Phase-Incoherent DQPSK Wavelength Conversion Using a Photonic Integrated Circuit

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***Abstract*—We investigate the performance of a large-scale, silica-on-silicon photonic integrated circuit for multiformat signal processing, and we experimentally demonstrate wavelength-conversion of (differential) quadrature phase-shift keying [(D)QPSK] signals. The circuit exploits phase-incoherent techniques to decode the input signal and to phase remodulate two phase-shift-keying components before combining them in a common QPSK output stream. Error-free wavelength conversion with 4-dB power penalty is reported at 44 Gb/s.**

***Index Terms*—Differential quadrature phase-shift-keying (DQPSK) wavelength conversion, hybrid integration, Mach–Zehnder, phase-incoherent processing.**

I. Introduction

ALL-OPTICAL wavelength (λ)-conversion will be a key for extended transparency, higher capacity and improved energy efficiency in future networks. Ideally, the λ-converters should be simple and cost effective, exhibit low consumption and small footprint, and be capable of handling different formats, as phase encoded signals, in particular (differential) phase-shift keying ((D)PSK) and quadrature phase-shift keying ((D)QPSK) signals, are going to copropagate and interface with on-off keying (OOK) data streams in modern networks.

Compared to the OOK and (D)PSK cases, the efforts on λ-conversion techniques for (D)QPSK signals are more recent and have resulted in a limited number of demonstrations. These include schemes based on $\chi^{(2)}$ effects inside periodically poled lithium niobate crystals [1], nondegenerated four-wave mixing (FWM)-based schemes inside Kerr media [2], [3] and semiconductor optical amplifiers (SOAs) [4], and schemes that coherently extract the in-phase (I) and quadrature (Q) components and generate a new QPSK signal using two SOA-based Mach–Zehnder interferometers (SOA-MZIs) [5], [6]. The first two types cannot regenerate any signal format and require high input powers. The latter schemes are inherently complex, as they need a locked local oscillator, while their regenerative potential is still to be confirmed for (D)QPSK signals.

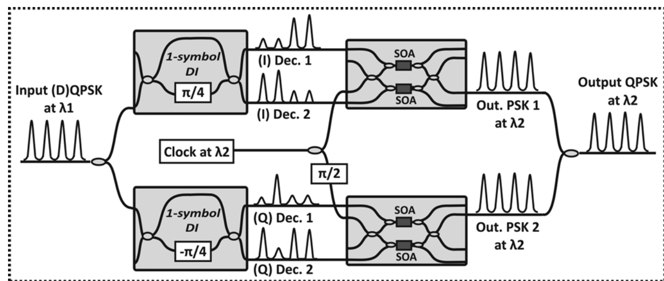

Fig. 1. Operating principle of the (D)QPSK wavelength-converter.

Recently, we presented a multiformat processing chip (MFPC) with two SOA-MZIs and a linear front end with delay interferometers (DIs) that uses simpler phase-incoherent techniques [7]. Using this device we showed OOK and DPSK regeneration at 22 Gb/s and indicated through simulations the potential for (D)QPSK λ-conversion [8]. With the present work, we complete the study of the MFPC demonstrating λ-conversion of 44 Gb/s DQPSK signals with 4 dB power penalty. To our knowledge, this is the first demonstration of (D)QPSK λ-conversion using phase-incoherent concepts.

II. Operation Principle and Experimental Setup

Fig. 1 describes the λ-conversion principle. The (D)QPSK stream at λ_1 is decoded by two 1-symbol DIs that operate with a relative 90° difference to recover the I and Q components. The complementary OOK outputs of each DI are forwarded to the control ports of the SOA-MZIs with their relative timing preserved. Each SOA-MZI modulates the phase of the clock pulses according to the data of the controls, and provides a PSK signal at λ_2 [8]. A phase shifter (PS) allows for a 90° difference between the clock pulses entering the upper and the lower SOA-MZI, thus enabling a QPSK signal at the final output after combination of the two PSK signals. The scheme is mostly appropriate for return-to-zero (RZ) DQPSK streams, and it is in principle compatible with ultra high-speed signals provided that appropriate push-pull techniques are used. Moreover, it can also facilitate in principle operation with non return-to-zero (NRZ) DQPSK signals at lower symbol rates if the optical clock is replaced by a continuous wave (CW) source.

It is noted that the λ-converter alters the data of the output signal compared to the input data, as it retrieves the differentially encoded data sequences of the input and phase remodulates the optical clock without the use of a differential precoder.

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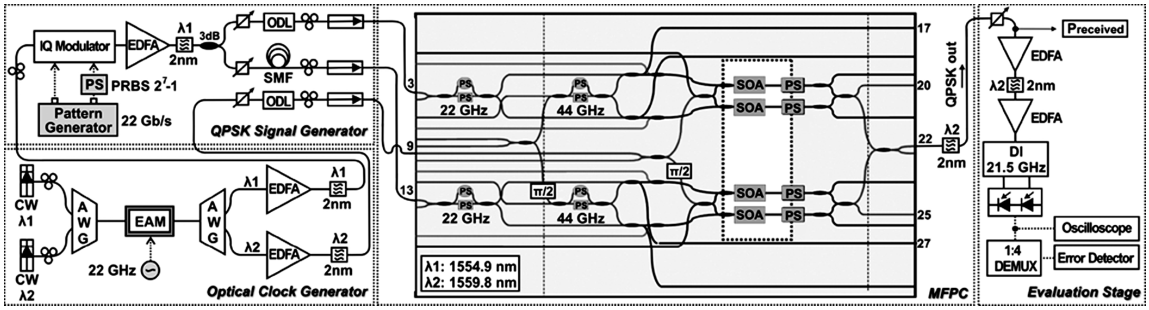

Fig. 2. Experimental setup.

Nevertheless, the data transformation is deterministic and reversible, and thus the original data can be recovered using additional precoders at the transmitter [9].

For the demonstration we used the MFPC presented in [8]. The chip contains 32 pigtailed optical ports, 4 DIs, 2 SOA-MZIs, 15 PS and a network of waveguides and couplers. The spectral dependence of the SOA gain and phase modulation index has been optimized for highest performance of the λ-converter within the 1535–1570 nm conversion range. Fig. 2 shows the setup for DQPSK λ-conversion at 22 Gbaud. The 1554.9 nm (λ_1) and 1559.8 nm (λ_2) CW were multiplexed with an arrayed-waveguide grating (AWG), and were driven into an electroabsorption modulator (EAM) for pulse carving at 22 GHz with $\sim$ 6 ps pulse width. The λ_2 optical clock entered the MFPC through port 9 with 1.3 mW, while the λ_1 clock was inserted into the $LiNbO_3$ IQ modulator. The latter was driven without differential precoding by two replicas of a $2^7 - 1$ long pseudorandom bit sequence (PRBS) shifted to each other by 55 bits. After amplification, the optical signal-to-noise ratio (OSNR) of the QPSK signal was 41 dB (0.01 nm resolution). The signal was split off-chip. Its parts followed optical paths of equal length in order to preserve their synchronization and were launched with 6.3 mW each through ports 3 and 13 into the 22 GHz DIs for decoding. Each DI comprised thermally tunable PS in both its arms allowing for a positive or negative phase-shift between its arms and thus for choosing among the I or the Q components of the signal. The decoded streams were forwarded to the SOA-MZIs as per the principle described above. The current in the SOAs was 300 mA and their temperature was set at 22.5°C. Synchronization on a symbol level between the decoded streams and the clock was achieved with optical delay lines (ODL). The λ-converted signal was taken from port 22, filtered and evaluated at the receiver. The received power was adjusted with a variable attenuator before amplification and balanced detection. A frequency offset of 0.5 GHz between the receiver DI and the symbol rate was present as an external DI at exactly 22 GHz was not available. Finally, the detector output was assessed through bit-error ratio (BER) measurements after the 1:4 electrical demultiplexer.

III. Results and Discussion

Fig. 3 presents the combined spectrum at the input ports 3 and 9 (solid lines) and the spectrum at port 22 before filtering (dashed lines). The RZ-QPSK spectrum at λ_1 has turned into a spectral distribution that relates to the combination of the four control signals of the SOA-MZIs. The spectrum of the λ_2 clock, on the other hand, has turned into an RZ-QPSK-like spectrum. The conversion efficiency, defined as the power ratio of the data

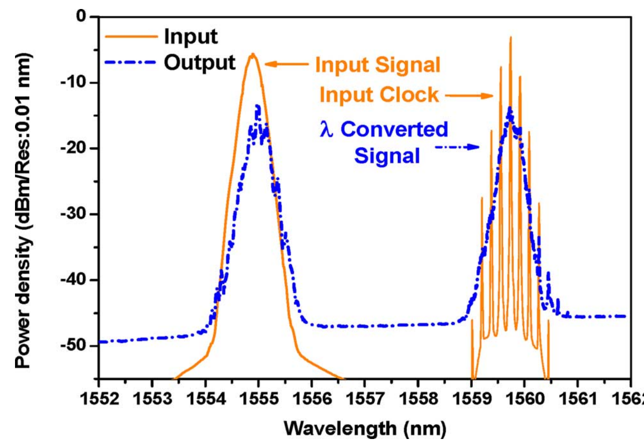

Fig. 3. Spectra at the input and output of the MFPC-based λ-converter.

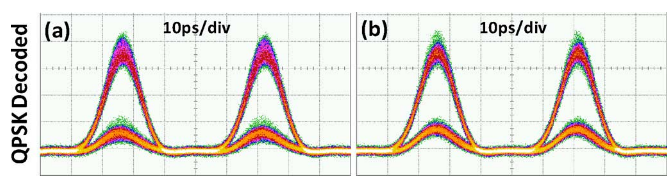

Fig. 4. Decoded signals after the (a) upper and (b) lower 22-GHz DI.

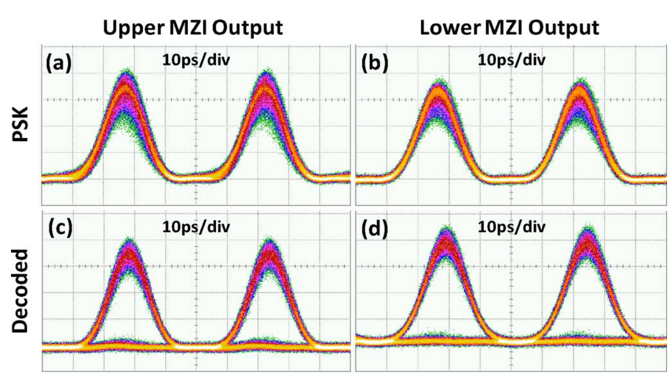

Fig. 5. PSK signals at the output of the (a) upper and (b) lower SOA-MZI, and (c), (d) the corresponding decoded signals.

signals at the input (after off chip splitting) over the converted signal at the output, was about -12 dB.

Figs. 4–6 present the successive steps of the λ-conversion. Fig. 4(a)–(b) depict the signals after the DIs, as monitored at ports 17 and 27. The eye-diagrams reveal the limited extinction ratio (ER) of the signals that will act as controls in the SOA-MZIs. It is noted that the limited ER of the decoded streams is an inherent characteristic of the DI-based decoding process [9], and does not originate from any imperfections of the MFPC or limitations of the setup. Fig. 5(a)–(b) present the PSK signals at the outputs of the SOA-MZIs, as monitored at ports

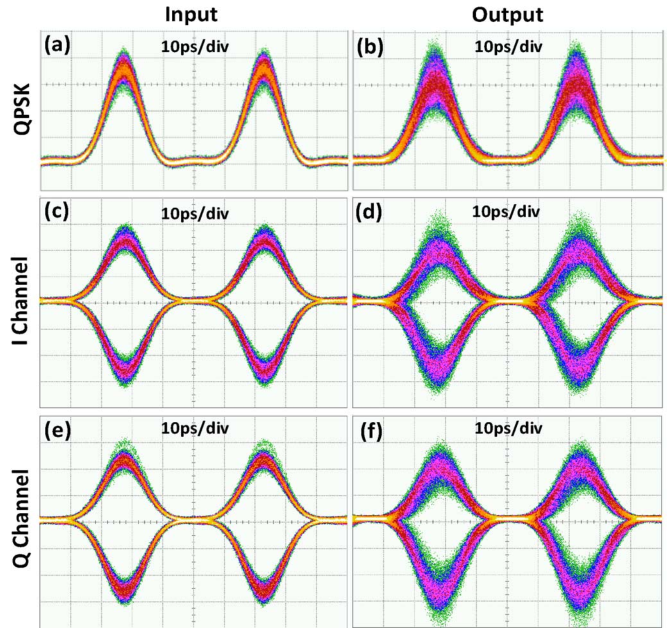

Fig. 6. Signals at the input (left column) and output (right column) of the wavelength converter: (a), (b) QPSK signals, and corresponding decoded (c), (d) I-channels and (e), (f) Q-channels detected with the balanced detector.

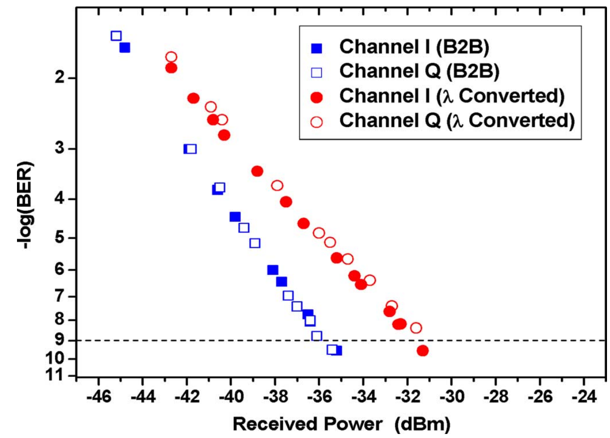

Fig. 7. BER curves for the back-to-back and the converted QPSK signals.

20 and 25. As observed, the low-quality of the control signals results in PSK signals with amplitude noise. The corresponding decoded streams, detected with a single-ended detector, are shown in Fig. 5(c)–(d). They both have amplitude jitter at the "1" level, but rather low noise at the "0" level, indicating the low phase-noise of the PSK signals [8]. Finally, Fig. 6 compares the input and the converted signals. Fig. 6(a)–(b) show the input and output QPSK signals and reveal the amplitude noise induced by the converter. Compared to the PSK signals at the output of the SOA-MZIs (Fig. 5(a)–(b)), the final QPSK stream has enhanced noise, since it is generated as the coherent combination of the two PSK signals. Fig. 6(c)–(f) depict the corresponding decoded channels. The output eye-diagrams are clearly open indicating successful operation. Unlike the simpler DPSK case, however, the technique does not exhibit regenerative properties for the input (D)QPSK signal due to the low ER of the decoded streams. Theoretical studies have shown, however, that (D)QPSK regeneration is possible with the use of additional 2R regenerators between the DIs and the SOA-MZIs [9].

The degradation induced by the λ-converter was quantified through the BER measurements of Fig. 7. The back-to-back (B2B) represents the case, where the input QPSK signal just before the off-chip splitter is directly driven to the evaluation unit. Error-free λ-conversion was achieved with 4 dB power penalty at the BER of 10^{-9}. Each curve corresponds to one of the four 5.5 Gb/s tributaries that constitute the I or the Q component of the signals. It is noted though that the variation between the tributaries was negligible in all cases due to the absence of any patterning effects. Due to the unavailability of electronic precoders, and thus the need for programming the BER tester with the expected bit patterns, the λ-converter was tested with the 2^7-1 long PRBS. Nevertheless, given the absence in previous investigations of the device with OOK and DPSK signals of any patterning effects even for the $2^{31}-1$ long PRBS [8] and any dependence on the order of the input PRBS, it is concluded that the performance and the power penalty of the DQPSK λ-converter would have been the same if the $2^{31}-1$ PRBS had been used. It is noted that the absence of any patterning effects is attributed to the use of a clock as input to the SOA-MZIs and the ultrafast ($\sim$ 20 ps) gain recovery of the SOAs, which is in turn due to their carefully engineered 15 quantum-well structure and their increased length (2.1 mm).

Further steps involve the investigation of the λ-conversion concept at 88 Gb/s (44 Gbaud) with on-chip splitting of the input (D)QPSK signal and use of the integrated 44 GHz DIs.

IV. Conclusion

We have investigated the potential for DQPSK λ-conversion using a photonic integrated circuit, which was recently used for OOK and DPSK regeneration. Based on the parallel DIs and SOA-MZIs of the circuit, we have achieved error-free λ-conversion of 44 Gb/s DQPSK signals with 4 dB penalty.

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