Experimental demonstration of a Gain-Flattening Filter for Few-Mode Fiber based on a Spatial Light Modulator

Ezra Ip(1), Ruo Yu Gu(1,2), Ming-Jun Li(3), Yue-Kai Huang(1) and Joseph Kahn(2)

[1]NEC Labs America, 4 Independence Way, Princeton, NJ 08540, US,
[2]Stanford University, Stanford, CA, US, [3]Corning Inc., Corning, NY, USA
E-mail address: ezra.ip@nec-labs.com

Abstract: We demonstrate a spatial light modulator-based few-mode fiber gain-flattening filter (FM-GFF). Arbitrary insertion loss is induced by a phase scattering function. We use the FM-GFF to flatten the output of a few-mode erbium-doped fiber amplifier.

OCIS codes: (060.4510) Optical Communications; (230.7408) Wavelength filtering devices; (230.6120) Spatial light modulators

1. Introduction

As information capacity of single-mode fiber becomes fully utilized, further capacity growth will come from parallel transmission. Recent years have seen dramatic advances in space-division multiplexing (SDM) technology. In particular, long-haul transmission exceeding 1,000 km has been demonstrated in strongly coupled MCF [1] and few-mode fibers (FMF) [2]. SDM provides an opportunity to reduce system cost per bit through integration. Few-mode erbium-doped fiber amplifiers (FM-EDFA) that can simultaneously amplify all modal channels with equalized gain has been demonstrated in [3,4]. A re-circulating loop experiment using space- and wavelength-division multiplexing (SDM/WDM) with all few-mode fiber components in the loop was also demonstrated in [5]. More recently, WDM switches based in FMF using a spatial light modulator (SLM) as the switching element was reported in [6,7]. Just as in single-mode fiber, a FM switch also can be configured as a "waveshaper" by programming wavelength-dependent loss on the input signal. As one of the limitations to the experiment in [5] was wavelength-dependent gain (WDG) of the FM-EDFA, which was not compensated inline owing to the lack of a gain flattening filter (GFF) based in FMF, an SLM-based few-mode GFF (FM-GFF) can potentially increase the achievable transmission distance. In this paper, we demonstrate an SLM-based FM-GFF and use it to equalize the WDG of a FM-EDFA.

2. Experimental Setup and Results

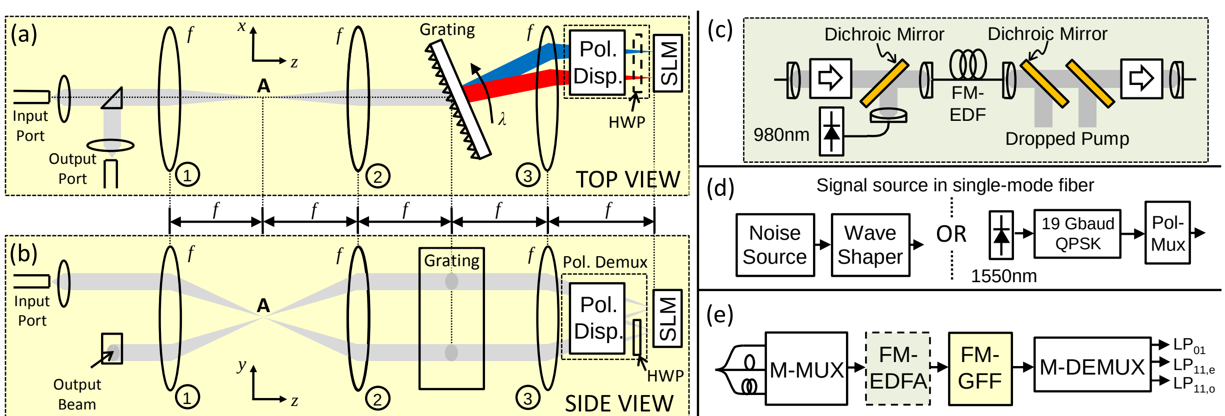

Fig. 1. Experimental setup of few-mode gain-flattening filter: (a) Top and (b) side views. (c) Few-mode erbium-doped fiber amplifier, (d) Signal sources in single-mode fiber, either white noise or 19-Gbaud DP-QPSK, (e) Setup for characterizing the FM-GFF.

The experimental setup of our SLM-based FM-GFF is shown in Fig. 1. At the front-end, two graded-index FMFs are terminated by 8 mm collimators, and a 45° prism stacks the two beams vertically at a mutual spacing of ~5 mm. The ports corresponding to the upper and lower beams are designated as input and output ports, respectively. The beams pass through three lenses of focal length $f = 200$ mm. Lens 1 focuses the vertically stacked beams to a common point A. The other lenses are positioned so that the setup from A to the SLM (with the polarization diversity optics removed) is a 4f system, thus projecting the FMF modes onto the SLM at a magnification factor of (200/8) = 25, with the $1/e$ beam radius of the LP_{01} mode being ~160 µm at the SLM. We use a Hamamatsu x10468 series liquid-crystal-on-silicon (LCoS) SLM which has 792×600 pixels over an active area of 16×12 mm (pixel size: 20 µm × 20 μm). Since the SLM is polarization sensitive, to allow polarization insensitive operation, a polarization displacer placed between Lens 3 and the SLM separates the *x*- and *y*-pols. vertically by ~5 mm. A half-wave plate (HWP) rotates the *x*-pol. to the *y*-pol. required for phase modulation by the SLM. For wavelength demultiplexing, a 940 lines/mm transmissive grating designed for C-band operation is placed at the focal point between lens 2 and 3, dispersing wavelength along the *x*-axis of the SLM at ~0.07 nm/pixel. The component losses of our setup are as follows: 0.8 dB for the prism, 0.2 dB for each lens, grating and polarization displacer, and 0.8 dB from reflection off the SLM. Coupling losses from free-space to the output FMF are 1.0 dB and 1.5 dB for the LP_{01} and LP_{11} modes, yielding a minimum insertion loss (IL) of 4.6 dB and 5.1 dB for the LP_{01} and LP_{11} modes. Compared with the FM switch demonstrated in [7], we have removed one output port, and aligned the remaining fibers so that the input port is maximally coupled to the output port when the SLM has flat phase. For the SLM, each pixel can be independently programmed with *B*=8-bit values. The phase modulation range exceeds 0 to 2π in the C-band. Let (*m*,*n*) denotes the pixel at the intersection of the *m*-th column and *n*-th row. We can induce wavelength-dependent IL by setting the pixel phases to the scattering function (SF):

$$\phi(m,n) = 2\pi \cdot A(m) \cdot \left[2\,rect\left(\frac{\text{mod}(n,k)}{K} \right) - 1 \right], \qquad (1)$$

where $rect(u) = \begin{cases} 1 & |u| < 1/2 \\ 0 & otherwise \end{cases}$, *K* is the period, and $A(m)$ is the amplitude of the SF applied to the wavelength at column *m*. The SF diffracts light at angles $\theta_d = \pm K\Lambda/\lambda$ away from the output port, and the amount that is diffracted is controlled by $A(m)$. Assuming the phase shift at each SLM pixel $x(m,n)$ increases linearly with applied pixel value, and $N = 2^B$ corresponds to a phase shift of 2π, we can convert the SF in (1) to quantized pixel values via $x(m,n) = \left\lfloor \frac{2^B}{2\pi} \phi(m,n) \right\rfloor + 2^{B-1}$. Fig. 2(a) shows simulated results for output power vs. SF amplitude ($N \cdot A(m)$) for the LP_{01} mode. For even values of *K*, the curves overlap, and IL is maximized at $N \cdot A(m) = N/4$ as expected (i.e., $\phi(m,n)$ takes on values of $\pm\pi/2$), while for odd values of *K*, the lack of symmetry between the positive and negative cycles of the SF reduces the diffraction efficiency, and hence the maximum achievable IL. We measured the output power vs. SF amplitude characteristic for our setup and the results are shown in Fig. 2(b). The difference between Figs. 2(a) and (b) arises from spatial filtering by the SLM. At higher spatial frequency (lower *K*), IL is maximized at $N \cdot A(m) > N/4$, since spatial lowpass filtering reduces the effective phase difference between adjacent pixels. The minima shift leftwards with increasing *K* as lowpass filtering becomes less severe. We also conducted experiment and simulation when the kernel of the SF is changed from a rectangular function to a sine wave. By employing best fit between experimental and simulated curves, we were able to estimate the spatial frequency response $H(k)$ of the SLM, whose amplitude is shown in Fig. 2(c). For optimum performance, especially when the setup is configured as a switch, we can digitally pre-compensate the SLM's spatial frequency response before setting its pixels. For the gain-flattening function required here, we select the SF in (1) with period *K*=4 for which a deep null exists in Fig. 2(b). Fig. 3(a) shows output power vs. SF amplitude for all three spatial modes at this period with white noise input (Fig. 1(d) left) and equal power in each mode. It is observed that all spatial modes are attenuated uniformly, and IL of 27 dB for all three modes is obtained at $N \cdot A(m) = 68$.

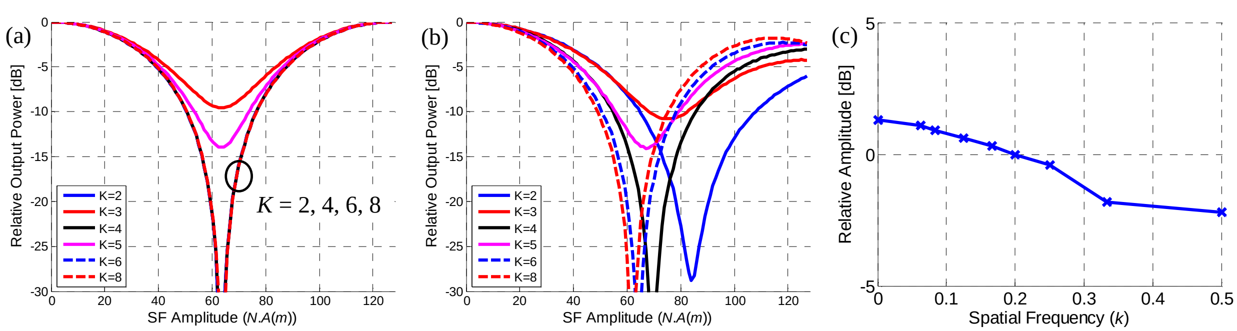

Fig. 2. Output power vs. scattering function amplitude: (a) simulated and (b) measured. (c) Estimate of SLM's spatial frequency response.

We investigated mode-dependent loss (MDL) by transmitting a 6×19-Gbaud signal through the FM-GFF and then coherently detecting the output with multiple-input multiple-output (MIMO) equalization (Fig. 1(d), right; and Fig. 1(e)). Using the method described in [8], the 6×6 MIMO channel matrix was estimated. The difference between the largest and smallest of the channel matrix's singular values (SVs) gives the channel's MDL. Fig. 3(b) shows the singular values vs. $N \cdot A(m)$, while Fig. 3(c) shows MDL vs. insertion loss. The MDL of ~5 dB at low IL is mostly due to the M-MUX and M-DEMUX, where we measured a back-to-back MDL of 4 dB when the FM-GFF was bypassed. Fig. 3(c) shows that at an IL of 7 dB, MDL has increased by 1 dB compared with its value at 0 dB IL. MDL generally increased with IL, and is possibly due to coupling between modes having odd- and even-symmetry in the vertical direction. Surprisingly, MDL is reduced beyond IL of ~20 dB. However, the received signal is very weak at these IL values, leading to poorer channel estimate, hence less reliable MDL.

Finally, we used the FM-GFF to flatten the gain of a FM-EDFA. Fig. 1(c) shows the setup of the FM-EDFA where the amplifying medium is a 6.25 meter long ring-doped FM-EDF previously reported in [5]. Fig. 4(a) shows the power spectra measured in each mode of the M-DEMUX when the FM-EDF is injected with white noise with flat spectrum between 1530 and 1565 nm at –10 dBm per spatial mode. The pump mode was adjusted to give equal gain to the signal LP_{01} and LP_{11} modes. We grouped the columns of the SLM into strips of 1 nm (~14 pixels), and set the SF amplitude of each strip to flatten the FM-EDFA gain. The power spectra at each mode after gain-flattening are shown in Fig. 4(b), demonstrating the successful operation of the FM-GFF.

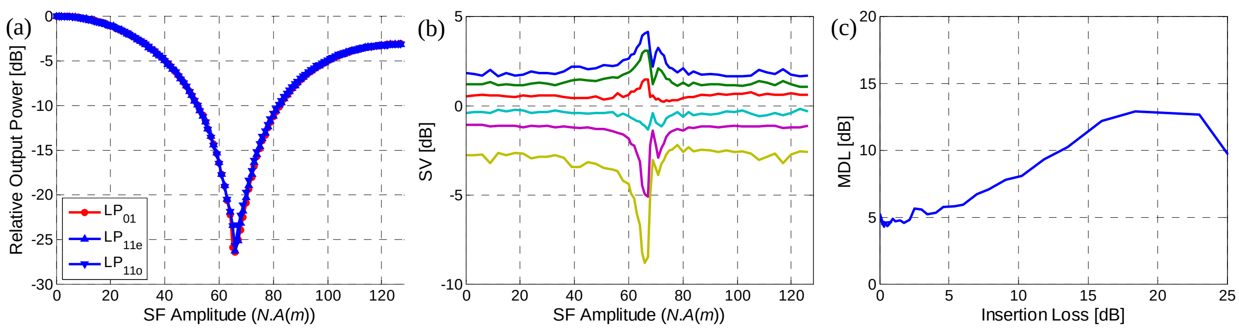

Fig. 3. (a) Output power vs. scattering function amplitude for the three spatial modes, (b) channel matrix singular values vs. scattering function amplitude, (c) mode-dependent loss vs. insertion loss induced by FM-GFF.

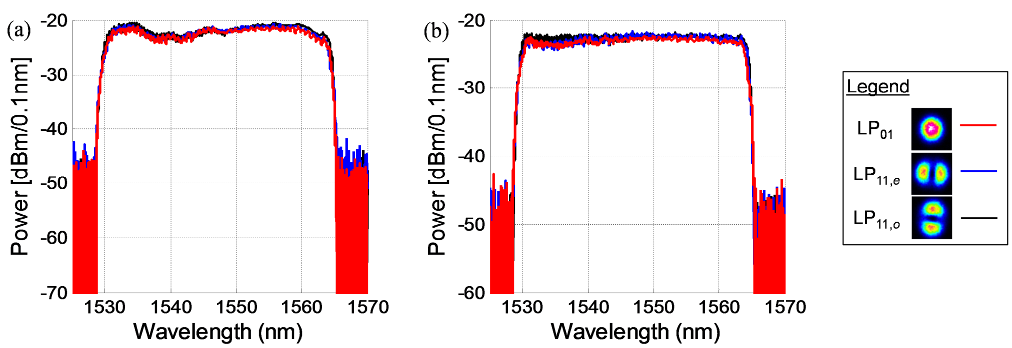

Fig. 4. Gain flattening experimental results, (a) output of FM-EDFA before FM-GFF, (b) after FM-GFF.

3. Conclusions

We constructed a gain-flattening filter for few-mode fiber using a spatial light modulator. A rectangular scattering function was used to induce arbitrary insertion loss at each wavelength. We found the FM-GFF induced negligible increase in MDL for IL values less than 7 dB. Using the device, we demonstrated gain flattening of a FM-EDFA.

4. References

[1] R. Ryf et al., "*Proc. OFC*, Paper PDP5C.2 (2012).
[2] S. Randel et al., *Proc. OFC*, Paper PDP5C.5 (2012).
[3] Q. Kang et al., *Proc. ECOC*, Paper P1.05, (2011).
[4] N. Bai et al., *Opt. Exp.*, 19, 16601–16611 (2011).
[5] E. Ip et al, *Proc. OFC*, Paper PDP5A.2 (2013).
[6] R. Ryf et al., *Proc. ECOC*, Paper PD1.C.4 (2013).
[7] R. Y. Gu et al., *Frontier in Optics*, paper FW6B.4(2013).
[8] S. Randel et al., *IEEE Summer Topical*, Paper MC4.1 (2013).