Modulation-Format-Independent Wavelength Conversion

Xingwen Yi, Runxiang Yu, Junya Kurumida, and S. J. Ben Yoo
Department of Electrical and Computer Engineering, University of California, Davis, 95616, USA, e-mail: yoo@ece.ucdavis.edu

Abstract: This paper provides a proof-of-concept demonstration of modulation-format-independent wavelength conversion with an optical hybrid and an IQ wavelength converter. Multi-format wavelength conversion results are presented by using a SOA-based integrated device.

OCIS codes: (060.2360) Fiber optics links and subsystems, (230.7405) Wavelength conversion devices

1. Introduction

Wavelength conversion is critically important for scalable and modular dynamic optical networks [1]. In addition, the ever-increasing requirement of spectrally efficient fiber transmission accelerates the development of emerging new modulation formats. As a result, multiple optical modulation formats can co-exist in the transparent optical network, which in turn requires a wavelength conversion technique capable of simultaneously supporting multiple modulation formats. Prior studies have demonstrated modulation-format-independent wavelength conversion based on four-wave mixing (FWM) or difference-frequency generation (DFG) [1]. However, these techniques do not provide signal regeneration capabilities. In this paper, we propose a concept of modulation-format-independent wavelength conversion (MFIWC) that employs optical hybrid and in-phase and quadrature (IQ) wavelength converter. This concept, unlike FWM or DFG, can provide an additional opportunity for signal regeneration. To prove its feasibility, we employ a semiconductor optical amplifier (SOA)-based device and an optical hybrid to realize wavelength conversion of NRZ-OOK, RZ-DPSK and RZ-DQPSK.

2. Principle of IQ Wavelength Converter

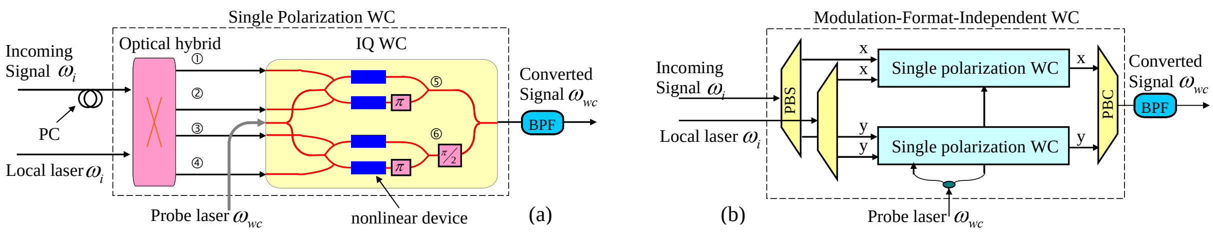

Fig. 1 Schematics of the proposed MFIWC for (a) single polarization; (b) both polarizations based on polarization diversity. BPF: bandpass filter. PBS/PBC: polarization beam splitter/combiner. PC: polarization controller.

Fig. 1(a) shows the generic schematics of the proposed MFIWC, (a) for single polarization and (b) for two polarizations using polarization diversity. It consists of two main devices: an optical hybrid and an IQ wavelength converter. Without loss of generality, a single polarization signal can be written as $s_i(t) = (I_i + jQ_i)\exp(j\omega_i t)$, where the subscript i stands for input, ω is the angular frequency of the optical carrier, and the phase noise term is dropped for simplicity. I and Q carry the transmitted information and can be arbitrary to represent any modulation format. A local laser input to the optical hybrid can be simplified as $l(t) = \exp(j\omega_i t + j\varphi_l)$, where φ is the random laser phase. The expression of the local laser indicates that there is frequency locking but no phase locking. After the optical hybrid in Fig. 1(a), similar to coherent optical detection, the optical field information is converted to the optical intensity. The second device in Fig. 1(a) is the IQ wavelength converter composed of a nested MZ interferometer (MZI) with non-linear devices, two parallel inner MZIs (I and Q) and an outside MZI. The IQ wavelength converter mimics the integrated IQ optical modulator for DQPSK modulation [2]: the latter is driven by RF signals whereas the former by optical signals. In Fig.1, each nonlinear optical device is assumed to only respond to the intensity of the input optical signal and have a proper low-pass function to filter out the unwanted high-frequency components after the optical hybrid. Therefore the IQ wavelength converter also mimics coherent optical detection. The probe laser for wavelength conversion is $l_{wc}(t) = \exp(j\omega_{wc} t + j\varphi_{wc})$. After combining the ⑤ and ⑥ ports by the outside MZI, the converted signal can be derived and formally written as

$$s_{wc}(t) = (I_i + jQ_i) \cdot \exp(j\varphi_l) \cdot l_{wc}(t) . \qquad (1)$$

The incoming optical signal is successfully converted to anther wavelength with an additional phase noise term that can be considered as a wider linewidth laser source at either the transmitter or receiver. Note that the phase noise term can be expanded to include frequency offset of local laser $l(t)$, which means that the frequency locking is not necessary but there will be an additional frequency shift of the converted signal. This paper focuses on wavelength conversion but there are several ways to enhance this technique: (i) it is possible to use optical phase locked loop (OPLL) with the optical hybrid to eliminate the phase noise term; (ii) the outputs of ①②③④ in Fig. 1(a) become digital with OPLL and the proposed MFIWC can provide an additional opportunity of signal regeneration; (iii) a conjugated wavelength conversion is readily available by changing the phase shifter of the outside MZI.

Based on the optical hybrid aided IQ wavelength converter, we further extend it to modulation-format-independent wavelength conversion by using polarization diversity, as illustrated in Fig. 1(b). The basic idea is to polarization de-multiplex the incoming signal, conduct IQ wavelength conversion for each polarization, and then polarization multiplex the signal of two polarizations. The polarization diversified wavelength conversion can be described by an equation similar to (1) but replacing all the terms with Jones vector. It can be shown that this wavelength converter is inherently an analog copier from the incoming signal to the converted signal, including all the four dimensions of optical field.

3. Implementation of IQ Wavelength Converter and Experimental Setup

It is apparent that the nonlinear devices in our proposed technique are critical for the performance. A few nonlinear phenomena can be used, e.g., cross gain modulation (XGM) and cross phase modulation (XPM). Although there are other devices, like electro-absorption modulator, we elect semiconductor optical amplifiers (SOAs) to demonstrate MFIWC for single polarization. In addition, a similar integrated SOA-MZI structure has been shown for RZ-OOK to RZ-QPSK format conversion [3].

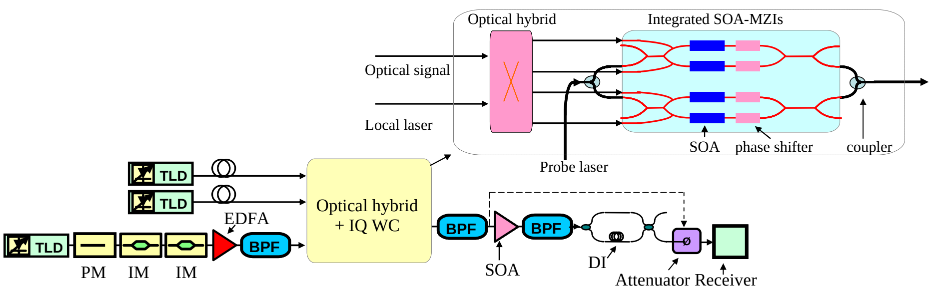

Fig. 2 Experimental setup of MFIWC for multiple modulation formats. The dash line is for OOK formats. TLD: tunable laser diode. DI: delay interferometer. PM:phase modulator. IM: intensity modulator. The local laser has 100-kHz linewidth and the other two lasers 20 MHz.

The inset in Fig. 2 shows the SOA based IQ wavelength converter revised from an integrated twin of SOA-MZIs. Special packaging is used to add two more external fused fiber couplers as an external interferometer, which is about 20 cm long with a mismatch between two arms below 100 μm. The optimal driving currents for four SOAs are found and then fixed throughout all the measurements at 425, 450, 470, 492 mA, whose differences reflect the undesirable non-uniform SOA response and insertion loss. The adjustment of phase shifters is necessary to compensate for some ambient changes.

Fig. 2 shows the experimental setup of MFIWC for multiple modulation formats. The transmitter includes a laser source at 1545 nm and three optical modulators that are selectively enabled to generate NRZ-OOK, RZ-DPSK, and RZ-DQPSK. DQPSK formats are generated by cascading an intensity modulator and a phase modulator with the help of electrical delay lines to their RF drivers for bit alignment. The transmitter is followed by an EDFA and a bandpass filter. For wavelength conversion, the local laser has the same wavelength as the transmitter. A polarization controller (PC) aligns the polarization states of the transmitted signal and the local laser. After the optical hybrid (or into the IQ wavelength converter), the optical powers of the transmitted signal and the local laser are respectively -6 dBm and -11 dBm for RZ formats, and -9 dBm and -14 dBm for NRZ formats. The probe laser is at 1540 nm and emits 5-dBm of power to the IQ wavelength converter after a PC. The converted signal is approximately -8 dBm with 35-dB OSNR. For OOK formats, the converted signal is filtered out and sent to a 10-Gb/s optical receiver directly. For DPSK and DQPSK formats, one more SOA and filter are used to suppress some intensity noise, which is not always necessary if the IQ wavelength converter can reduce intensity noise. For DPSK and DQPSK formats, a delay interferometer and single-ended optical detection by the same receiver are used. Due to the DQPSK generation scheme and BER tester limitation in this experiment, only PRBS 2^7 is used as data to measure BER. The optical power is measured before the optical receiver for the following BER curves.

4. Measurement Results and Discussions

To characterize the IQ wavelength converter, a single sideband input signal has been applied in measuring its response with an optical spectrum analyzer. All the modulators are disabled and the wavelength of the local laser is offset a few GHz to the transmitted laser, which makes the transmitted signal an almost ideal single sideband signal. Following the theoretical prediction in Fig. 3(a), the outputs from SOA-MZIs are carrier-suppressed and the output after wavelength conversion has single sideband. However, in experiment, both SOA-MZIs only provide about 15-dB carrier suppression ratio and the converted single sideband signal has -12-dB vestigial sideband. It is noted that the nonlinear response of SOAs is the mix of XGM and XPM, which generates further distortion shown by the high-order sideband. Therefore it is convenient to identify the main distortion sources by using the single sideband input signal. Fig. 3(b) is another way to characterize the IQ wavelength converter. The transmitter generates 10-Gb/s RZ-DPSK and the received power of the receiver after wavelength conversion is set to -20 dBm. The wavelength offset of the local laser degrades the BER performance as shown in Fig. 3(b). This degradation, especially the asymmetry, is against the principle of the IQ wavelength converter and is mainly caused by the imbalance of the I and Q branch. We expect that a better IQ matched wavelength converter will be less sensitive to the wavelength offset of local laser.

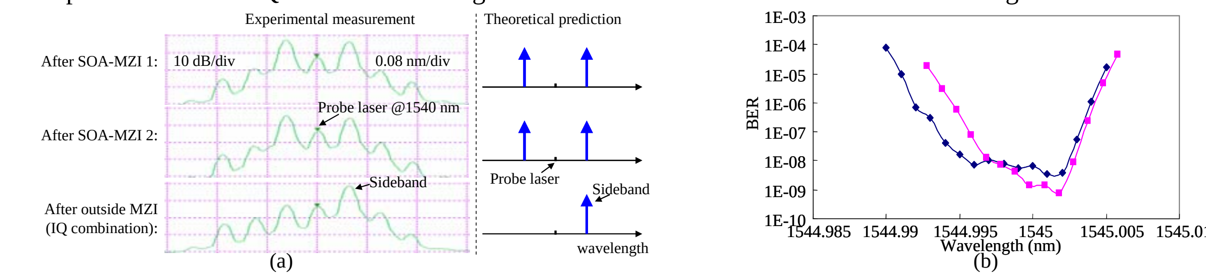

Fig. 3 (a) Optical spectra with a single sideband input after SOA-MZIs and IQ combination by experiment (left) and theory (right). Resolution is 0.02 nm. (b) Experimental BER degradation versus wavelength offset of the local laser. The two curves are repeated measurements.

Fig. 4 shows the wavelength conversion results of 2.5-Gb/s NRZ-OOK, 10-Gb/s RZ-DPSK and 20-Gb/s RZ-DQPSK. The excessive noise and power penalty of the converted RZ-OOK are mainly because the IQ mismatch, including amplitude and phase, converts some phase noise to intensity noise. RZ-DPSK detected by the destructive port has about 2-dB power penalty at 10^{-9} BER. The constructive port has a slightly worse eye-diagram. RZ-DQPSK has a BER floor of 10^{-5} and the main reason is that it is more susceptible to the distortion of the IQ wavelength converter. It is clear that DQPSK demands further improvement of the wavelength converter, such as higher speed SOAs, more uniform response of the four SOAs and more uniform insertion loss of the passive devices.

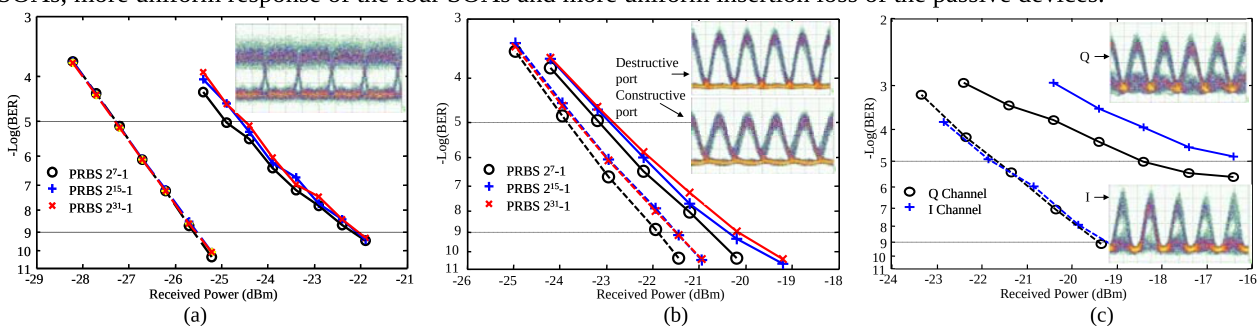

Fig. 4 BER curves before (with dash lines) and after (with solid lines) wavelength conversion of (a) 2.5-Gb/s NRZ-OOK, (b) 10-Gb/s RZ-DPSK (destructive port only), (c) 20-Gb/s RZ-DQPSK (single-ended detection). The insets are the eye-diagrams after wavelength conversion.

5. Conclusion

We have proposed a generic concept capable of modulation-format-independent wavelength conversion by using optical hybrid and IQ wavelength converter. Then we have employed a SOA-based integrated device as IQ wavelength converter in experiment. Wavelength conversion results of NRZ-OOK, RZ-DPSK and RZ-DQPSK have been demonstrated. In addition to wavelength conversion, this technique can provide other enhancing opportunities, including signal regeneration for different modulation formats.

6. References

[1] S. J. B. Yoo, IEEE/OSA JLT, vol. 14, no. 6, pp. 955-966, Jun. 1996.

[2] A. H. Gnauck, P. J. Winzer, “Optical phase-shift-keyed transmission,” IEEE/OSA JLT, vol. 23, no. 1, pp. 115-130, Jan. 2005.

[3] K. Mishina et al., Optics Express, Vol.15, No.12, pp.7774-7785, 2007.