Low-Crosstalk Few-Mode EDFA for Single-Mode Fiber Trunk Lines and Networks

Ning Wang(1), Inwoong Kim(2,+), Olga Vassilieva(2), Tadashi Ikeuchi(2), He Wen(1), J. E. Antonio-Lopez(1), J. C. Alvarado-Zacarias(1), Pierre Sillard(3), Cedric Gonnet(3), Huiyuan Liu(1), Shengli Fan(1), Md Selim Habib(1), Rodrigo Amezcua-Correa(1), and Guifang Li(1,*)

(1) CREOL, The College of Optics and Photonics, University of Central Florida, Orlando, Florida 32816, USA
(2) Fujitsu Laboratories of America, Inc., Richardson, TX 75082, USA
(3) Prysmian Group, Parc des Industried Artois Flandres, Douvrin, 62138, France
*+Inwoong.Kim@us.fujitsu.com, *li@creol.ucf.edu*

Abstract: We propose a low-crosstalk few-mode EDFA based on the unitary property of the coupling matrix of symmetric photonic lanterns and experimentally demonstrate a three-channel few-mode EDFA with a 20 dB gain and crosstalks below -10 dB.

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1. Introduction

Few-mode (FM) erbium-doped fiber amplifiers (EDFA) have been investigated extensively in recent years [1,2] as they are essential for long-haul mode-division multiplexed (MDM) transmission systems. Alternatively, one FM-EDFA can replace several parallel single-mode EDFAs, reducing the overall cost for single-mode fiber (SMF) trunk transmission lines or networks. Several schemes have been demonstrated to realize FM-EDFAs [3,4]. A popular approach is to use the low-loss all-fiber photonic lantern (PL) as the spatial mode (de)multiplexer [5-6]. In this configuration, crosstalk between different channels is inevitable even with mode-selective photonic lantern (MSPL), because of the high crosstalk (around -3dB) between degenerate modes. In this paper, we propose and experimentally demonstrate a low-crosstalk FM-EDFA exploiting the unitary property of the coupling matrix of the PL. We show theoretically that mode crosstalk can be suppressed in a retro-reflection configuration even if a non-modes-selective PLs are used for (de)multiplexing. Experimentally, we demonstrate a low crosstalk 3-mode EDFA even though use a high-crosstalk symmetric PL was used as the spatial (de)multiplexer. The on-off gain of the three channels are greater than 20dB and the crosstalk of each channel is lower than -10dB.

2. Theory

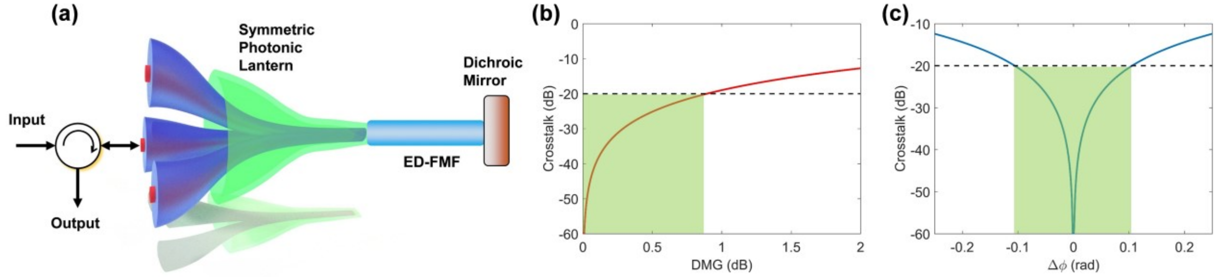

Fig. 1. (a) Schematic setup of the low-crosstalk FM-EDFA based on the retro-reflection of a symmetric PL, (b) calculated channel crosstalk with increase of DMG between the first two LP modes, and (c) crosstalk vs phase difference between the first two mode groups.

The schematic setup of the proposed FM-EDFA with low-crosstalk is shown in Fig. 1(a). Each input signal is launched into one port of a symmetric PL through a circulator. At the output of the PL, the signal is amplified by the erbium-doped few-mode fiber (ED-FMF). The resulting signal is reflected back by a dichroic mirror (DM) and amplified by the ED-FMF again in the reverse direction before being coupled out through the PL and the circulator. The relationship between the input signal amplitudes $\boldsymbol{A}_{in}$ and output signal amplitudes $\boldsymbol{A}_{out}$ can be expressed as:

$$\boldsymbol{A}_{out} = \boldsymbol{M}_{MUX}^{T} \cdot \boldsymbol{G}^{T} \cdot \boldsymbol{G} \cdot \boldsymbol{M}_{MUX} \cdot \boldsymbol{A}_{in} \qquad (1)$$

where the matrix $\boldsymbol{M}_{MUX}$ is the transfer matrix of the symmetric PL. For a lossless PL, it is unitary, for example,

$$\boldsymbol{M}_{MUX} = \begin{pmatrix} 1/\sqrt{3} & 1/\sqrt{3} & 1/\sqrt{3} \\ \sqrt{2/3} & -1/\sqrt{6} & -1/\sqrt{6} \\ 0 & 1/\sqrt{2} & -1/\sqrt{2} \end{pmatrix} \qquad (2)$$

for a 3-to-1 symmetric PL [7]. The Matrix $\boldsymbol{G}$ is the coupling matrix of the ED-FMF. For a short length of fiber, it can be assumed to be a diagonal matrix. One can easily verify that when all the elements of matrix $\boldsymbol{G}$ are equal, the total transfer matrix of the system will be diagonal because $\boldsymbol{M}_{MUX}$ is unitary. That means there will be no channel crosstalk. However, because of differential modal gain (DMG) and modal dispersion, the amplitude and phase of the elements in $\boldsymbol{G}$ are not always equal. We simulated the effect of DMG on the crosstalk, and the result is shown in Fig. 1(b). We can see that the crosstalk increases as the DMG grows. In order to suppress the crosstalk to below -20dB, the DMG need to be less than 1dB. Fig. 1(c) depicts the effect of phase difference between the first two mode groups on the crosstalk. In order to suppress the crosstalk to below -20dB, the phase difference should be within $2m\pi \pm \pi / 25$.

3. Experimental Setup and Results

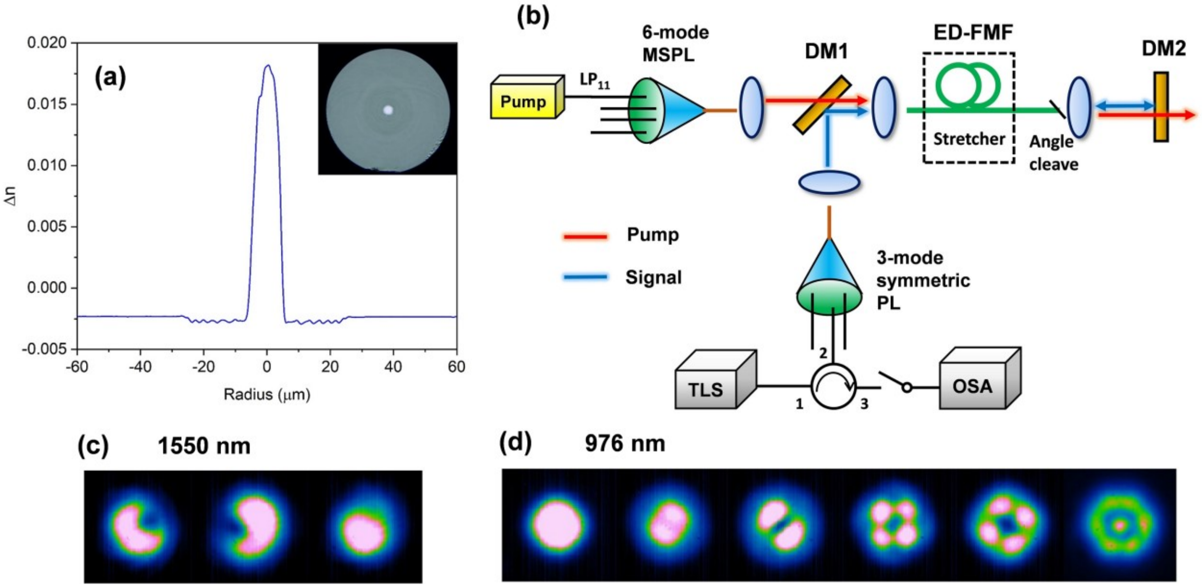

Fig. 2. (a) Refractive index profile of the ED-FMF, inset: cross section microscope image of the ED-FMF, (b) experimental setup of the low-crosstalk FM-EDFA, (c) output mode profiles of the 3-mode symmetric PL measured at signal wavelength, and (d) output mode profiles of the 6-mode MSPL measured at pump wavelength.

The active fiber used in the experiment was an ED-FMF fabricated in house. The core and cladding diameter of the ED-FMF is 10μm and 125μm. Fig. 2(a) shows the fiber refractive index profiles and its cross-sectional microscope image. It is a step-index fiber with a NA of 0.24, which supports 3 LP modes at the signal wavelength. The core area was doped with erbium ions with a concentration of $4.5 \times 10^{25} m^{-3}$. The experimental setup of the low-crosstalk FM-EDFA is shown in Fig. 2(b). The signal form the tunable laser source (TLS) was launched into the port 1 of the circulator, and further went into the 3-to-1 symmetric PL from port 2. The input signal power was set to be -10dBm at the wavelength of 1550nm. The output mode profiles of each port of the symmetric PL was measured by a CCD camera, as shown in Fig. 2(c). They are superpositions of the LP_{01} and LP_{11s} modes. The pump light from a 976nm pump diode was launched in to a 6-mode MSPL for pump mode control. We also measured the output mode profiles of the MSPL at the wavelength of 976nm. The patterns of the lowest 6 LP modes (LP_{01}, LP_{11a}, LP_{11b}, LP_{21a}, LP_{21b}, and LP_{02}) were clearly observed, as shown in Fig. 2(d). The DMG of a FM-EDFA basically depends on the degree of overlap between pump and signal mode intensity profiles. For this ED-FMF, we find that by using the LP_{11} mode as the pump, the DMG between LP_{01} and LP_{11s} signal modes are minimum. We used a 980/1550nm DM to combine the pump and signal beams, and coupled them into the ED-FMF by a 20X microscope objective lens. The length of the gain fiber is 3 meters, which was angle cleaved. The amplified signal at the output of the ED-FMF was reflected by another DM, and coupled back into the ED-FMF and amplified again in the reverse direction. The resulting signal was coupled out of the three single-mode ports of the PL. The port under test is detected through port 3 of the circulator.

We slightly stretched the ED-FMF to adjust the phase difference in order to suppress the channel crosstalk. An optical spectrum analyzer (OSA) was used to measure the output powers in all 3 ports of the photonic lantern.

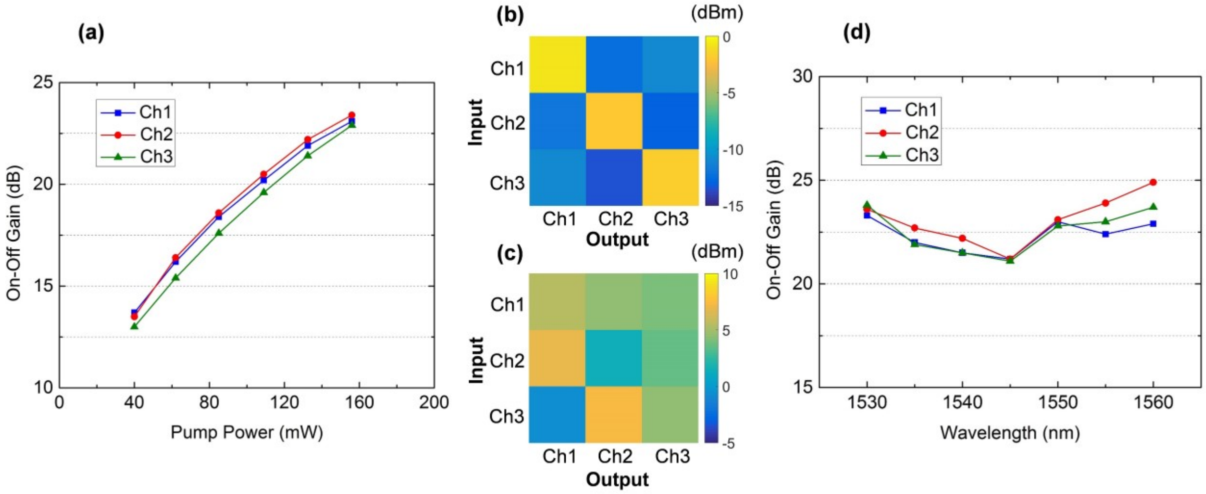

Fig. 3. Experimental results (a) On-off gain of each channel vs pump power, (b) transfer matrix of the FM-EDFA after reflection, (c) transfer matrix of a pair of 3-mode symmetric PL, and (d) on-off gain of each channel at different signal wavelength.

We characterized the on-off gain of each channel. The results of all the three channels are shown in Fig. 3(a). We can see that the on-off gain of all the three channels are larger than 20dB when the pump power of the LP_{11} mode is larger than 140mW. At the pump power of 156mW, the on-off gain of the three channels are 23.1dB, 23.4dB and 22.9dB, respectively. We fixed the pump power to be 156mW, and measured the transfer matrix of the retro-reflecting amplifier. The result is shown in Fig. 3(b). As we can see, the matrix is nearly diagonal, the crosstalks of all three spatial channels are between -10dB to -15dB. In comparison, we also measured the transfer matrix of a pair of 3-mode symmetric PL without retro-reflection. The result is shown in Fig. 3(c). There is no obvious one-to-one relationship observed, the selectivity are no more than 3dB for all the channels. One of the reasons for the residual crosstalk in the retro-reflecting FM-EDFA is the phase difference between the three modes. The other reason comes from the mode mismatch between the PL and ED-FMF, which will affect the total transfer matrix of the amplifier. Both are not fundamental problems and can be improved in the future by using core size matched ED-FMF and better phase control. Finally, we swept the input signal wavelength across the C-band, and measured the on-off gain for the three channels, as shown in Fig. 3(d). We can see that the on-off gain of all the three channels are greater than 20dB for the signal wavelength ranges from 1530nm to 1560nm. The highest gain appears at 1560nm, the on-off gain for each channel are 22.8dB, 24.9dB, and 23.7dB, respectively.

4. Conclusion

We proposed a low-crosstalk FM-EDFA by exploiting the unitary property of the coupling matrix of the PL. We experimentally demonstrated a 3-channel FM-EDFA using a high-crosstalk 3-to-1 symmetric PL. The on-off gains are larger than 20 dB over the entire C-band for all the three channels and the crosstalks are below -10 dB. With further development and optimization, the multi-channel amplifier presented here could replace multiple single-mode EDFAs in SMF trunk lines and networks.

5. References

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