Demonstration of a Cost-Effective WSS-Free Colorless Flex-Grid ROADM with Coherent Detection and Wavelength Monitoring for Optical Metro Networks

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***Abstract*—A novel WSS-free ROADM based on optical splitter/coupler and coherent detection is experimentally demonstrated, cost-effectively achieving similar functions and performances as a WSS-based ROADM for metro applications. Colorless and flex-grid functions are also demonstrated.**

Keywords—Metro Network; ROADM; WSS-free

I. INTRODUCTION

With the rapid developments of 5G, virtual reality (VR), augmented reality (AR), and enterprise services, optical transport network is facing tremendous challenges [1-2]. Recently, computing force network (CFN) is becoming a hot topic for industry and academia, which also propose new requirements for optical transport network (OTN), such as high-capacity, high-bandwidth, low latency, etc. The traditional OTN equipment based on electrical cross has the advantages of strong operation administration and maintenance (OAM) functions and flexible route schedule, which has been widely deployed in the world. However, the growth of the electrical process ability cannot satisfy these new requirements well. Optical layer networking may be a promising way to overcome the bottleneck to achieve high-capacity schedule and reduce latency induced by optical-to-electrical conversion. Many impressive results of wavelength selective switch (WSS) based reconfigurable optical add-drop multiplexer (ROADM) for optical layer networking have been presented [3-6]. However, limited by the cost of WSS, WSS-based ROADM is mainly deployed for backbone network as high-degree schedule node. For metro network applications, low-cost AWG-based fixed OADM are massively applied to perform optical layer networking rather than using WSS-based ROADM, resulting in fixed wavelength channel and schedule. Manual connection of optical fiber between wavelength division multiplexing (WDM) multiplexer/ demultiplexers and OTN optical modules should be required if wavelength schedule is needed to be adjusted. With different modulation formats and channel spacing, flex-grid would be benefit to flexible networking. Design of cost-effective flex-grid ROADM is crucial to high-capacity and low latency optical metro networks.

In this paper, we propose and demonstrate a WSS-free colorless flex-grid ROADM with coherent detection and wavelength monitoring for optical metro networks. With broadcast transmission of optical splitter and coherent characteristic of the optical module, colorless function of ROADM is achieved by adjusting the central wavelength of the local oscillator. Optical coupler combined with variable optical attenuators (VOAs) in each branch of the optical coupler is used to perform wavelength aggregation and control adding wavelength. We further propose a method based on multi-carrier pilot-tone OAM management with optical coupler, performing that the allocation of wavelength resources can be online monitored. The experimental tests are carried out to verify the feasibility of the WSS-free colorless flex-grid ROADM. The results show that the WSS-free ROADM has the similar functions and transmission performance with WSS-based ROADM. The flex-grid ability is also demonstrated by adding/dropping 100-GHz-spacing 400-Gb/s DP-16QAM-PCS signals, 75-GHz-spacing 200-Gb/s DP-QPSK signals, and 50-GHz-spacing 100-Gb/s DP-QPSK signals together.

II. ARCHITECTURE AND PRINCIPLE

The architectures of the conventional WSS-based ROADM node and the proposed WSS-free ROADM node are shown in Fig. 1(a) and Fig. 1(b), respectively. The architecture of conventional WSS-based ROADM node consists of a WSS for dropping wavelength and another WSS for adding wavelength. In the proposed WSS-free ROADM architecture, for dropping wavelength, the WSS is replaced by an optical

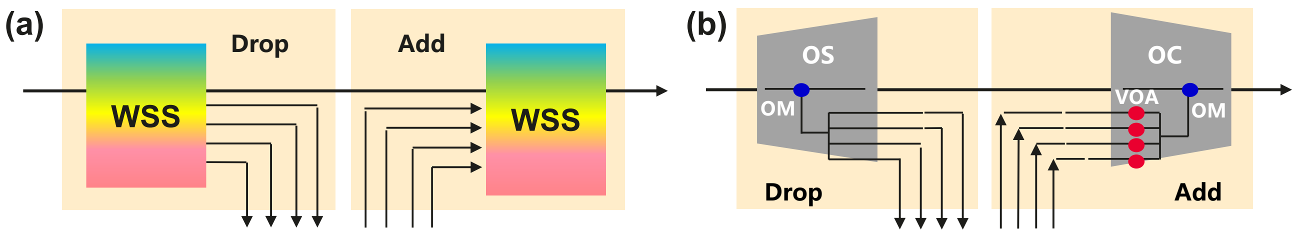

Fig. 1 The architectures of (a) the conventional WSS-based ROADM node and (b) the proposed WSS-free ROADM node, respectively. OS: optical splitter. OC: optical coupler. OM: OAM monitor.

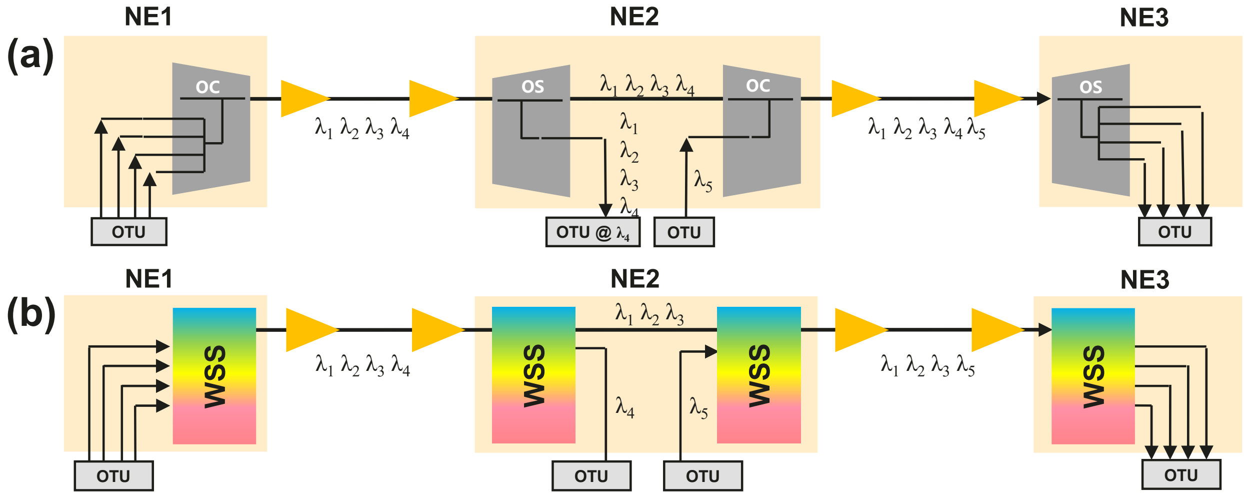

Fig. 2 The networking testbed for (a) the proposed WSS-free ROADM scheme and (b) the conventional WSS-based ROADM scheme.

splitter to broadcast all wavelengths to each coherent optical modules and the coherent optical module can adjust the central wavelength of the local oscillator to choose dropping wavelength. Meanwhile, an optical coupler instead of the wavelength-add WSS to perform wavelength aggregation and several VOAs are applied in each branch of the optical coupler to control adding wavelength. Moreover, optical OAM information are modulated on the service signals by pilot-tone technology and detected at the ingress port of optical splitter and the egress port of the optical coupler, supporting online monitoring and dynamic allocation of wavelength resources.

The principle of reconfigurable wavelength add and drop in this WSS-free colorless flex-grid ROADM scheme can be described as follows:

In the dropping wavelength direction, WDM optical signals centered at the wavelengths from λ_1 to λ_N launched into the ROADM node is firstly fed into a 1×N optical splitter. Here, one egress port of the optical splitter is connected to the optical coupler at the adding wavelength side to perform all wavelengths pass-through the node. The other N-1 ports of the optical splitter are connected to several coherent optical modules one by one. With the broadcast transmission of optical splitter, each optical module receives same WDM optical signals centered from λ_1 to λ_N rather than only the target signal at the wavelength of λ_x by using WSS. Based on the coherent characteristic of the optical module, the central wavelength of the local oscillator is subsequently tuned to the wavelength λ_x of the target signal. In this way, the target dropped signal is effectively detected and the other received WDM signals in the same optical module are regarded as background noise by coherent beating. By adjusting the central wavelength of the local oscillator, any WDM optical signals centered at the wavelengths from λ_1 to λ_N can be selected at one optical module, performing colorless function of ROADM.

In the adding wavelength direction, N-1 WDM signals centered at the wavelengths from λ_{N+M} to $\lambda_{N+M+N-2}$ are generated from corresponding optical modules, respectively, and combined together with the passed WDM optical signals centered from λ_1 to λ_N by a 1×N optical coupler. The adding wavelengths can be managed by adjusting the tunable lasers in the coherent optical modules. The VOAs applied in each branch of the optical coupler can equalize the optical power of each channel. To overcome the limitation of wavelength collision by using optical coupler, we introduce multi-carrier pilot-tone OAM management with optical coupler, in which different carrier frequencies are applied to mark each OAM channel of the WDM signals. Thus, the WDM signals modulated by multi-carrier OAM information could be easily differentiated by different carrier frequency. With the help of OAM detection at the ingress port of optical splitter and the egress port of the optical coupler, the allocation of wavelength resources can be online monitored. The attenuation value of the VOA would be increased after receiving the OAM information to block the overlapped wavelength if it occurs. It can be seen that the adding wavelengths in one ROADM node must be different from that of other nodes in same optical network by using optical coupler instead of WSS.

Moreover, reconfigurable adding and dropping WDM signals with different modulation formats, channel spacings, and central wavelengths can be obtained by only setting the coherent optical modules as the optical splitter and optical coupler are independent of WDM.

III. Experimental Results

To validate the effectiveness of the proposed WSS-free ROADM scheme, a networking testbed from Node 1 to Node 3 is established as shown in Fig. 2. Each node is connected by a 20-dB fixed optical power attenuator for emulating the overall loss introduced by fiber transmission links. The generation and reception of optical signals is achieved by commercial single-carrier 100-Gb/s DP-QPSK optical transform units (OTU) with a back-to-back (B2B) optical signal to noise ratio (OSNR) tolerance of 10.5 dB at the 25%-overhead forward error-correction (FEC).

At Node 1, four WDM signals, whose central frequencies range from 193.4 to 193.7 THz with a frequency spacing of 100 GHz, are firstly multiplexed by a WSS or an optical splitter and amplified by an erbium-doped fiber amplifier (EDFA) to 1 dBm per wavelength channel. Figure 3(a) has depicted the optical spectrum at the output end of Node 1. At Node 2, the 193.4-THz channel is dropped and meanwhile the

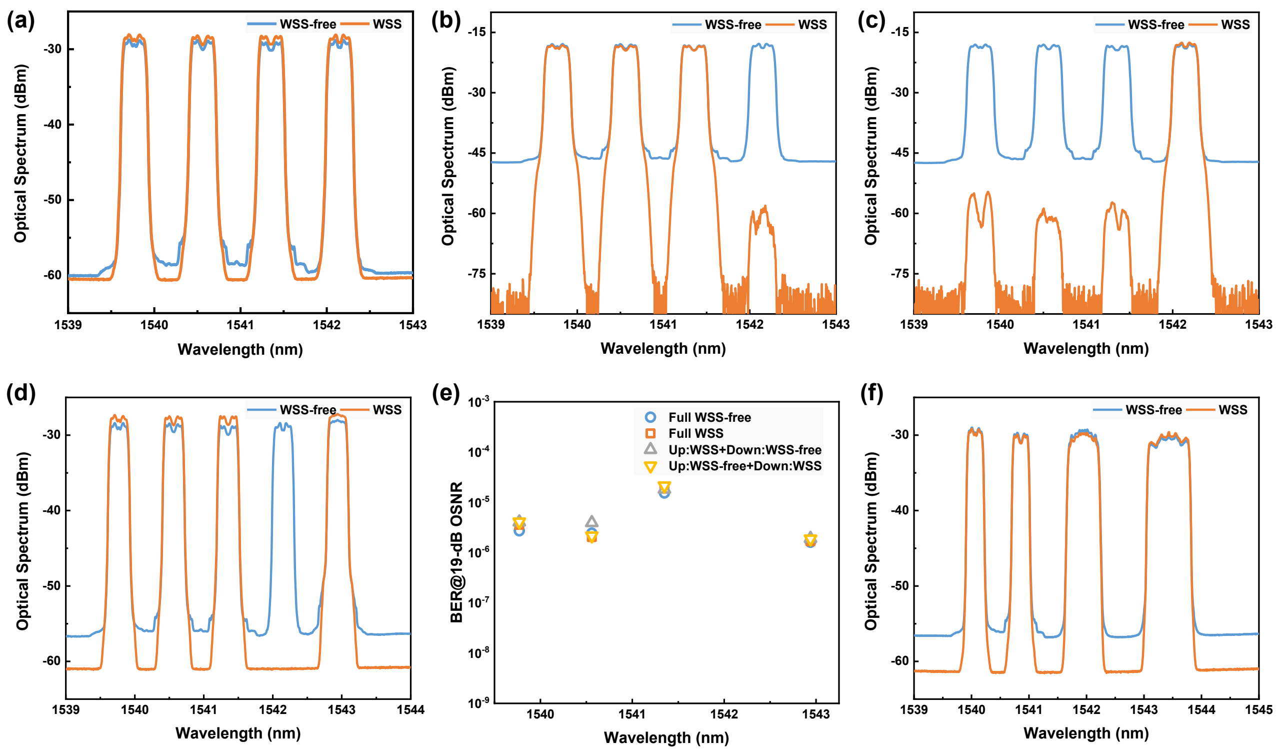

Fig. 3 The optical spectral (a) at the output end of Node 1, (b) passed through Node 2, (c) before the down-link OTU of Node 2, and (d) at the output end of Node 2; (e) Measured BERs at 19-dB OSNR for 4 wavelength channels detected at Node 3 under 4 different networking schemes; (f) Combined spectrum with different modulation formats, channel spacings, and central wavelengths.

remaining 3 wavelength channels directly pass for the WSS-ROADM scheme, but for the WSS-free ROADM scheme all the four channels are evenly split and sent into the down-link OTU and the up-link optical coupler simultaneously. Figure 3(b) shows the optical spectrum of the bypass wavelengths in Node 2. The optical spectrum before the down-link OTU of Node 2 is shown in Fig. 3(c), while Fig. 3(d) depicts the spectrum of the WDM signal at the output end of Node 2 after combing with the up-link 193.3-THz channel. Finally, all the wavelength channels are dropped and received by the down-link OTUs of Node 3. After adjusting the received OSNR to 19 dB, the bit error rates (BERs) corresponding to the WSS-ROADM based and the WSS-free ROADM based networking schemes are measured and shown in Fig. 3(e). At the same time, the BER of the hybrid networking scheme consisting of up-link WSS combined with downlink WSS-free ROADM or vice versa is also evaluated as depicted in Fig. 3(e). We can see that all BERs at the same wavelength channels are similar, which verifies the feasibility of the proposed WSS-free ROADM based networking scheme. Finally, 100-GHz-spacing 400-Gb/s DP-16QAM-PCS signals, 75-GHz-spacing 200-Gb/s DP-QPSK signals, and 50-GHz-spacing 100-Gb/s DP-QPSK signals are combined and verified under the testbed. Figure 3(f) shows the combined spectrum, demonstrating the flex-grid ability of the proposed WSS-free ROADM scheme.

IV. Conclusion

A novel architecture of a cost-effective WSS-free colorless flex-grid ROADM for optical metro networks has been proposed and demonstrated. By using optical splitter/coupler and coherent detection, colorless and flex-grid functions are performed by adjusting the central wavelength and channel spacing of the OTN optical module. With the help of multi-carrier pilot-tone OAM management, wavelength collision during channel adding can be online monitored and avoided.

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