Experimental Demonstration of a Spatial Light Modulator-based Few-Mode Fiber Switch for Space-Division Multiplexing

Ruo Yu Gu[1,2], Ezra Ip[1], Ming-Jun Li[3], Yue-Kai Huang[1], Joseph M. Kahn[2]

[1] NEC Laboratories America, Princeton, NJ, USA ezra.ip@nec-labs.com,
[2] Stanford University, Stanford, CA, USA, [3] Corning Inc., Corning, NY, USA.

Abstract *We demonstrate a 1×2 wavelength-division multiplexing switch for few-mode fiber based on a spatial light modulator. We measure its crosstalk, frequency roll-off, mode dependence and other transmission characteristics.*

Introduction

In response to saturating capacity achievable in single-mode fiber, space-division multiplexing (SDM) has become an established research area. Parallelization and component integration can potentially reduce power consumption, device footprint and system cost. It is hoped that a combination of multi-core and multi-mode technology will enable up to two orders of magnitude increase in capacity per fiber. Long-haul transmission using few-mode fiber (FMF) has already been demonstrated[1], along with few-mode amplifiers that can simultaneously amplify parallel modal channels in a single doped FMF. Another key element in optical networks is the optical switch. Few-mode diplexers[3] and wave blockers[4] have been demonstrated to date. Ultimately, a practical switch should allow bandwidth allocation at a frequency granularity comparable with single-mode devices. Due to mode coupling, it is likely that systems based in FMF will continue using wavelength-division multiplexing (WDM), with all spatial modes of a wavelength being allocated as a spatial superchannel to allow multiple-input multiple-output (MIMO) processing at the receiver. We recently proposed a few-mode (FM) switch of this type, using a spatial light modulator (SLM) as the switching element. In this paper, we provide the first experimental demonstration of an SLM-based FM switch.

Switch Architecture

Fig. 1(a) and (b) show top and front views of our SLM-based few-mode switch. At the left are three graded-index FMFs terminated by 8 mm collimators. Two 45° prisms, (i) and (ii), are used to stack the three beams vertically at a mutual spacing of 4 to 5 mm. The port corresponding to the middle beam is designated as the input port, and the other two are outputs ports. The beams pass through three f = 200 mm lenses, a grating, and a polarization demultiplexer (Pol-Demux) before impinging on the SLM. Lens 1 focuses the vertically stacked beams to point A. The setup between A and the SLM (with the Pol-Demux removed) is a 4f system. The magnification factor from FMF to the SLM is (200/8) = 25, and the 1/e beam radius at the SLM is ~160 μm for the LP_{01} mode. The beams corresponding to Ports 1 and 2 impinge on the SLM at vertical angles of $\theta_1 \approx 1.2°$ and $\theta_2 \approx 1.4°$ relative to the input beam. Programming the SLM with a linearly varying phase in the vertical (y) direction will switch the input beam to the desired output port. Wavelength switching is enabled by a 940 lines/mm transmissive grating placed at the focus of Lens 2, while Lens 3 parallelizes the spectral components so they impinge the SLM at normal incidence in the horizontal plane at a wavelength resolution of

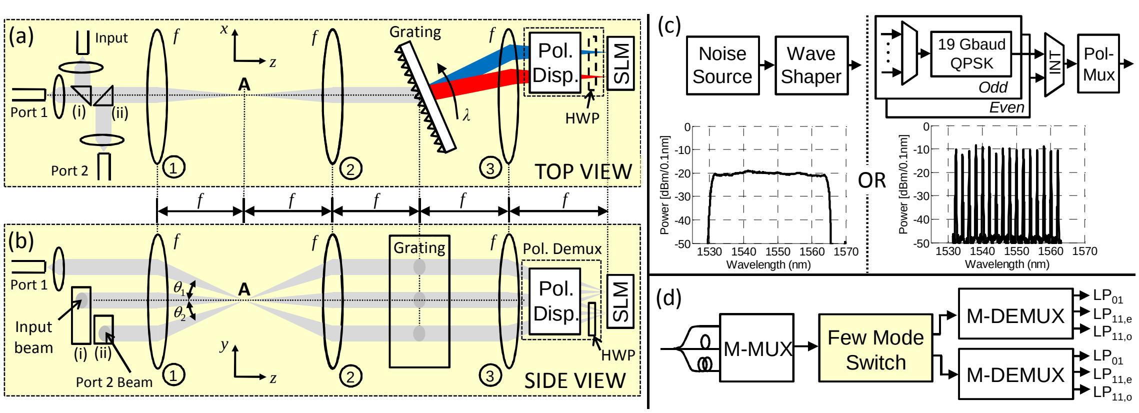

Fig. 1. (a) Top and (b) Side view of few-mode switch. (c) Input signals for switch characterization chosen from either white noise or 16λ×6×19-Gbaud QPSK, (d) Experimental Setup for switch characterization.
HWP: Half wave plate, INT: Interleaver, Pol. Disp: Polarization Displacer, Pol. Demux: Polarization Demultiplexer,

3.5 nm/mm. The reflective liquid-crystal-on-silicon (LCoS) SLM used in the experiment has 800×600 pixels in an active area of 16×12 mm (20 μm square per pixel), and is polarization sensitive. To enable polarization insensitive operation, we place a polarization displacer between Lens 3 and the SLM to separate the *x*- and *y*-polarizations by ≈ 5 mm in the vertical direction. A half-wave plate (HWP) rotates the *y*-pol. to the *x*-pol. required for phase modulation by the SLM. The signals from the three FMFs thus focus onto two horizontal strips at the SLM, each strip corresponding to one polarization. Wavelength is mapped to the horizontal axis at ≈0.07 nm/pixel. The setup here is the same as [5], with the addition of Lens 3 due to using a transmissive grating, as well as the Pol-Demux.

The SLM allows phase modulation at each pixel by 8-bit programmable phases spanning a range greater than 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. Setting the pixels to:

$$x(m,n)=\lfloor \mathrm{mod}((N/2\pi)\phi(m,n),N)\rfloor, \qquad (1)$$

where $\lfloor x \rfloor$ is the floor function, and N = 220 is the value required for a 2π phase shift at DC. $\phi(m,n)=2\pi\left[\frac{\Lambda}{\lambda}n\sin(\theta(m))+A(m)(-1)^n\right]$ is the phase function that induces a vertical angular tilt of $\theta(m)$ on the wavelength impinging the *m*-th column. Λ = 20 μm is the pixel width. The optical setup is aligned so that when $x(m,n)=0$, the input beam is reflected back to the input port. The pixel setting described allows arbitrary insertion loss by varying the amplitude *A(m)* of an alternating phase dither which diffracts light at large angle away from the output ports. Fig. 2 shows the measured attenuation characteristic. $d=N\cdot A(m)$ is the dither value. All modes are attenuated equally. A maximum attenuation of 25 dB is observed at d ≈ 80, where neighboring pixels have phase shift of π. Note that $d>N/4$ due to spatial lowpass filtering by the SLM.

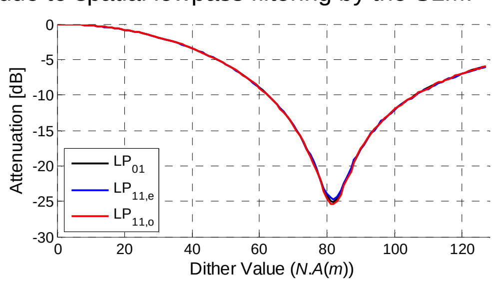

Fig. 2. Attenuation vs. Phase dither amplitude.

Results and Discussion

We characterized the FM switch using the setup shown in Fig. 1(d). The input to the mode-multiplexer (M-MUX) is either white noise with flat power spectral density (PSD) between 1530 nm and 1565 nm, or a 16λ DP-QPSK signal at 19 Gbaud at channel spacing of 2 nm (Fig. 1(c)). Details of the M-MUX and the decorrelation delays can be found in [2]. We set all six spatial-polarization modes to have equal power at the FM switch input. At the FM switch outputs, two mode demultiplexers (M-DEMUX) are connected to measure either the PSD at each mode with an optical spectrum analyzer, or each modal output is connected to a synchronized sampling scope followed by coherent detection and offline digital signal processing. Fig. 3 shows the spectra measured at Ports 1 and 2 when: (a) all input power is switched to Port 1, (b) all input power is switched to Port 2, and (c) the input spectrum is divided into 2 nm wide (250 GHz) channels, with odd channels (1532.29–1560.20 nm) switched to Port 1 and even channels (1534.25–1562.23 nm) switched to Port 2. We observe crosstalk suppression >22 dB for Fig. 3(a), and >35 dB for Fig. 3(b).

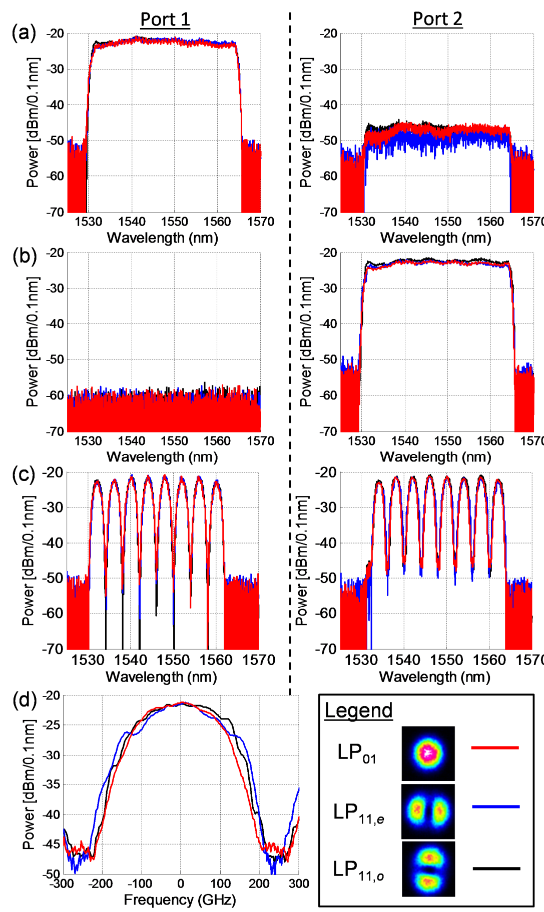

Fig. 3. Optical spectra measured at the output ports for each mode when input signal is routed to: (a) Port 1, (b) Port 2, and (c) odd/even channels 250 GHz wide are routed to Ports 1 & 2. (d) Close-up of channel at 1550.12 nm.

Crosstalk arises from non-ideal characteristics of the SLM, which include (i) quantization of the programmable phases, (ii) edge effects between neighboring pixels, (iii) spatial quantization of the ideal linear ramp as discrete pixels, and (iv) spatial lowpass filtering by the SLM. In numerical simulations, we found that (i) and (ii) produce negligible effects, while (iii) and (iv) can cause spurious diffraction orders that can couple to the undesired port. Of these, (iv) has the strongest effect, and crosstalk was only marginally suppressed with digital pre-compensation. We found that placing the output FMFs at different angles $|\theta_1| \neq |\theta_2|$ relative to the input port can reduce crosstalk. The positions of the output ports were iteratively optimized.

Fig. 3(c) confirms the switch operates as expected. The sharpness of the frequency roll-off is limited by the ratio between beam size at the SLM and horizontal wavelength resolution[5]. Fig. 3(d) shows a close-up of the frequency characteristic for the channel at 1550.12 nm (Port 2). The $LP_{11,e}$ characteristic has plateaus around the central peak, which are caused by the horizontally distributed energy lobes of the $LP_{11,e}$ mode[5]. Defining the transition bandwidth to be between where one of the modes is attenuated by ≥3 dB, and where all three modes are attenuated by >20 dB, our FM switch has transition BW of around 125 GHz. The losses for our switch are 0.8 dB per prism, 0.2 dB per lens, grating and pol. disp., and 0.8 dB for the SLM. Coupling losses from free-space to the output FMF are 1.0 dB / 1.5 dB for LP_{01} / LP_{11}, respectively, giving a total insertion loss of 4.6 dB / 5.1 dB for the LP_{01} / LP_{11} modes at Port 1.

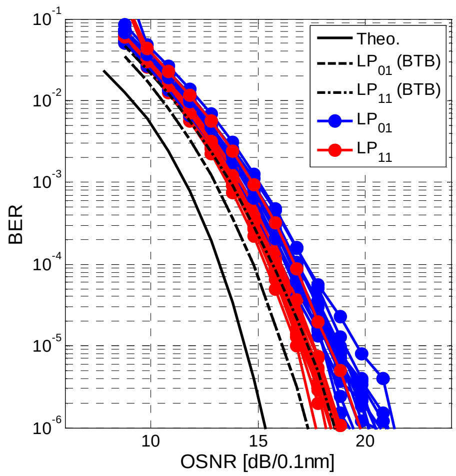

Fig. 4. BER vs. OSNR for 16λ×6×19-Gbaud QPSK.

To verify that the switch does not induce unexpected modal effects, a 16λ×6×19-Gbaud QPSK signal was transmitted (Fig. 1(c)). The center wavelengths of the channels were set to the centers of the passbands of Fig. 3(c). Thus, eight of the channels were switched to Port 1 and the remainder to Port 2. Fig. 4 shows the BER vs. OSNR characteristic for all 16 channels. It is observed that the switch causes a 1 to 3 dB power penalty compared with FMF back-to-back (BTB) at BER=10^{-3}. The LP_{01} mode has worse BER due to its sampling scope having lower bandwidth. We also investigated the channel matrix induced by the switch[6]. Detuning the wavelength of a 6×19-GHz QPSK channel from the center of the passband will not only cause higher insertion loss, but mode coupling between LP_{01} and $LP_{11,e}$ modes. We computed the singular values (SV) of the channel matrix at 10 GHz steps. Fig. 5 shows the normalized SVs versus detuning frequency for the channels at 1548.11 nm (Port 1) and 1550.12 nm (Port 2). The spread in SV increases towards the passband edge. The ~4 dB spread in SV is at 0 GHz is mostly due to the M-MUX/M-DEMUX (~3.5 dB for FMF BTB). When the detuning frequency is 250 GHz (the channel is switched to the other port), all modes are suppressed, and the SV spread is actually smaller than at ±200 GHz.

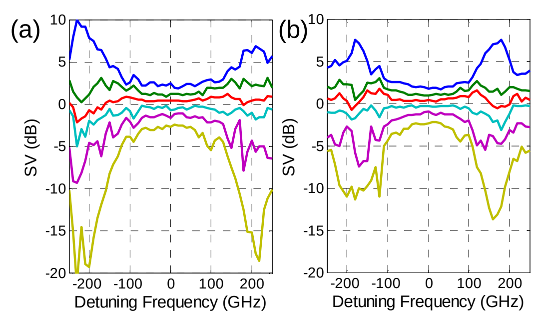

Fig. 5. Channel SV's vs. detuning frequency for channels at (a) 1548.11 nm (Port 1) and (b) 1550.12 nm (Port 2).

Conclusions

We constructed a 1×2 few-mode WDM switch using a spatial light modulator. Crosstalk <–22 dB and transition bandwidth <125 GHz was achieved. We transmitted and detected a 16λ×6×19-GHz QPSK signal through the switch with low power penalty. Channel analysis shows the FM switch has low mode dependence.

References

[1] S. Randel et al., OFC'12, PDP5C.2 (2012)
[2] E. Ip et al., OFC'13, PDP5A.2 (2013).
[3] X. Chen et al., Opt. Exp.. **20**, 14302-14307 (2012).
[4] N. Fontaine et al., OFC'13, OTh1B (2013).
[5] E. Ip et al., ECOC'13, Th.1.C.2 (2013).
[6] S. Randel et al., IEEE Summer Topical, MC4.1 (2012).