Heterogeneous Space-Division Multiplexing and Joint Wavelength Switching Demonstration

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Abstract: We demonstrate a six spatial-mode, wavelength-routing network interoperable with few-mode, coupled-multi-core, and single-mode fiber spans using a custom 57-port wavelength-selective switch configured for joint-switching of spatial-superchannels.

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1. Introduction: Need for Joint Switch Compatible with all Types of Fibers

Space-division multiplexing (SDM) uses parallel spatial paths in novel fibers to provide capacity increases over single-mode fiber (SMF) systems. These spatial paths can be the cores in a multi-core fiber (MCF), the spatial modes in a few-mode fiber (FMF), and even parallel strands of SMF. All these fibers are suitable for transmission and some key results include >305-Tb/s over 19-core fiber [1], 1.01-Pb/s over 52-km of 12-core fiber [2], 177-km of FMF supporting six spatial modes [3], and 1705 km of coupled-core MCF (CC-MCF) [4].

It is unclear which SDM fiber provides the best performance, and in the future, network operators may deploy different SDM fibers throughout the network. Figure 1a) shows such a network with 4 nodes that uses six spatial channels. The nodes are interconnected with three different SDM fibers: six parallel SMF strands, an amplified FMF span with six spatial modes, and an amplified CC-MCF with six-cores. To route signals through the network, wavelength selective switches (WSSs) can be used in switching nodes to direct wavelength channels between different locations. In an SDM network with different fibers, the WSS must be capable of interfacing and routing the different spatial modes of each type of SDM fiber in addition to handling the multiplicity of the additional spatial channels. Previous

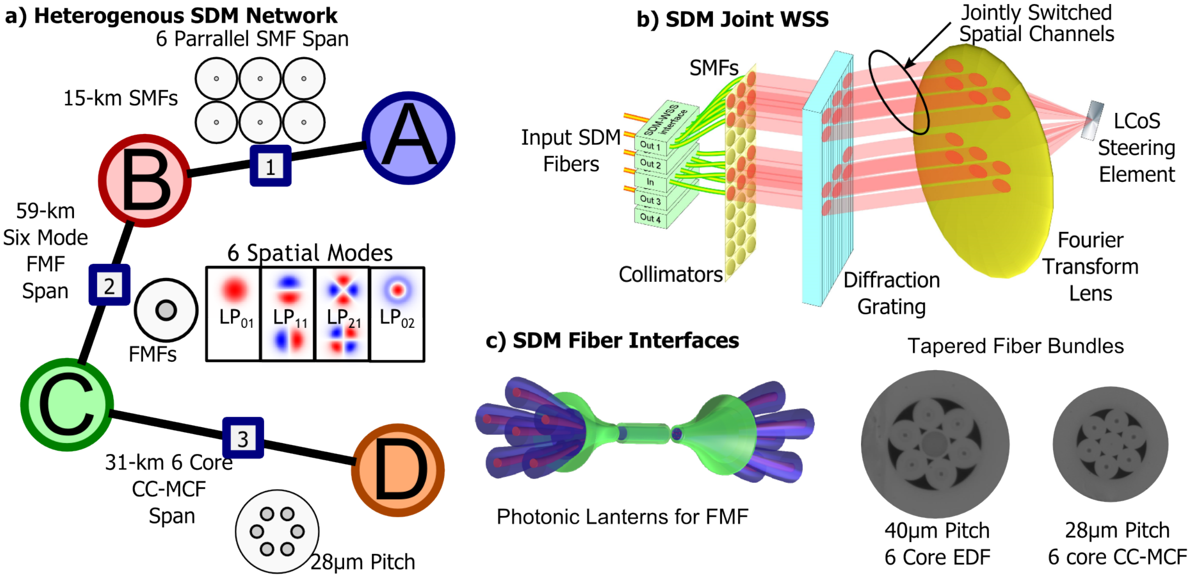

Fig. 1: a) Heterogenous SDM network with different six spatial-mode fiber spans. b) Joint wavelength selective switch (WSS) for simultaneously switching all modes. The beam forming optics to optimize resolution and port count, and the polarization diversity optics are not shown. c) Photonic lantern fiber interface for FMF and tapered fiber bundles for interfacing to the six-core span.

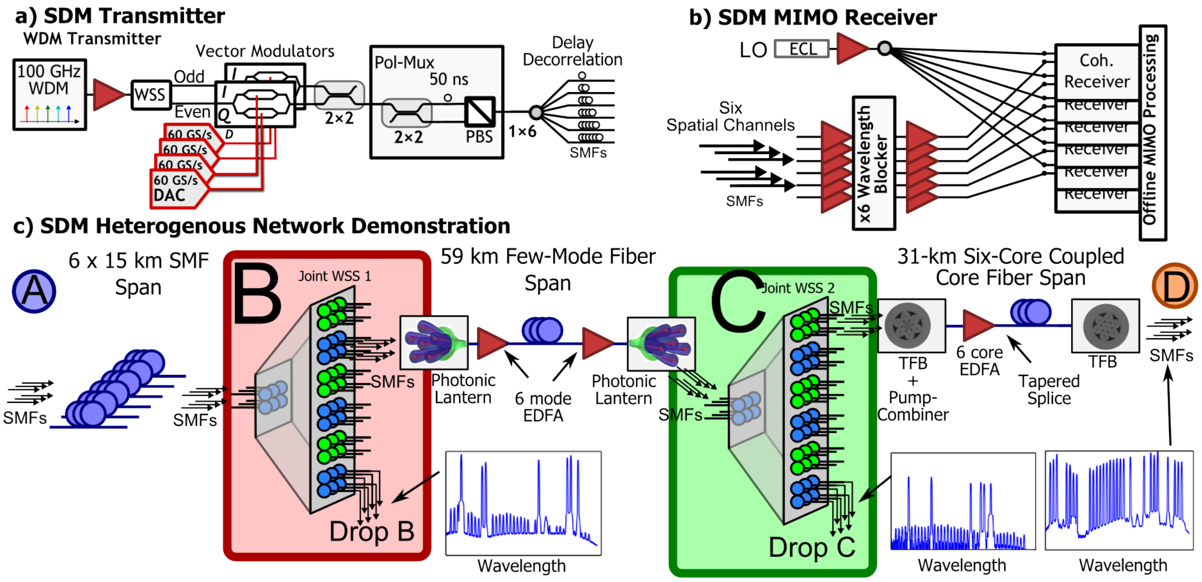

Fig. 2: a) Transmitter with six spatial channels. b) SDM receiver with offline MIMO processing. c) Experimental arrangement. Spectral insets are measured after the first receiver amplifier. ECL: External Cavity Laser, LO: Local Oscillator.

WSS demonstrations include a 1×2 for 7-core MCF built using a commercial 1×20 SMF WSS [5], a 1×11 for three mode FMF built from a commercial twin 1×24 [6], a 1×2 WSS with internal spatial-diversity with 3 spatial-mode FMF inputs [7], and a 1×9 WSS with direct 3 spatial-mode FMF operation [8]. All these switches use 1 dimensional fiber array to layout the spatial-modes and ports.

Here, we build a new type of WSS that arranges the SMF ports in a 2D array which can accommodate more spatial channels, can interface with all six-spatial channel SDM fibers, and can also jointly switch 6 spatial modes to 8 output ports. Using two joint WSS, we demonstrate a heterogenous network with 3 separate SDM fibers and wavelength routing at two separate network locations. The 59-km FMF span contains two cladding-pumped FMF amplifiers [9], and the CC-MCF span contains a multi-core (MC) cladding-pumped erbium doped fiber amplifier (MC-EDFA) at its input [10].

2. Joint Wavelength Selective Switch for SDM: Compatibility with Parallel SMF, FMF, and CC-MCF

Spatial channels, unlike wavelength channels, are susceptible to crosstalk. Multiple-input multiple-output (MIMO) processing can unscramble crosstalk provided that all spatial-channels are routed together as a unit from the transmitter to the receiver. Otherwise, MIMO processing cannot undo the crosstalk which will reduces the system capacity [11]. Additionally, having a single WSS that is designed to switch modes as a unit can obtain a much greater throughput at a cost commensurate with today's SMF WSS. Under these constraints, it makes sense to optimize the SDM WSS and other switching elements to jointly switch the modes rather than to individual switch modes.

Figure 1b) describes the operation principle of a joint WSS for six parallel spatial channels. The spatial channels on the SDM input fibers are first demultiplexed into SMFs that are coupled to freespace Gaussian beams. Demultiplexing the modes into identical Gaussian beams insures that each mode has same spectral transmission and same loss in the WSS. Figure 1c) shows two SDM demultiplexers to interface with the WSS and SDM fibers: a six-mode mode-selective photonic lantern (PL) [12] to excite the modes of the FMF with 2-dB insertion loss and two tapered fiber bundles (TFB) to couple signals and multi-mode pump light into the CC-MCF and the MC-EDFA. The WSS fiber ports modes are arranged into a 2D pattern (19×3), with all 6 modes from a SDM fiber arranged across two rows and the SDM fibers accommodated vertically. A diffraction grating angularly disperses the different wavelengths and a focusing lens converges the beams to a common spot on the liquid crystal on silicon (LCoS) steering element which applies blazed saw-tooth holograms in the vertical direction to simultaneously steer all beams to different ports. Signals input into the central column return on the central column, whereas signals on the left and right columns switch places. All signals from each row converge to the same spot on the LCoS and thus have the exact same passband shape and switching characteristic.

We built two of the flexgrid WSSs with 57 ports (19 rows × 3 columns), 0.5 dB spectral resolution of 78 GHz for 100-GHz spaced channels, and 5-8 dB insertion loss. Higher resolution could be obtained by illuminating more lines on the diffraction grating. Figure 3a) shows a 100-GHz interleaver passbands across the entire C-Band (5-THz) for all

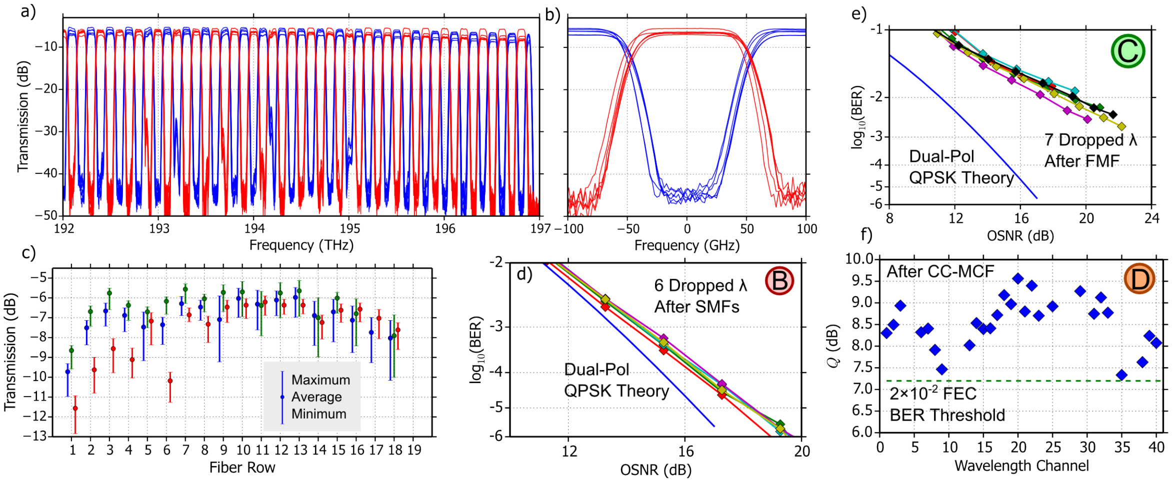

Fig. 3: Interleaver passbands for a group of six spatial channels a) across entire C-Band and b) a single 100-GHz channel. c) IL statistics for all ports across the C-band. BER performance for the wavelengths dropped at d) node B and e) node C and the f) through channels at node D.

six modes. Figure 3b) shows a single passband, which shows only 1-2 dB insertion loss variation among the six spatial channels. Figure 3c) shows the insertion loss statistics for 18 rows (54 ports) across the entire C-band. Degradation of some of the ports are due to pointing errors of the prototype fiber array and are not inherent to the design of the switch.

3. Networking Experiment

Figure 2b) overviews the networking testbed from node **A** to node **D** of the hypothetical network in Fig. 1a). Figure 2a) shows the SDM transmitter which produces 40, 100-GHz spaced WDM channels, each with 30-GBd Quadrature Phase Shift Keyed (QPSK) modulation. Two I/Q modulators separately modulate the even and odd wavelengths and a polarization delay multiplexer, and fiber delays decorrelate the polarization modes and six spatial modes (12 total spatial and polarization channels). Figure 2b) describes the SDM receiver that uses six polarization diversified coherent receivers which share a common local oscillator (LO). Each coherent receiver contains a polarization diversified optical hybrid, 4 balanced photodetectors and 4 40-GS/s analog-to-digital converters (LeCroy Labmaster 9zi). To measure each wavelength channel, each received spatial mode is amplified, the wavelength is selected using the wavelength blocker array, and then amplified again before sending into the signal ports of the optical hybrids. A 12×12 frequency-domain MIMO equalizer is used to unscramble the 12 launched spatial and polarization channels. For noise-loading ASE is injected at the transmitter.

Node **A** and **B** are connected with parallel strands of 15-km SMF. At node **B**, 6 wavelength channels (25%) are dropped into six SMFs, and the remaining 34 are sent through to the amplified FMF span. Figure 2d) shows the Bit-Error-Rate (BER) curves for the dropped SMFs. The through channels are sent through the FMF span which has two cladding pumped FMFs to recover for the joint WSS, and the FMF losses. At node **C**, 7 additional wavelengths are dropped again into six SMFs. The BER performance of the dropped channels show approximately 3.5-dB power penalty at a BER of 1×10^{-3} compared to the dropped SMF channels. The remaining 27 wavelengths are coupled into an amplified CC-MCF span using a TFB. Figure 3f) shows the BER represented as Q-factor at the output of the span which includes transmission through two WSS, 3 SDM amplifiers, a 15-km parallel SMF span, a 59-km six mode FMF span, and a 31-km six-core CC-MCF span. All BERs were above the soft forward error correction limit of 2×10^{-2}.

In conclusion, we have demonstrated a heterogenous SDM network with spatial multiplicity of six, using 3 types of SDM fiber spans and a large port count joint-switching WSS supporting six-spatial modes.

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