ps/(nm km) for both LP_{01} and LP_{11} modes. The fiber was optimized to minimize the differential group delay (DGD) between LP_{01} and LP_{11} mode, and a DGD of 2.6 ns was measured for a 96-km long fiber. Through Raman amplification the power of a pump laser at 1455 nm is transfered to a signal wavelength at 1560 nm [5]. This process is phase insensitive but polarization dependent. In our experiment we use a depolarized pump laser. In general both pump and signal can be coupled into all modes of the 6-mode FMF and the amplification is then approximatively governed by

$$\frac{dS_M}{dz} = \gamma_{\mathrm{R}} \left(\sum_N f_{N,M} P_N \right) S_M, \text{ and} \qquad f_{N,M} = \frac{\iint_{-\infty}^{+\infty} I_N(x,y) I_M(x,y)\, dxdy}{\iint_{-\infty}^{+\infty} I_N(x,y)\, dxdy \iint_{-\infty}^{+\infty} I_M(x,y)\, dxdy} \tag{1}$$

where S_M is the power at the signal wavelength in mode M, P_N is the power at the pump wavelength in mode N, z is the position along the fiber, and γ_{R} is related to the cross section of spontaneous Raman scattering. The intensity overlap integrals $f_{N,M}$ depends on the intensities I_N and I_M of the signal mode N, and the pump mode M, respectively. Note that Eq. 1 assumes fast power averaging which is only valid if the length of the amplifier is much longer than the beat length between modes due to phase velocity differences. In order to understand why this condition is satisfied for the degenerate LP_{11} modes of a FMF, the real fiber waveguide modes forming the LP_{11} mode have to be considered. The modes are the TE_{01}, TM_{01}, and the two fold degenerated HE_{21}, and have three distinct phase-velocities. The beat lengths are found to be on the order of 1 to 10 m for a typical step-index FMF. In order to achieve equal amplification for all modes, in our experiment we launch all of the depolarized pump power into a single LP$_{11}$ mode. This launch condition divides the pump power equally among all four real fiber waveguide modes associated to the LP$_{11}$ mode. No light is launched into the LP$_{01}$ mode as doing so typically produces larger gain for the LP$_{01}$ signal than for the LP$_{11}$ signal, whereas nearly the same gain is obtained for both LP$_{01}$ and LP$_{11}$ mode when launching the pump into LP$_{11}$ mode. This can be verified by evaluating Eq.1. In our experiment we use backward Raman pumping, where the pump is counter propagating with respect to the signal. The experimental arrangement to couple the pump and to mode multiplex the signal (Raman-MMUX) is shown in Fig.1 a). Light from the Raman pump is collimated by means of a collimator (CL) and a phase plate with a horizontal π-phase jump (HPM) is used to generate an LP$_{11}$ like phase profile, the beam is then imaged onto the end facet of the FMF using lenses with focal lengths $f_1 = 3.9$ mm and $f_2 = 100$ mm. The total pump power is 2 W with 1.25 W coupled into the FMF. The origin of the 2.04-dB loss is 1.1 dB due to mode mismatch [4], 0.7 dB due to parasitic reflections, and 0.24 dB due to the collimator. In order to separate the signal from the pump beam, three dichroic beams splitters (DS) were cascaded to achieve a pump suppression of > 72 dB into the signal ports. The mode multiplexing of the signal path is a similar arrangement as for to the pump, but two additional beam splitters BS1 and BS2 with splitting ratios of 33:66 and 50:50, respectively, are used to separate the three polarization multiplexed modes, and two phase masks with different orientations are used to select the LP$_{11}$ modes, whereas no phase mask is required for the LP$_{01}$ mode. In order to measure Raman gain, a FMF of 137 km length was attached between the Raman-MMUX and a second MMUX. A broadband light source was attached to the input MMUX and the signal received in the Raman-MMUX was detected on an optical spectrum analyzer. The resulting on-off gain is plotted in Fig. 1 b) for all three mode selective ports of the Raman-MMUX. A maximum gain of 8 dB is observed in the wavelength region between 1550 and 1570 nm; the gain variation between the modes is < 0.5 dB. We also calculated the equivalent noise figure at the end of the FMF [5]. The results are reported in Fig. 1 c). The equivalent noise figure is -1.5 dB in the 1550 to 1570 nm range, and a small ripple produced also noticeable in the non amplified signal is present for the LP11 mode.

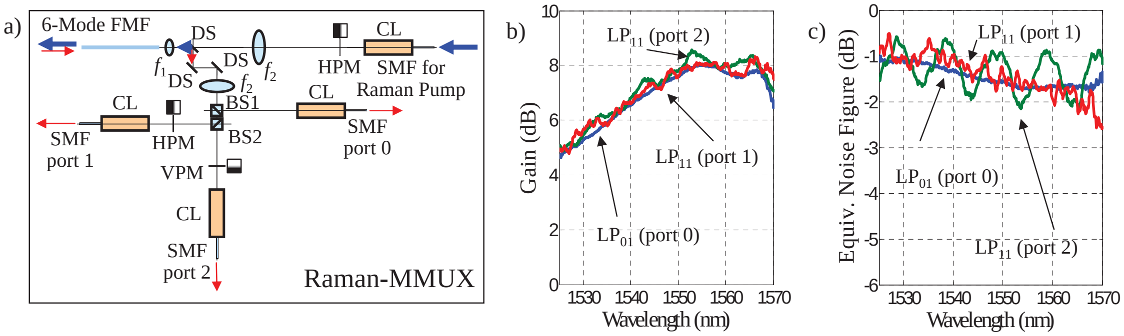

Fig. 1. a) Experimental arrangement of mode multiplexer with backward Raman pump coupler. b) On-off Gain of the Raman amplification. c) Equivalent noise figure at the FMF end.

In order to evaluate the system implication of the equivalent noise figure of the Raman amplifier we have evaluated the total noise figure of a span consisting of 137-km FMF, a Raman-MMUX, and an Erbium doped fiber amplifier (EDFA). The total noise figure was calculated using the concatenation formula for optical amplifiers [5] and we assumed a noise figure of 4 dB for the EDFA. With no Raman amplification (EDFA-only) we obtain a noise figure of 12 dB when the fiber loss (28 dB) is subtracted. With Raman amplification, we still need an EDFA to overcome the total span loss (hybrid system) but the noise figure is now 4.8 dB after subtracting the fiber loss. Therefore a noise figure advantage of 7.2 dB can be expected. The considerable improvement in noise figure is mainly do to the fact that the Raman amplification acts before the MMUX, whereas the EDFA amplifies after the MMUX. The MMUX has an insertion loss of 8 dB, which in the hybrid system can then be completely compensated by the Raman amplifier before the loss occurs. Note that when lower loss MMUX or FMF EDFAs will become available the noise figure improvement will be more modest.

The reported gain of 8 dB is obtained for a pump power of 1.25 W. The Raman gain efficiency cannot be directly compared to SMF because the pump is shared between all modes. Note that there is a real power advantage compared to using three individual SMF. In fact following Eq. 1 the power penalty for sharing the pump among all modes results in a factor 1.5, whereas the benefit compared to three SMF is a factor of 3. The Raman amplifier in a 6-mode FMF therefore consumes only half of the power. Further the FMF fiber used in this work has an effective area that is 1.6 times larger compared to a standard SMF, which therefore requires larger pump powers.

3. Transmission experiment

In order to validate the performance of the Raman amplifier we performed a single-span transmission experiment over 137-km FMF as shown in Fig. 2 a). We generated a 20-GBaud QPSK signal by modulating the light of an external cavity laser (ECL) using a double-nested $LiNbO_3$ modulator. We used two independent De Bruijn bit sequences (DBBS) of length 2^{12} for the In-phase (I) and quadrature (Q) component. The signal is then polarization multiplexed introducing a delay of 25 ns between the polarizations. After passing through a noise loading section, the signal is split into three copies which are connected to the input-MMUX with relative delays of 49 and 97 ns. The 6 signals are then transmitted through a total of 137 km of fiber consisting of three connectorized spools of 96, 9, and 33 km, respectively, that are interconnected by using regular FC-PC connectors. At the end of the fiber the Raman-MMUX provides Raman gain and separates the modes which are sent to three polarization-diversity coherent receivers (PD-CRX). A fully synchronized 16-channel prototype of the LeCroy LabMaster modular digital storage oscilloscope (DSO) operating at 40 GS/s with 20 GHz of bandwidth is used to capture the 12 high-speed electrical signals coming from the PD-CRX. A second ECL is used as local oscillator (LO) laser. The four million samples captured on each of the 12 inputs of the DSO are subsequently analyzed by MIMO DSP as described in [3]. The algorithm consists of a network of 6×6 feed-forward equalizers (FFEs) with L taps, where the FFE coefficients are adapted over the first 500,000 symbols by a data-aided algorithm based on the least-mean-square estimator (LMS). This assures fast convergence before the algorithm is switched to decision-directed LMS for the remaining symbols. The bit-error rate (BER) is evaluated over the last one million bits. The resulting BER curves are plotted in Fig. 2 b) with amplification (circles) and without amplification (squares). As can be noted the performance with pump on- and off is similar for received OSNR values < 16 dB. OSNR value > 16 can only be reached with hybrid Raman-EDFA system, thus confirm the improved performance of the hybrid system. A BER of 10^{-3} is achieved however with a considerable penalty of 6 dB.

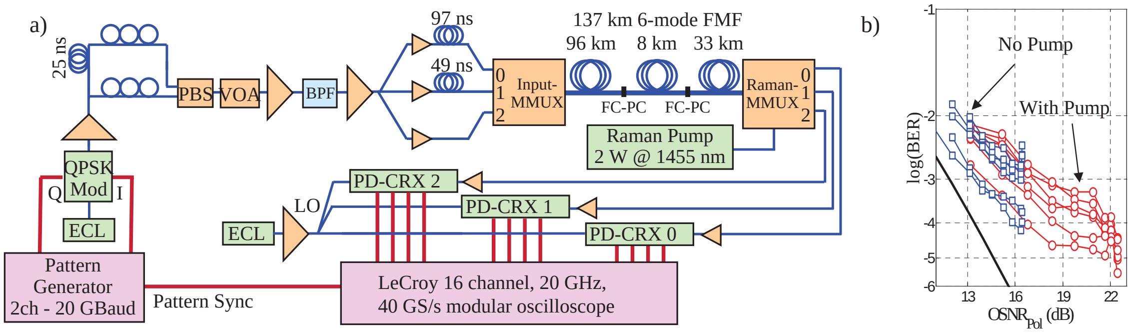

Fig. 2. a) Experimental transmission set-up. QPSK-Mod: QPSK Modulator, PBS: Polarization beam splitter, VOA: Variable optical attenuator, BPF: Bandpass filter. EDFAs are represented as triangles. b) BER curves for 137-km transmission pump on (circles) and pump off (square).

In conclusion we have demonstrated distributed Raman amplification with backward pumping in a FMF. A mode-equalized gain of 8 dB was obtained by coupling 1.25 W of Raman pump power into one LP_{11} mode. The equivalent noise figure at the end of the FMF was -1.5 dB, and a 7.2-dB improvement of the span noise figure is expected compared to an EDFA-only system. We also demonstrated the transmission of 6 mode-multiplexed 20-GBaud-QPSK signals over a record single span distance of 137 km using 6×6 off-line MIMO DSP.

References

1. A. Li, et .al., "Reception of mode and polarization multiplexed 107Gb/s CO-OFDM signal over a two-mode fiber," *OFC*, p. PDPB8, 2011.
2. M. Salsi, et. al., "Transmission at 2x100Gb/s, over two modes of 40km-long prototype few-mode fiber, using LCOS based mode multiplexer and demultiplexer," *OFC*, p. PDPB9, 2011.
3. S. Randel, et. al., "6 x 56-Gb/s mode-division multiplexed transmission over 33-km few-mode fiber enabled by 6× 6 MIMO equalization," *Optics Express*, vol. 19, no. 17, pp. 16 697–16 707, 2011.
4. R. Ryf, et.al.,"Mode-division multiplexing over 96 km of few-mode fiber using coherent 6 x 6 MIMO processing," *Submitted to JLT*.
5. J. Bromage, "Raman amplification for fiber communications systems," *J. Lightwave Technol.*, vol. 22, pp. 79–93, 2004.