Petabit-class Optical Networks Based on Spatial-Division Multiplexing Technologies

Hideaki Furukawa, Ruben S. Luís
Network Systems Research Institute
National Institute of Information and Communications Technology
Koganei, Tokyo 184-8795, Japan
furukawa@nict.go.jp

***Abstract*—We have developed a spatial division multiplexing (SDM) based hierarchical optical switching testbed capable of handling optical signals with elastic granularity from 10 Tb/s to 1 Pb/s. We have demonstrated some network scenarios of add/drop, express, protection switching, optical channel grooming and SDM tributaries with coupled and uncoupled spatial channels. This demonstration made use of large-scale and low-loss optical switches based on MEMS technology and three types of SDM fibers. This is a major step toward the early implementation of petabit-class backbone optical networks capable of supporting the increasing requirements of internet services such as broadband video streaming, 5G mobile networks or Internet of Things.**

Keywords— spatial division multiplexing; optical networks; optical switching;

I. SDM BASED OPTICAL NETWORKS

Optical networks have become an indispensable infrastructure underpinning the digital economy and supporting the intensive data networking needs of industry, commerce, academic institutions, governments and individuals worldwide. Since the amount of network traffic has increased dramatically, the capacity limit of conventional optical networks based on wavelength division multiplexing (WDM) technologies has been concerned. To extend the capacity limit and cope with ever-increasing traffic, spatial division multiplexing (SDM) technologies have been recently studied and developed for short and long reach backbone networks as well as datacenter networks.

The main new types of optical fibers studied are multi-core fibers (MCFs) in which multiple cores are arranged in an optical fiber and multimode fibers that support multiple propagation modes in a single core with a larger core diameter. Up to now, successful transmission experiments of large capacity have been reported for MCFs [1]-[9]. Especially, although requiring potentially resource intensive MIMO processing without separation of spatial sub-channels, higher spatial multiplicity few-mode (FM)-MCFs with over 100 spatial channels have been reported and recently used to demonstrate over 10 Pb/s throughput in a single fiber [8][9]. Recently, we have demonstrated the record transmission of 10.66 Pb/s with a spectral efficiency of 1158.7 bit/s/Hz using a 38-core 3-mode fiber [9].

978-3-903176-21-8 © 2020 IFIP

On the other hand, such high transmission-capacity cannot be fully utilized without transparency and flexibility in the network nodes. Especially, SDM optical switching technologies are expected to extend point-to-point transmission to optical networks connecting multiple points. Recently, we have successfully demonstrated a spatial super-channel (SSC) optical packet switching with switching capacity of 83.3 Tb/s with by using a developed high-speed spatial optical switch system [10]. However, Petabit-class transmission requires Petabit-class switching technologies to manage and reliably direct large amounts of data through complex networks. Up to now, such technologies have been beyond reach because the existing approaches are limited by complexity and/or performance.

In this paper, we present the first large-scale optical switching testbed capable of handling 1.08 Pb/s optical signals [11]. This testbed made use of large-scale and low-loss optical switches based on MEMS technology, multi-core joint switches for protection and three types of SDM fibers such as 22-core single-mode fibers, 7-core single-mode fibers and 3-mode fibers. This network uses a hierarchical architecture consisting of SDM layer and WDM layer so that low-loss spatial switches in SDM layer can reduce the node cost and enable long-distance transmission. This has been the first demonstration of an SDM network node with capacities comparable to recent Petabit-class SDM transmission experiments.

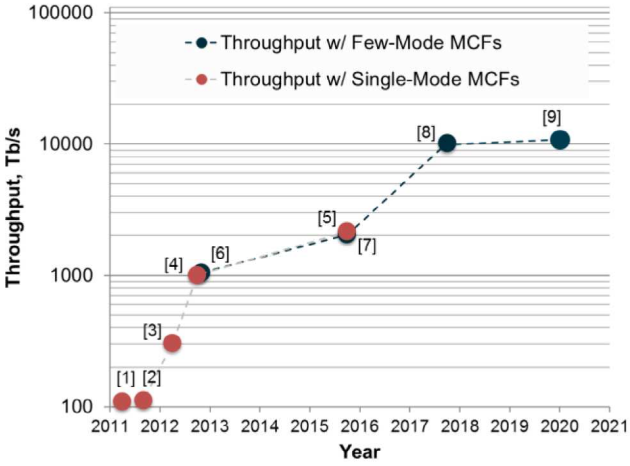

Fig. 1. MCF transmission experiments.

II. DEMONSTRATIONS

Many SDM node architectures for effectively utilizing spatial and wavelength resources have been proposed [12]. Jinno et al. propose a spatial channel (SCh) network with a hierarchical SDM node architecture with low-loss spatial switches in order to realize node cost reduction and long-distance transmission [13]. The WDM layer can be spatially bypassed by the low loss spatial optical switch of the SDM layer. Based on this hierarchical node architecture, we developed a hierarchical optical cross connect as shown in Fig. 1(a). Optical channels (OChs) consisting of one or more wavelengths within one or more SChs are carried by spatial cross-connects (SXCs) through SDM transmission media. Thus, OChs can bypass overlying wavelength cross-connects (WXCs) located at a WDM layer.

We demonstrated the following 4 fundamental scenarios that constitute the building blocks of SDM optical networks as shown in Fig 2(b).

Scenario A. Switching of 1 Pb/s SChs on SDM layer
Scenario B. Redundant configuration to support network failures or fiber breaks and protection switching
Scenario C. Management of lower-capacity OChs (10 Tb/s) on WDM layer within the 1 Pb/s network
Scenario D. Branching of 1 Pb/s SChs into coupled and uncoupled SChs with various capacities on different types of optical fibers

In Scenario A, SXC forwards up to 22 SChs, each carrying >49 Tb/s over the entire C-band for a total throughput of 1.08 Pb/s. We utilize a 44×44 MEMS switch and transmission through a 22-core single-mode MCF. We demonstrate optical add/drop/express for 1.08 Pb/s SChs on SDM layer. In Scenario B, we exploit joint spatial switching to realize 1+1 spatial-multiplex section protection (MSP). We use a combination of 7-core multi-core acousto-optic modulator (MC-AOM)-based shutters and 7-core multi-core mirror-based switches (MC-SWs) as a protection switch. This allows joint protection of up to 21 SChs with a throughput of 1.03 Pb/s. In Scenario C, we demonstrate optical add/drop/express for OChs using a wavelength selective switch (WSS) on WXC. In Scenario D, we show the compatibility with uncoupled and coupled SChs. Usually, coupled SChs requires joint switching and temporal alignment of the optical paths. We compare a 346.4 Tb/s OCh carried by 7 uncoupled SChs over a 7-core MCF with a 148.4 Tb/s OCh carried by 3 coupled SChs over a 3-mode few-mode fiber (FMF).

Here, we show a diagram of the experimental setup and results only for scenario A as shown in Fig. 3. The detail of experiments for other scenarios are given in [11]. Figure 3(a) shows a setup for full add/drop with SChs. At the transmitter (TX), we produced 202 polarization-multiplexed (PM)-64-ary quadrature amplitude modulation (QAM) signals at 24.5 Gbaud aligned with the 25 GHz flex grid between 1527.60 nm and 1567.74 nm. An inter-channel band gap of <500 MHz was possible by using a wide band optical comb generator as light source, which eliminated frequency wandering between carriers [14]. Three of the 202 carriers were selected using a band-pass filter (BPF) for a high quality sliding test band and performance measurement. They were split into odd and even carriers by an interleaver (IL) and modulated by a pair of dual-polarization IQ modulators (DPIQMs) driven by 4 arbitrary wavelength generators (AWGs) operating at 49 GS/s. The remaining 199 channels were generated using a DPIQM driven by an AWG with replicated and delayed output. An LCOS-based optical processor (OP) flattened the dummy band spectrum and carved a notch to accommodate the test band. After recombining test and dummy bands, the 202 OChs composed a SCh with a pre-forward error correction (FEC) throughput of 59.38 Tb/s. We assumed a 20% FEC overhead, which set a minimum Q-factor threshold of 5.7 dB. Hence, the estimated post-FEC throughput was 49.49 Tb/s. The SCh was amplified and split into 22 decorrelated replicas generating 22 SChs with a post-FEC throughput of 1.08 Pb/s.

The SXC node used a 44×44 unidirectional switch implemented with a 64×64 non-blocking bi-directional 3D MEMS switch. 22 add ports could be arbitrarily switched to 22 west line side output ports. Similarly, 22 east line side input ports could be switched to the drop ports or the west side ports.

The switch insertion loss ranged from 2.1 dB to 4.5 dB and its crosstalk was <-44 dB. Laser inscribed 3D waveguide multicore fan in/outs multiplexed the line side ports in and out of a 22-core MCF with the west signals boosted by erbium-doped fiber amplifiers (EDFAs) with 21 dBm output power. The

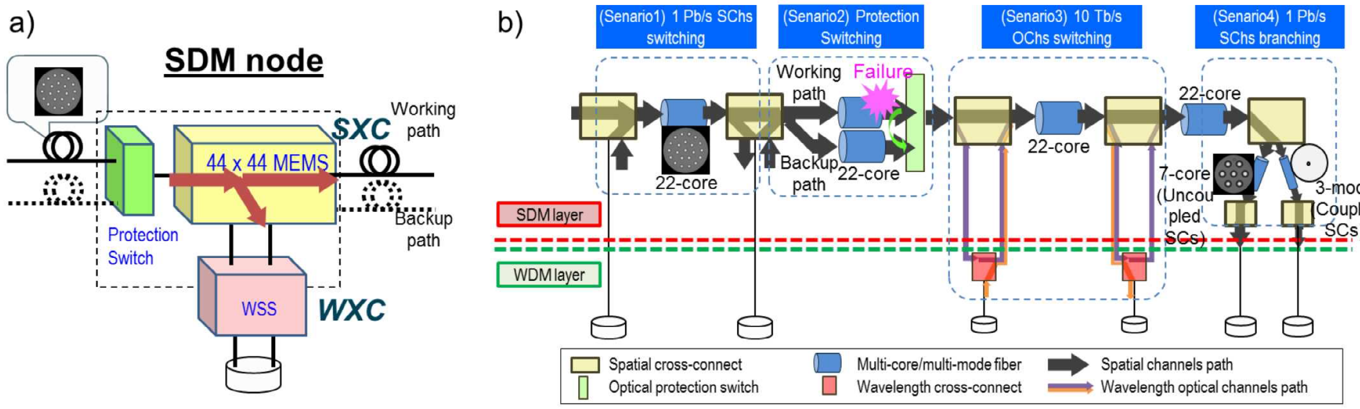

Fig. 2. (a) Hierarchical SDM node architecture. (b) Experimental SDM network testbed and network scenarios.

MCF cores were homogeneous trench-assisted cores arranged on a double ring structure within a 260 µm cladding, as shown in the inset A of Fig. 3(a). The maximum combined fiber and fan in/out loss and crosstalk were 15 dB and -42 dB, respectively.

At the receiver (RX), a switch selected the dropped SCh under analysis, which was pre-amplified by two EDFAs with a BPF in-between, to isolate the channel under analysis. A coherent receiver (CoRX) with a local oscillator (LO) followed by a real-time oscilloscope (RT-DSO) operating at 80 GS/s detected, sampled and stored traces for offline processing. The digital signal processing was implemented using MATLAB and C and consisted of resampling and normalization stages, followed by a 33-tap 2×2 multiple input-multiple output (MIMO). The taps were updated using a least-mean squares data-aided algorithm, switching to a decision directed algorithm after convergence. Carrier recovery was performed within the equalizer loop. Bit-error rate and Q-factor were computed by error-counting over 5 traces with 10 µs (1.225×10 6 symbols). We also considered an express scenario, as shown in Fig. 3(b). In this case, the 22 SChs were transmitted through the MCF before input into the east line side of the SXC and switched to the west line side, bypassing any overlying WDM layer. Fig. 3(c) shows the estimated Q-factor values for the full add-drop and full express cases. It is shown that all OChs reached Q-factor values above 5.7 dB. We note that some penalty was present for the shorter wavelengths due to bandwidth limitations of the EDFAs used in the experiment. Also, the long edge of the C-band was affected by power fluctuations of the comb generator near its seed wavelength of 1558 nm.

III. CONCLUDING REMARKS

We have demonstrated the large-scale optical switching testbed capable of handling 1 Pb/s optical signals. This demonstration made use of state-of-the-art SDM optical switches, three types of SDM fibers, and included the routing of signals with capacities from 10 Tb/s to 1 Pb/s. This has been the first demonstration of an SDM network node with capacities comparable to recent Petabit-class SDM transmission experiments.

ACKNOWLEDGMENT

The authors wish to thank to Takeshi Makino, Takahiro Hashimoto, Hiroyuki Sumimoto, and Tomoji Tomuro for technical supports.

REFERENCES

[1] J. Sakaguchi, et al., "109-Tb/s (7x97x172-Gb/s SDM/WDM/PDM) QPSK Transmission Through 16.8-km Homogeneous Multi-Core Fiber," OFC2011, PDPB6 (2011).

[2] B. Zhu, et al., "112-Tb/s Space-Division Multiplexed DWDM Transmission with 14-b/s/Hz Aggregate Spectral Efficiency Over a 76.8-km Seven-Core Fiber," Opt. Express 19, 16665-16671 (2011).

[3] J. Sakaguchi, et al., "305 Tb/s Space Division Multiplexed Transmission Using Homogeneous 19-Core Fiber," J. Lightwave Technol. 31, 554-562 (2013).

[4] H. Takara, et al., "1.01-Pb/s (12 SDM/222 WDM/456 Gb/s) Crosstalk-Managed Transmission with 91.4-b/s/Hz Aggregate Spectral Efficiency," ECOC2012, Th.3.C.1 (2012).

[5] B. J. Puttnam et al., “2.15 Pb/s transmission using a 22 core homogeneous single-mode multi-core fiber and wideband optical comb,” ECOC2012, Paper PDP3-1 (2012).

[6] D. Qian, et al., "1.05Pb/s Transmission with 109b/s/Hz Spectral Efficiency using Hybrid Single- and Few-Mode Cores," FiO/LS2012, FW6C.3 (2012). 5GMF White Paper "5G mobile communications systems for 2020 and beyond," (2016). http://5gmf.jp/en/

[7] D. Soma et al., “2.05 Peta-bit/s super-nyquist-WDM SDM transmission using 9.8-km 6-mode 19-core fiber in full C band,” ECOC2015, Paper PDP3-1 (2015).

[8] D. Soma, et al., “10.16 Peta-bit/s Dense SDM/WDM transmission over Low-DMD 6-Mode 19-Core Fibre across C+L Band,” ECOC2017 Th.PDP.A.1 (2017).

[9] G. Rademacher, et al., "10.66 Peta-Bit/s Transmission over a 38-Core-Three-Mode Fiber," OFC 2020, Th3H.1 (2020).

[10] J. M. D. Mendinueta, et.al., "Converged Inter/Intradata Center Optical Network with Packet Super-channels and 83.33 Tb/s/port," J. Lightwave Technol. 37, 2, pp. 571-578, (2019).

[11] R. S. Luis, et.al., "Demonstration of a 1 Pb/s spatial channel network node,," ECOC2019, Paper PD.3.5 (2019).

[12] D. Marom, M. Blau, ‘Switching solutions for WDM-SDM optical networks’, IEEE Communications Magazine, 53, 2, pp. 60-68 (2015).

[13] M. Jinno, ‘Spatial channel network (SCN): Opportunities and challenges of introducing spatial bypass toward the massive SDM era [Invited]’, Journal of Optical Communications Networks, 11, (3) pp. 1-14 (2019).

[14] B. Kuo, et.al., ‘Wideband para- metric frequency comb as coherent optical carrier’, J. Lightwave Technol. 21, pp. 3414–3419 (2013).

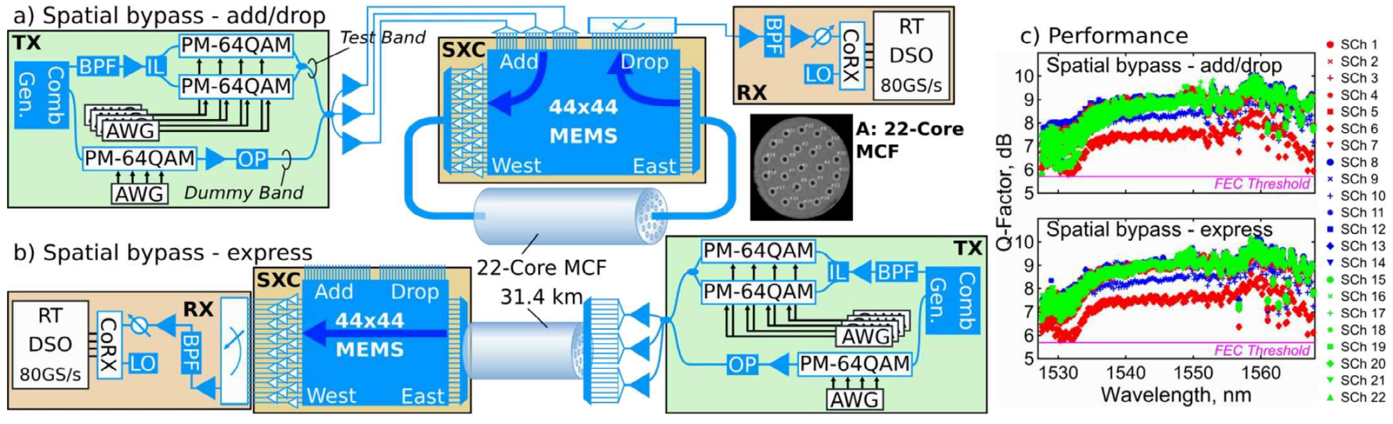

Fig. 3. Experimental setups for scenario A with full add/drop (a) and full express (b) switching. c) Q-factors estimated for all 202 OChs within each of the 22 SChs for full add/drop and express.