

# A $32 \times 10$ Gb/s DWDM Metropolitan Network Demonstration Using Wavelength-Selective Photonic Cross-Connects and Narrow-Band EDFAs

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**Abstract**—The feasibility of a  $32 \times 10$  Gb/s dense wavelength-division-multiplexed (DWDM) all-optical short-reach metropolitan network using dynamically reconfigurable three-dimensional microelectromechanical-system-based wavelength-selective photonic cross-connects (WSPXC) is experimentally investigated. Full DWDM amplification at the high-capacity node is performed with low-cost narrow-band erbium-doped fiber amplifiers whose channel gain variation is compensated per span using the inherent channel equalization capability of the WSPXC. With Reed-Solomon forward error correction, bit-error rates better than  $10^{-15}$  are possible for all 32 channels over 400 km of single-mode fiber and ten transitions through the WSPXC nodes.

**Index Terms**—Optical fiber communication, photonic switching systems, wavelength-division multiplexing.

## I. INTRODUCTION

ALL-OPTICAL transparent dense wavelength-division-multiplexed (DWDM) metropolitan networks with high throughput and large add-drop capacity photonic cross-connects (PXC) have emerged as a next-generation alternative to today's networks based on optoelectronic switching [1], [2]. Optically transparent nodes can be realized with wavelength-selective PXC (WSPXC) using large-scale non-blocking three-dimensional microelectromechanical-system (3-D MEMS) optical switches [3]–[5] or broadcast-and-select architectures based on wavelength blockers [6]. While both WSPXC architectures provide future-proof dynamic reconfigurable wavelength switching, channel add-drop, and inherent dynamic channel equalization, the 3-D MEMS-based optical switch provides a lower loss solution as the mesh node degree as well as the number of channel add-drops per node increase.

In cost-sensitive all-optical short-reach metropolitan networks, further cost reduction is desirable. Recently, nonzero dispersion-shifted fibers for metropolitan networks were introduced that eliminate the need for dispersion compensation, which reduces both the optical loss and the overall network cost [7], [8]. A  $32 \times 10$  Gb/s DWDM short-reach metropolitan network was demonstrated using low-cost directly modulated transmitters over four nodes and four spans of 25.5 km of negative dispersion fiber [7]. In another 32-channel metropolitan

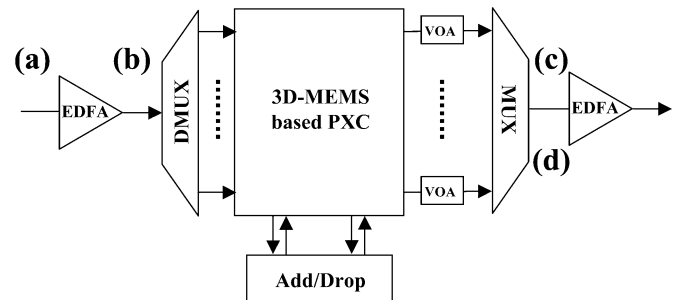


Fig. 1. Schematic of the wavelength-selective metropolitan DWDM node based on a 3-D MEMS WSPXC and narrow-band input and output EDFAs.

network employing 155 km of positive dispersion fiber and ten nodes, further cost-reduction at the node was achieved by grouping wavelengths into wavebands at the expense of reduced network level dynamic wavelength flexibility provided with the WSPXC architectures [8].

In this letter, we demonstrate a  $32 \times 10$  Gb/s all-optical DWDM metropolitan network over a total distance of 400 km and 10 WSPXC nodes that are based on low-loss, high-capacity, and nonblocking 3-D MEMS optical switches [3], [4]. Full DWDM amplification at the WSPXC node, which is conventionally performed with gain-flattened erbium-doped fiber amplifiers (EDFAs), is realized with low-cost narrow-band and lower output saturation power EDFAs that are typically used for single-channel or waveband amplification [7]. The channel gain excursion due to the absence of gain-flattening filters in the EDFAs is compensated per span with the inherent channel equalization capability of the WSPXC [4]–[6].

## II. METROPOLITAN WSPXC NODE

Fig. 1 shows the schematic of the WSPXC node for dynamic short-reach metropolitan networks. The core of the WSPXC is a  $256 \times 256$  3-D MEMS optical switch with typical path losses of 2 dB, and low polarization and wavelength-dependent losses of 0.1 and 0.2 dB, respectively [3]. When the nonblocking optical switch with negligible optical crosstalk (worst case of 60 dB) is combined with wavelength-granular optical multiplexers (MUXs) and demultiplexers (DMUXs), a dynamically reconfigurable WSPXC node with wavelength switching and any channel add-drop is realized [4]. The 256-port 3-D MEMS switch can, therefore, support full wavelength switching of eight DWDM trunks, each carrying 32 wavelengths at 10 Gb/s,

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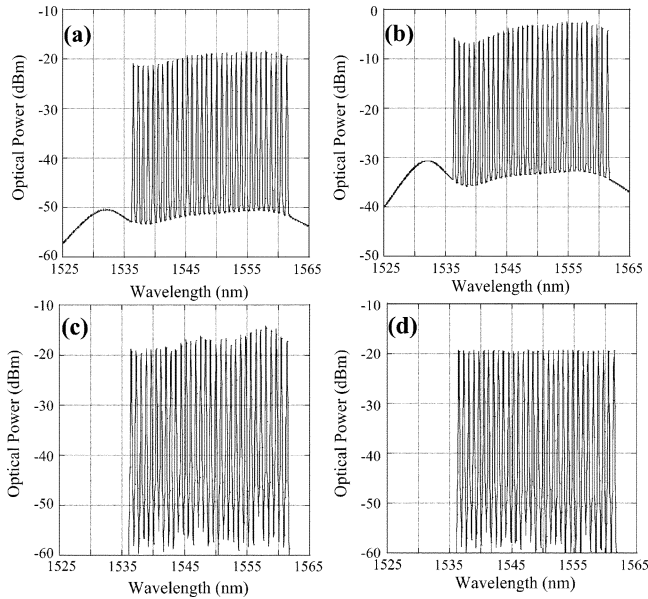


Fig. 2. Optical spectrum of the 32-channel DWDM signals (with reference to Fig. 1) measured (a) before the input EDFA (incoming spectrum shaped by the prior output EDFA), (b) after the input EDFA and before the WSPXC, (c) after the WSPXC without channel equalization, and (d) after the WSPXC with channel equalization.

for a total switching capacity of 2.56 Tb/s. Alternatively, with four DWDM trunks, the WSPXC node can support 1.28-Tb/s capacity while also providing 100% add-drop capability. It should be noted that this high-performance WSPXC architecture is not limited to metropolitan networks, but can also be employed in regional and long-haul DWDM networks.

The (D)MUXs used in the WSPXC are based on thin-film filters with a maximum loss of 5 dB and a flat-top filter shape with a minimum 3-dB bandwidth of 0.6 nm ensuring cascading ability [4]. At the input and output of the WSPXC, low-cost narrow-band and single-stage EDFAs with a minimum channel gain and maximum noise figure of 15 and 7 dB, respectively, and an output saturation power of 12 dBm are used. The per span channel power variation due to the two nongain-flattened EDFAs and the WSPXC are controlled before the optical MUX such that an equalized DWDM spectrum is achieved either before or after the output EDFA. While channel equalization in our experiments were performed with variable optical attenuators (VOAs) in an open-loop configuration, optical attenuation by detuning the mirrors of 3-D MEMS optical switches, which reduces both the cost and insertion loss of the WSPXC, has recently been demonstrated [5]. In Fig. 2, the evolution of the optical spectrum within a given span (with specific references to Fig. 1) is shown where DWDM equalization is set to before the output EDFA, and the 32 wavelengths are specifically selected to avoid the EDFA gain peak for reduced gain variation. Fig. 2(a) shows a 2.9-dB channel gain excursion before the input EDFA due to the prior node's output EDFA while the input EDFA then additionally increases the channel variation to 4.7 dB [Fig. 2(b)]. The channel loss variation of the 3-D MEMS optical switch and the WSPXC, which are random in comparison to the EDFA gain spectrum, are less than 1 and 3 dB, respectively, with a maximum WSPXC loss of less than

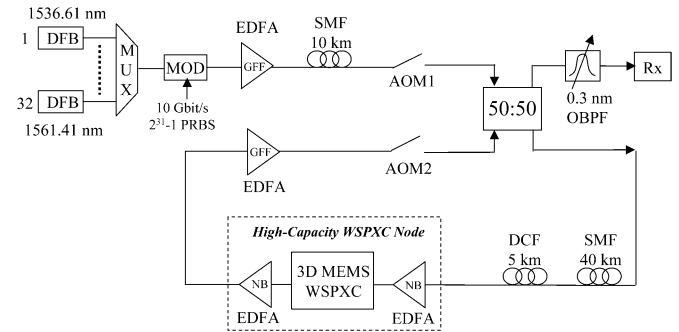


Fig. 3. 32 × 10 Gb/s metropolitan network experimental setup. GFF: Gain-flattening filter. NB: Narrow-band. OBPF: Tunable optical bandpass filter. Rx: Optically preamplified receiver.

15 dB. Fig. 2(c) and (d) show the filtered DWDM spectrum at the output of the optical MUX without and with channel equalization, respectively. Channel equalization within 0.4 dB, which is mainly limited by the accuracy of the manual mechanical VOAs, is achieved over all wavelengths from an unequalized WSPXC node channel variation of 5.4 dB.

### III. EXPERIMENTAL RESULTS

The performance of the WSPXC node with narrow-band EDFAs was experimentally investigated in a recirculating loop representing a short-reach all-optical metropolitan network with a 400-km total length and ten WSPXC nodes (Fig. 3). At the transmitter, 32 distributed feedback laser sources with 100-GHz spacing and ranging from 1536.61 to 1561.41 nm are multiplexed into a LiNbO<sub>3</sub> modulator. Each wavelength is encoded with an electrical 10-Gb/s pseudorandom bit stream of  $2^{31} - 1$  and then decorrelated in 10 km of single-mode fiber (SMF) before entering the recirculating loop using an acousto-optic modulator (AOM) and a 3-dB coupler. The low per channel fiber launch power of  $-7$  dBm avoids fiber nonlinearities within the network and matches the per channel power after the node output EDFA. The recirculating loop consists of a 40-km SMF span followed by 5 km of dispersion-compensating fiber and a total loss of 14 dB. The DWDM wavelengths are then amplified with the input narrow-band EDFA and inserted into the WSPXC. The WSPXC is then followed by the output narrow-band EDFA and a gain-flattened EDFA, which is employed to overcome the recirculating loop specific losses, such as the AOM and 3-dB coupler, with minimal disturbance on the DWDM spectral shape. At the receiver, the DWDM signals are demultiplexed using a 0.3-nm tunable optical filter before the preamplifier EDFA.

Due to the nature of the recirculating loop experiment and the placement of the WSPXC node, the DWDM channel spectrum equalization is set after the output EDFA rather than before the output EDFA as discussed in the preceding section (Fig. 2). Fig. 4 shows the output spectrum measured at the output of the WSPXC node after (a) one loop, and (b) ten loops. The channel power variation increases to 1.5 dB after ten loops, which is due to the repetitive feature of the recirculating loop. It should be noted that in a real network deployment, VOAs operated with closed-loop control would ensure better than 0.2-dB accuracy per span channel equalization. Fig. 5 shows the measured

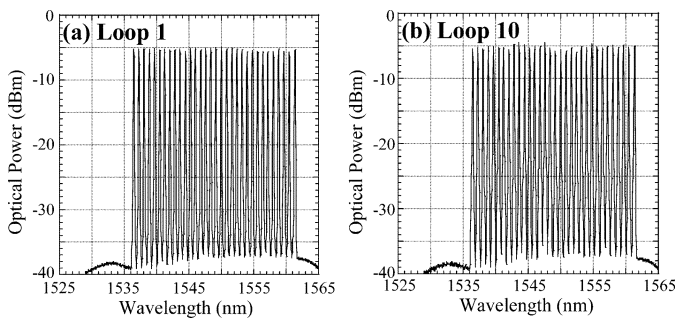


Fig. 4. Optical spectrum of the 32-channel DWDM signals measured at the output of the WSPXC node after (a) one loop, and (b) ten loops.

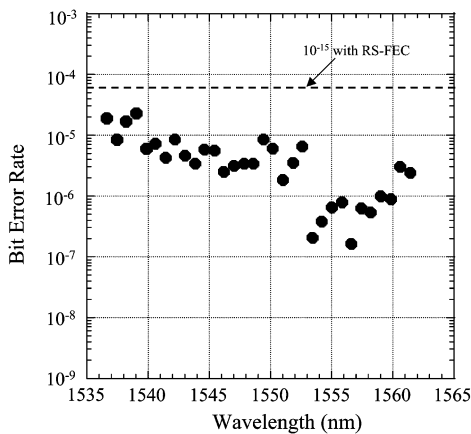


Fig. 5. BER measurements for all 32 DWDM channels after 400 km and ten WSPXC nodes (ten loops).

bit-error rates (BERs) at an average received power of  $-20$  dBm for all 32 channels after 400 km and ten WSPXC nodes with a worst-case BER of  $2.3 \times 10^{-5}$ . Due to the higher noise figure of the EDFAs at shorter wavelengths, these channels perform slightly worse; however, all 32 channels exhibit BERs better than  $6 \times 10^{-5}$ , which corresponds to a corrected BER of  $10^{-15}$

using the standard 255/239 Reed–Solomon forward error correction (RS-FEC) with 7% overhead.

#### IV. CONCLUSION

A high-performance dynamically reconfigurable WSPXC DWDM node based on 3-D MEMS and low-cost narrow-band EDFAs was experimentally investigated for applications in cost-sensitive short-reach metropolitan networks. After ten WSPXC nodes and 400 km, all 32 wavelengths performed better than the RS-FEC code limit for error-free operation. Further cost reduction and performance improvement is expected by detuning the MEMS mirrors for DWDM channel equalization functionality.

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