Recent Progress in On-chip Multiplexing/Demultiplexing Silicon Photonic Devices and Technologies

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Abstract— In this paper, we review our recent works in on-chip multiplexing/demultiplexing silicon photonic devices and technologies. On-chip demultiplexing of polarization and wavelength multiplexed OFDM/OQAM 64/128-QAM signals using silicon 2D grating coupler and microring resonators and on-chip two/three mode (de)multiplexing of OFDM 64/128/256-QAM signals using tapered silicon asymmetrical directional couplers are demonstrated in the experiments.

1. INTRODUCTION

The rapid growth of data traffic has driven the increasing demand for employing advanced modulation formats and multiplexing techniques both in optical fiber transmission and photonic signal processing. Various advanced multi-level modulation formats and multiplexing techniques have facilitated improved transmission capacity and processing throughput, including the use of m-ary phase-shift keying (m-PSK), m-ary quadrature amplitude modulation (m-QAM), orthogonal frequency-division multiplexing (OFDM), wavelength-division multiplexing (WDM), and polarization-division multiplexing (PDM) [1, 2]. Although separate bulky devices have been used to enable different (de)multiplexing functions, they cannot meet the demand for compactness, integration and multi-functionality. So one challenge would be to explore compact integrated photonic devices and technologies to enable on-chip multiplexing/demultiplexing.

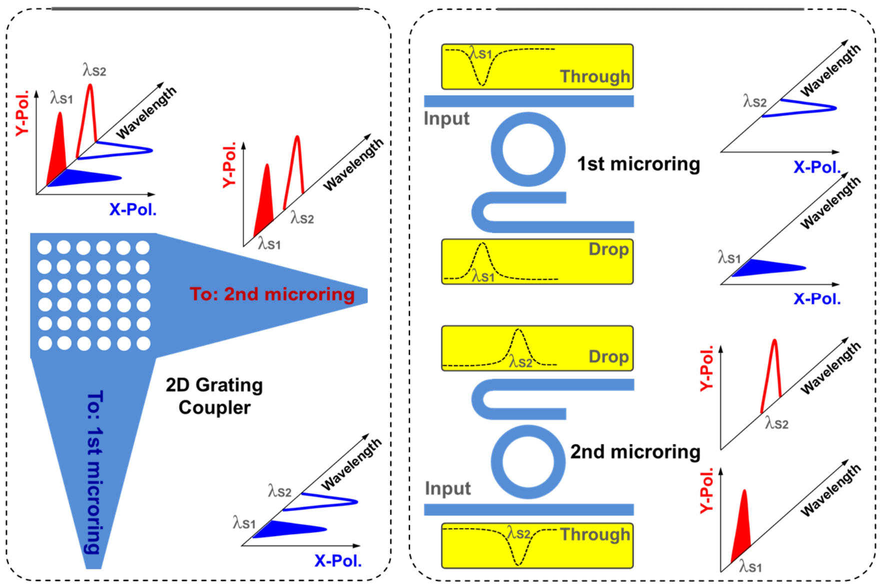
Silicon-on-insulator (SOI) is an attractive low cost integration platform for fabricating photonic integrated circuits owing to its high index contrast and compatibility with complementary metal-oxide-semiconductor (CMOS) technology [3, 4]. In this scenario, a valuable goal would be to develop on-chip multiplexing/demultiplexing technologies using silicon photonic devices.

In this paper, we review our recent progress in on-chip multiplexing/demultiplexing silicon photonic devices and technologies, including: 1) on-chip polarization and wavelength demultiplexing of OFDM/OQAM m-QAM signals [5]; 2) on-chip two/three mode (de)multiplexing of OFDM m-QAM signals [6].

2. ON-CHIP POLARIZATION AND WAVELENGTH DEMULTIPLEXING OF OFDM/OQAM M-QAM SIGNALS [5]

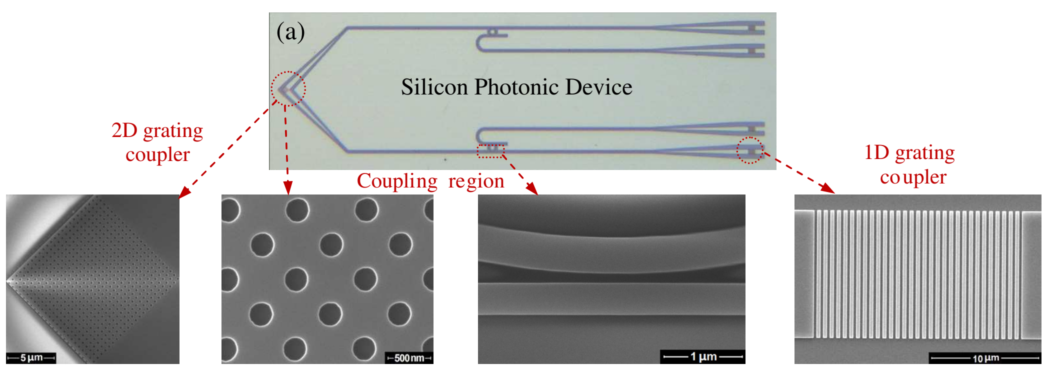
Figure 1 illustrates the concept and principle of the proposed on-chip polarization and wavelength demultiplexer. As shown in Fig. 1(a), the polarization multiplexed signals are vertically fed into the silicon 2D grating coupler. By adjusting the input polarization state, the x-polarization (X-Pol.) and y-polarization (Y-Pol.) of the polarization multiplexed signal can be respectively coupled into the two waveguides (TE mode) which are connected to the 2D grating coupler, resulting in the polarization demultiplexing. Since each polarization after the polarization demultiplexing can still have multiple wavelength channels, wavelength demultiplexing is then followed. Shown in Fig. 1(b) is a simple scheme of two wavelength demultiplexing (S1: signal 1 at λ_{s1}, S2: signal 2 at λ_{s2}) using two silicon microring resonators with different resonance wavelengths which are equal to the two signal wavelengths (λ_{s1}, λ_{s2}). Those two microring resonators are respectively connected to the two output ports of the 2D grating coupler. The insets in Fig. 1(b) are schematic transmission spectra of through and drop ports of microring resonators. As shown in Fig. 1(b), the drop (through) port of the 1st microring and the through(drop) port of the 2nd microring can demultiplex wavelength λ_{s1} (λ_{s2}). Consequently, on-chip polarization and wavelength demultiplexer is applicable with integrated 2D grating coupler and microring resonators.

We fabricated the silicon photonic device by the electron beam lithography (EBL) and inductively coupled plasma (ICP) etching. An SOI wafer with top silicon layer of 220 nm and SiO_2 layer of 3 μm was adopted. Fig. 2(a) shows the microscope image of the fabricated on-chip polarization and wavelength demultiplexer which is composed of a 2D grating coupler connected with two microring resonators. Figs. 2(b)–(e) show the scanning electron microscope (SEM) images of the 2D grating coupler, coupling region between the bus waveguide and bending waveguide of microring resonator, and 1D grating coupler for easy fiber coupling.



(a) Polarization Demultiplexing (b) Wavelength Demultiplexing

Figure 1: Concept and principle of on-chip demultiplexing of polarization and wavelength multiplexed signals. (a) Polarization demultiplexing using a silicon 2D grating coupler. (b) Wavelength demultiplexing using two silicon microring resonators [5].



(b) (c) (d) (e)

Figure 2: Fabricated silicon photonic device for on-chip simultaneous polarization and wavelength demultiplexing. (a) Microscope image and (b)–(e) SEM images of silicon photonic device. (b) 2D grating coupler. (c) Some of holes in the 2D grating coupler. (d) Coupling region between the bus waveguide and bending waveguide of microring resonator. (e) 1D grating coupler for easy fiber coupling [5].

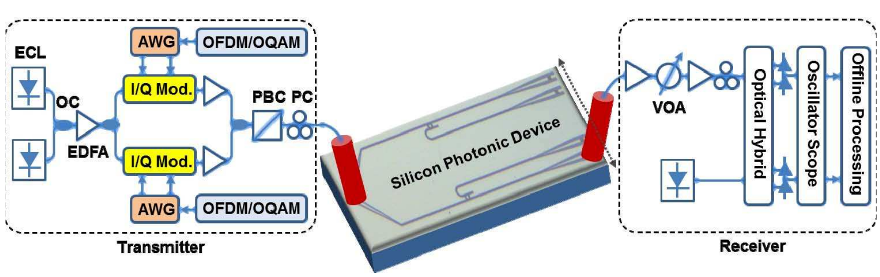
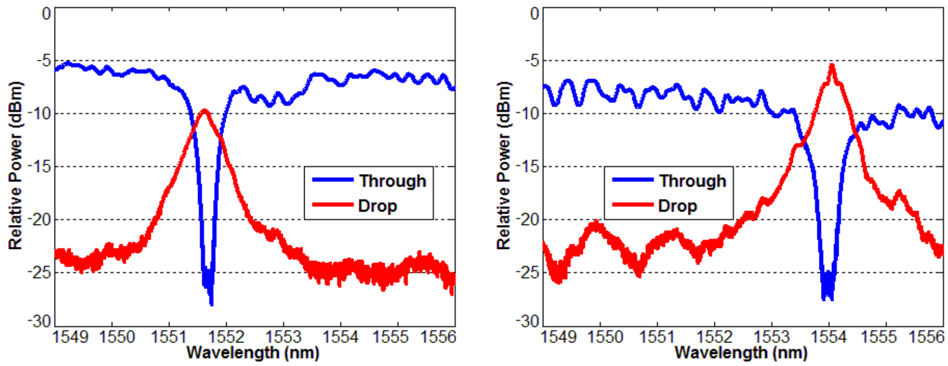


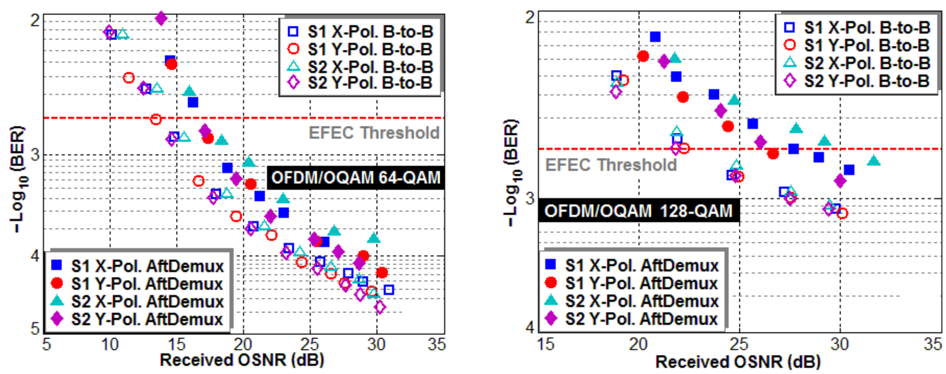
Figure 3: Experimental setup for on-chip demultiplexing of polarization and wavelength multiplexed OFDM/OQAM m-QAM signals. ECL: external cavity laser, EDFA: erbium-doped fiber amplifier, AWG: arbitrary waveform generator, I/Q Mod.: in-phase/quadrature modulator, PBC: polarization beam combiner, PC: polarization controller, VOA: variable optical attenuator [5].

Figure 3 shows the experimental setup for on-chip demultiplexing of polarization and wavelength multiplexed OFDM/OQAM m-QAM signals. At the transmitter, two external cavity lasers (ECL) at 1551.7 and 1554.1 nm are combined, amplified and then equally divided into two parts, each passing through an optical I/Q modulator (I/Q Mod.) to carry OFDM/OQAM signal. Two arbitrary waveform generators (AWGs) at 10 Gs/s are used to produce two single side band (SSB) electrical OFDM/OQAM m-QAM signals, which are respectively fed into the two I/Q modula-



(a) (b)

Figure 4: Measured spectra at through and drop ports of the (a) upper and (b) lower microring resonators [5].



(a) (b)

Figure 5: Measured BER performance. (a) OFDM/OQAM 64-QAM signals. (b) OFDM/OQAM 128-QAM signals [5].

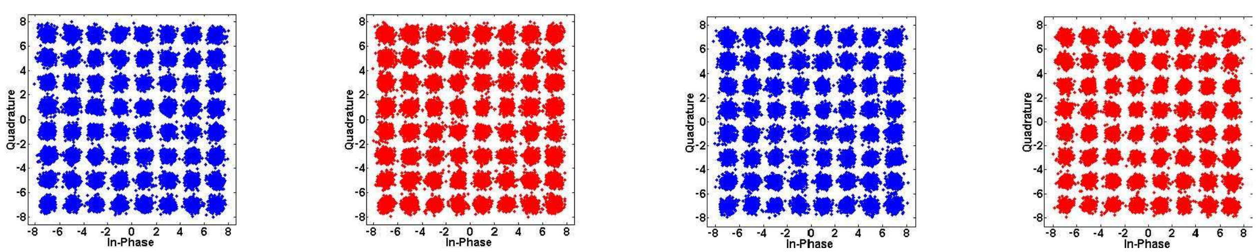


Figure 6: Measured constellations of demultiplexed OFDM/OQAM 64-QAM signals [5].

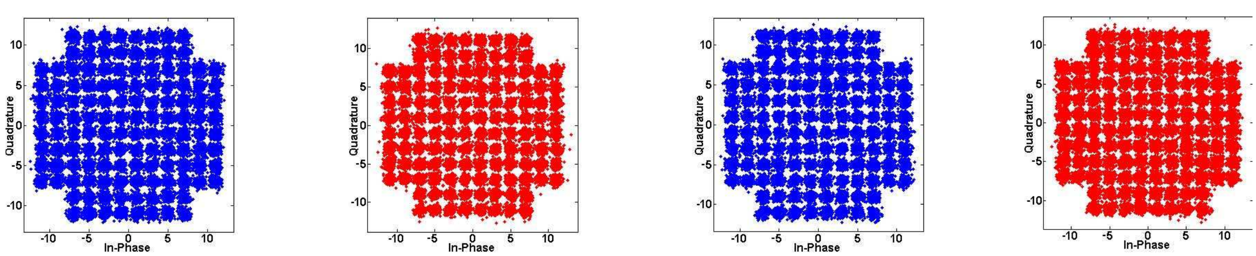
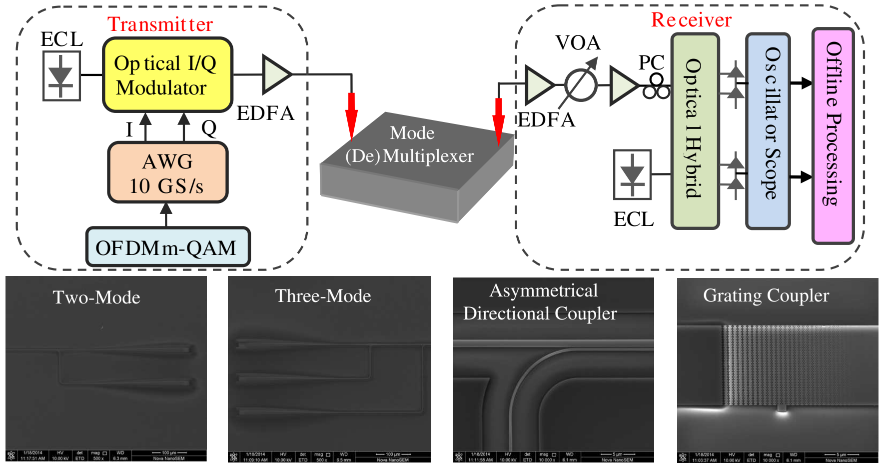
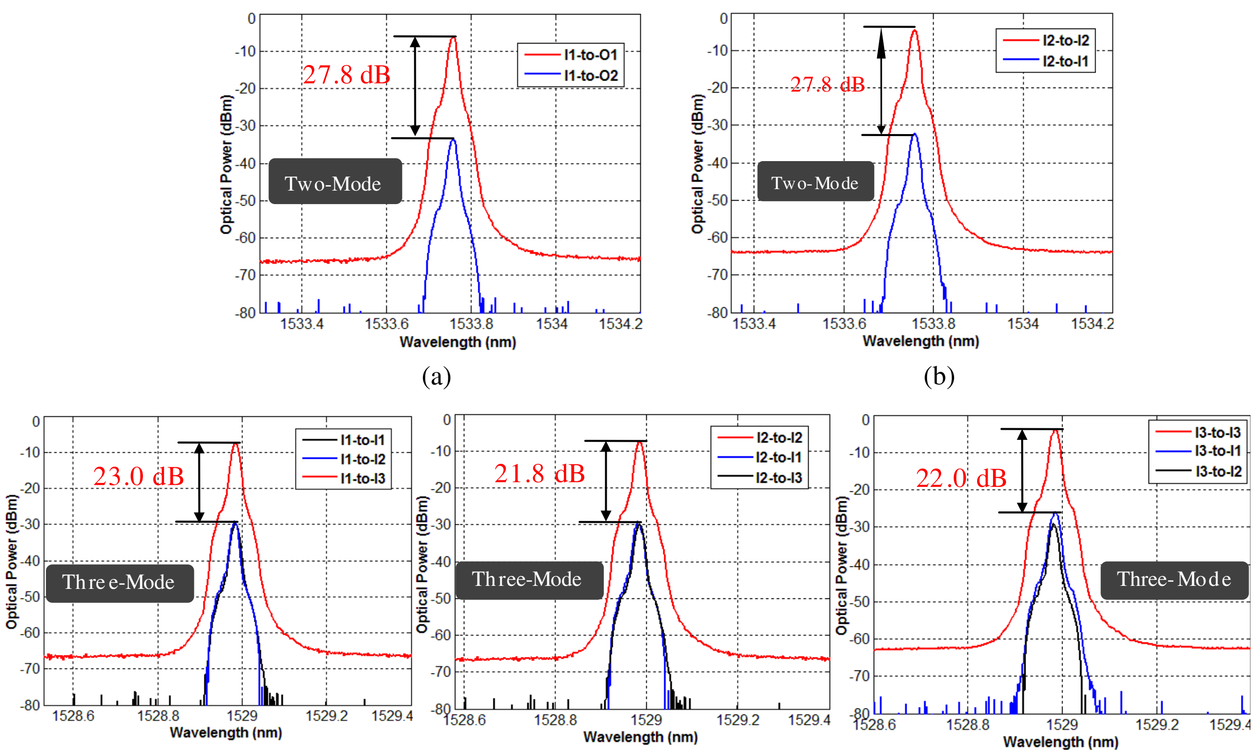


Figure 7: Measured constellations of demultiplexed OFDM/OQAM 128-QAM signals [5].



(a) (b) (c) (d)

Figure 8: Experimental setup for on-chip two/three mode (de)multiplexing. ECL: external cavity laser, PC: polarization controller, AWG: arbitrary waveform generator, EDFA: erbium-doped fiber amplifier, VOA: variable optical attenuator. (a)–(d) SEM images of two-mode (de)multiplexer, three-mode (de)multiplexer, asymmetrical directional coupler, and apodized grating coupler [6].



(c) (d) (e)

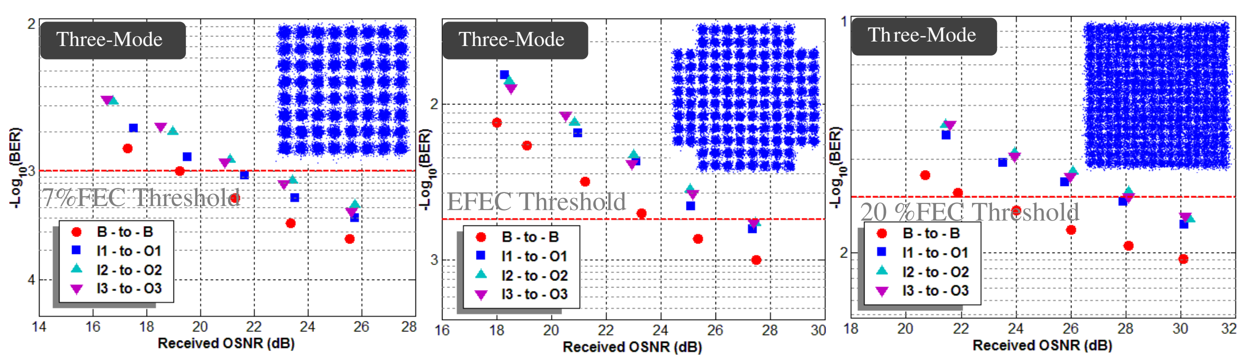
Figure 9: Measured spectra for (a), (b) two-mode (de)multiplexing and (c)–(e) three-mode (de)multiplexing [6].

tors. The OFDM/OQAM baseband signal is constructed with 82 OFDM subcarriers, in which 78 subcarriers are loaded with payloads using m-QAM modulation mapping while 4 subcarriers are selected as pilot subcarriers to estimate the phase noise. The two polarization parts from two I/Q modulators are combined with a polarization beam combiner (PBC) to output polarization and wavelength multiplexed OFDM/OQAM m-QAM signals. Note that all the devices before PBC are polarization maintained. We use vertical fiber coupling system to couple optical signal from fiber to silicon photonic device, and vice versa. A polarization controller (PC) is used to adjust the polarization state of polarization and wavelength multiplexed OFDM/OQAM m-QAM signals, so that two orthogonal polarizations are matched to the TE modes of two waveguides connected to the 2D grating coupler. At the receiver, a variable optical attenuator (VOA) is applied to adjust the optical signal-to-noise ratio (OSNR). A local oscillator is fed into a coherent receiver to mix with the received signals. The two RF signals corresponding to I/Q components are fed into a Tektronix real-time scope and processed offline.

Figure 4 shows measured transmission spectra at through and drop ports of two microring resonators. One can clearly see that two wavelength demultplexing (S1: 1551.7 nm, S2: 1554.1 nm) is achievable using these two microring resonators.

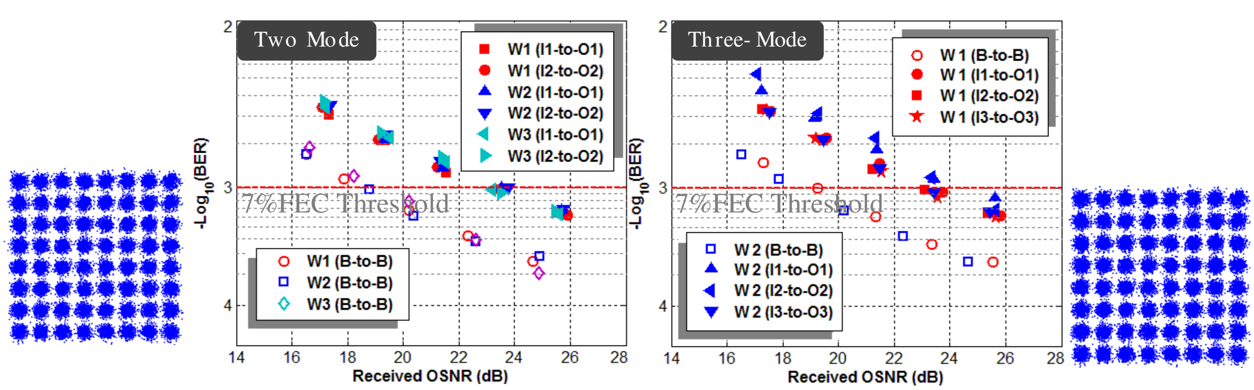
Figure 5 plots measured BER performance for on-chip polarization and wavelength demultiplexing. 35.8-Gbit/s OFDM/OQAM 64-QAM and 41.8-Gbit/s OFDM/OQAM 128-QAM signals are employed in the experiment. The observed OSNR penalties at a bit-error rate (BER) of 2e-3 (enhanced FEC (EFEC) threshold) are less than 4 dB for 35.8-Gbit/s OFDM/OQAM 64-QAM and 6.8 dB for 41.8-Gbit/s OFDM/OQAM 128-QAM. Shown in Figs. 6 and 7 are measured constellations after polarization and wavelength demultiplexing (two polarizations, two wavelengths) for 35.8-Gbit/s OFDM/OQAM 64-QAM and 41.8-Gbit/s OFDM/OQAM 128-QAM signals.

Remarkably, the fabricated on-chip polarization and wavelength demuplexer can also work in an opposite way, i.e., multiplexing four channels (two polarizations, two wavelengths) into polarization and wavelength multiplexed OFDM/OQAM m-QAM signals. Moreover, several future improvements could be considered as follows: 1) flexibly shifting the resonance of microring resonator by electrical control (carrier injection) or thermal control (thermo-optic effect); 2) integrating more number of microring resonators to enable multiple (> 2) wavelength demultiplexing; 3) incorporating mode-division multiplexing functionality to explore wider applications, e.g., on-chip polarization, wavelength and mode multiplexing/demultiplexing.



(a) (b) (c)

Figure 10: Measured BER curves for three-mode (de)multiplexing of OFDM (a) 64-QAM, (b) 128-QAM and (c) 256-QAM signals [6].



(a) (b)

Figure 11: Measured BER curves for two-mode (de)multiplexing (three wavelengths) and three-mode (de)multiplexing (two wavelengths) with OFDM 64-QAM signals. Inserts are constellations [6].

3. ON-CHIP TWO/THREE MODE (DE)MULTIPLEXING OF OFDM M-QAM SIGNALS [6]

Shown in Fig. 8 is the experimental setup for on-chip two/three-mode (de)multiplexing. Fig. 9 shows the measured transmission spectra from inputs (I1, I2, I3) to the demultiplexed outputs (O1, O2, O3), respectively. For two-mode (de)multiplexer, the corresponding mode crosstalk from I1 and I2 to the demultiplexed O2 and O1 is −27.8 and −27.8 dB, respectively. For three-mode (de)multiplexer, the corresponding mode crosstalk from I1, I2 and I3 to the demultiplexed O2/O3, O1/O3 and O1/O2 is −23.0, −21.8 and −22.0 dB, respectively. Fig. 10 shows measured BER performance of OFDM m-QAM data transmission as a function of received OSNR for three-mode (de)multiplexering. OSNR penalties of 2, 4 and 6 dB are obtained for three-mode (de)multiplexing of OFDM 64-, 128- and 256-QAM signals, respectively.

Additionally, we simultaneously transmit three wavelengths for two-mode (de)multiplexing and two wavelengths for three-mode (de)multiplexing with OFDM 64-QAM signals. The OSNR penalty is less than 4 dB as shown in Fig. 11.

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