Integrated Circuits for Wavelength Division De-multiplexing in the Electrical Domain

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Abstract *We propose a new concept for a single-chip multi-channel WDM receiver which can scale toward Tbps operation. The receiver, consisting of a single photonic IC and a single electrical IC, multiplies data detection capacity by the number of electrical subcarrier channels. In a first demonstration, two BPSK-modulated wavelength channels have been successfully demodulated.*

Introduction

Tbps WDM super-channels are expected to lead to improved spectral efficiency and higher overall system capacity[1,2]. Current systems typically consist of several precisely spaced, but uncorrelated optical carriers[1,3]. Demodulation requires an optical de-multiplexer and an array of coherent receivers, each tuned to a discrete optical carrier. As DAC and ADC speed and resolution improve, the number of optical carriers can be reduced and higher order modulation formats may be used, albeit at the cost of reduced optical reach[1].

In this work, we propose a coherent receiver architecture which is scalable to Tbps single optical carrier rates while maintaining optical reach. Fig. 1 shows a schematic of the proposed receiver in which a single coherent receiver converts several modulated optical carriers to RF subcarriers, and an array of image reject mixers de-multiplexes the subcarriers to recover the data. The total capacity is ultimately limited by the bandwidth of the photo-detectors (PDs) and the de-mux IC, and by the modulation spectral efficiency. The architecture can scale beyond 1 Tbps capacity using 200 GHz bandwidth detectors and ICs together with dual polarization 16-QAM[4,5].

Coherent single chip multi-channel receivers

The WDM receiver has a simple circuit configuration, can provide high spectral efficiency, and accommodates a range of channel spacing and data modulation formats. Fig. 1 shows a receiver that de-multiplexes six WDM channels simultaneously using a single photonic IC (PIC) and a single electrical IC

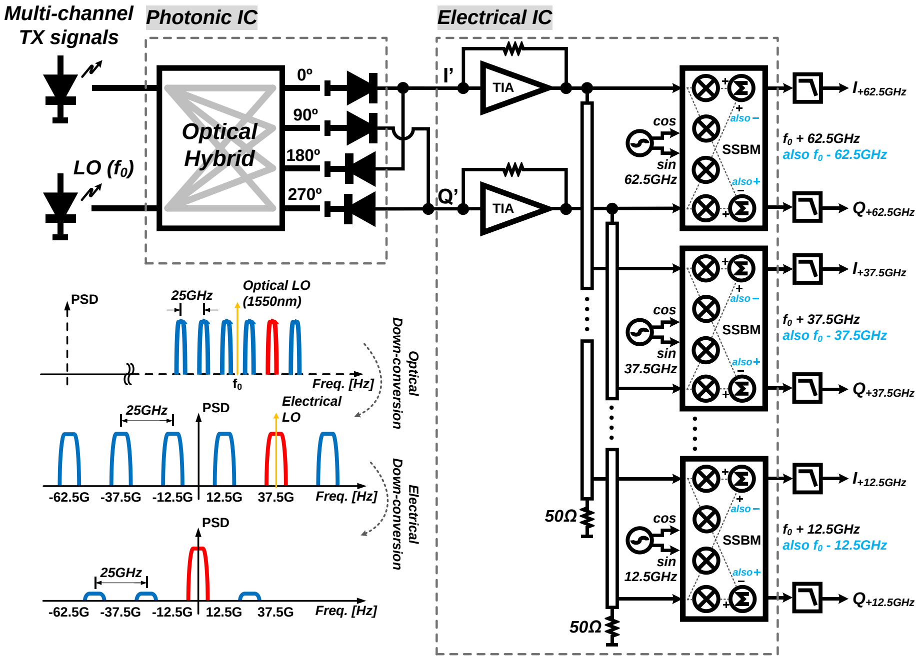

Fig. 1: A schematic for a coherent single-chip multi-channel WDM receiver and its de-multiplexing flows for six-modulated channels

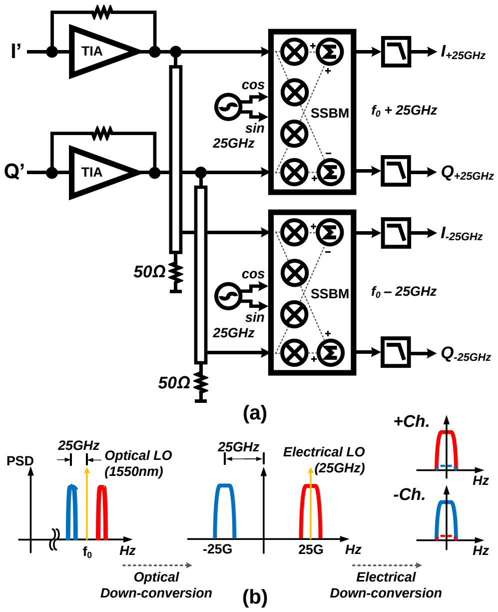

Fig. 2: (a) An electrical IC schematic for the two-channel WDM receiver and (b) signal spectra at different stages during de-multiplexing

(EIC). The PIC consists of 90 degree hybrid and balanced PDs which are in a standard coherent balanced detection configuration. The PDs must have wide bandwidth to support many WDM channels. The six-channel WDM receiver requires > 75GHz 3-dB bandwidth given 25GHz channel spacing. The EIC consists of input trans-impedance amplifiers (TIAs), clock and RF distribution, and broadband (> 75GHz) analog single sideband mixers for image rejection, which doubles the optical detection bandwidth. .

The de-multiplexing process for the multi-channel carriers (based on Fig. 1) is as follows:

1. Multi-channel transmitted (TX) signals are received in the optical domain,
2. All modulated carriers are optically mixed and down-converted with a local oscillator (LO) laser through a 90 degree optical hybrid and balanced PDs,
3. Then, I' and Q' sub-carriers in the electrical domain are located at ±62.5GHz, ±37.5GHz, and ±12.5GHz,
4. All sub-carriers are amplified through TIAs and down-converted again by the arrayed image rejection single sideband mixers and electrical LOs for the each channel,
5. Finally, only the desired channel signal is near DC and the data is recovered by DSPs.

Depending on the PDs and the demux electrical IC bandwidth, the de-multiplexing capacity can be determined. For example, with 200GHz devices, > 500Gbps (10Gbaud x 16-channels x 4 bits/symbol (16-QAM)) is feasible using a single PIC + EIC WDM receiver without polarization multiplexing.

In order to prove the proposed receiver concept, a 2-channel 50GHz-spaced WDM receiver has been designed using Teledyne's 300GHz f_t / f_{max} 500nm InP HBT process. A simplified IC schematic is shown in Fig. 2 (a), and a photograph of the designed electrical IC for two-channel WDM receiver which has a detection span of 50GHz to 90GHz (optical carrier spacing) can be seen in Fig. 3. As shown in Fig. 2 (b), two carriers with 50GHz spacing are used to transmit data, and these carriers are optically mixed by an LO laser whose frequency lies in the middle of the carriers, at f_0. Then, the two modulated carriers are down-converted to the electrical domain with 50GHz spacing at ±25GHz. The two RF subcarriers are amplified by TIAs and then down-converted again by a 25GHz electrical LO, and the two independent sets of channel data are recovered through different outputs of +channel and -channel via simple DSP processes.

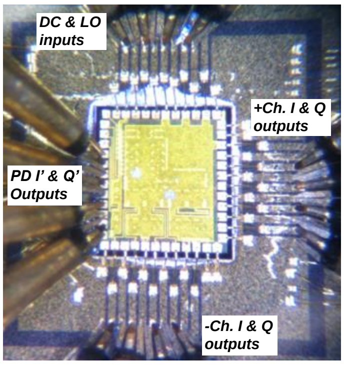

Fig. 3: A photograph of an electrical IC for the two channel WDM receiver

System setups and test results

To verify the new electrically de-multiplexed WDM receiver concept, the two channel WDM receiver IC has been tested using the test setup represented in Fig. 4. First, three free-running distributed feedback (DFB) lasers are used, laser 1 (1549.16nm) as f_0 + ~25GHz transmitted carrier, laser 2 (1549.66nm) as f_0 – ~25GHz transmitted carrier, and laser 3 (1549.45nm) as an LO laser at f_0. Due to limited wavelength control, ~56.4GHz frequency spacing with a 28.2GHz electrical LO has been utilized. The two channels were modulated by 2.5Gbps binary phase-shift-keying (BPSK) data with two pseudo-random binary sequence (PRBS) pattern generators and Mach-Zehnder modulators (MZMs). PRBS 2^{15}-1 and 2^{31}-1 data are applied to the two channels, and the modulated carriers are combined in a 50%/50% directional coupler. One arm of the directional coupler output goes to the WDM receiver, and the other is used for monitoring signal quality in an optical oscilloscope.

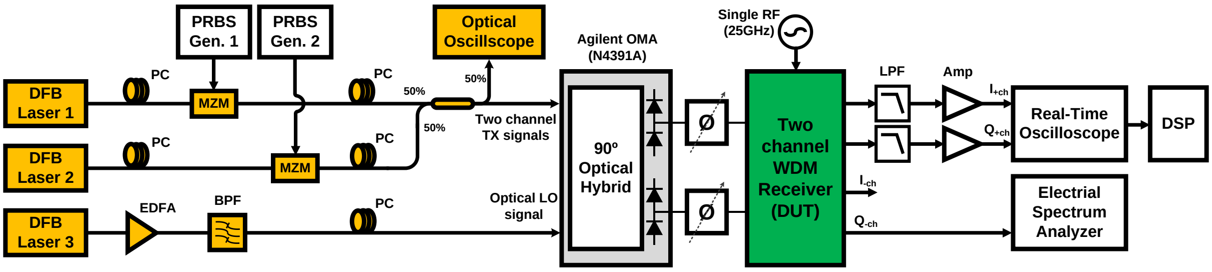

Fig. 4: Test setup for the two-channel WDM receiver

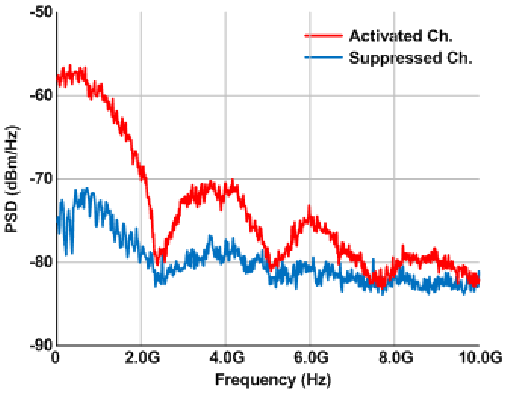

Fig. 5: Measured spectral outputs (red: activated ch. spectrum and blue: suppressed ch. spectrum) (RBW: 2MHz, VBW: 100kHz)

The standard PIC parts are replaced by an Agilent optical modulation analyzer (OMA) N4391A in this test. The OMA includes a free-space 90 degree optical hybrid and balanced PDs which are expected to have > 33GHz bandwidth. In the OMA, optical to electrical path length has been carefully matched below < 50ps using additional RF cables and phase shifters, and the connection between the OMA and the WDM receiver was maintained at 50 Ω by using k-band RF cables and four-finger RF probes. The WDM receiver outputs for one channel are low-pass filtered, amplified, monitored, and finally saved by the real-time oscilloscope, and frequency and phase errors are compensated by offline DSP. Meanwhile, the other channel is connected to a spectrum analyzer to determine whether the down-converted signal intensity is activated or suppressed as shown in Fig. 5. The spectral results show 15dB (~5x voltage) image suppression ratio due to imperfect amplitude and phase balance on I' and Q' between the OMA to the WDM receiver. Fig. 6 shows eye diagrams after the offline DSP. Fig. 6 (a) is the activated +channel eye output and (b) is the suppressed –channel eye output from a single modulated carrier. As expected, only Fig. 6 (a) shows open eye diagram compared with (b). Regarding two modulated carriers, both ±channels on Fig. 6 (c), (d) show open eye diagram outputs, proving that the dual channel WDM receiver can receive both channels simultaneously. The 50%/50% directional coupler was added to the transmitter after the single-sided transmission tests and as a result, the received power in Fig.6 (c), (d) is half the received power in Fig.6 (a), (b). This degraded the signal to noise performance as expected.

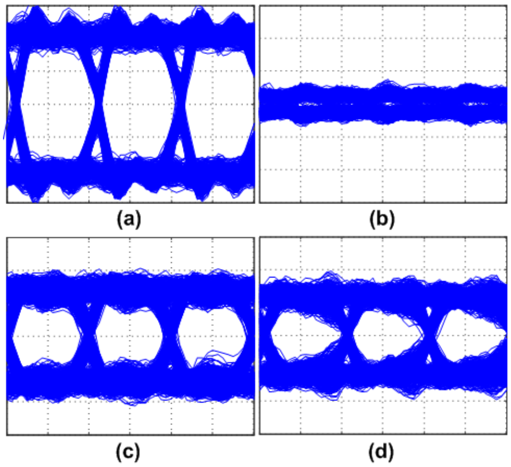

Fig. 6: Output eye diagrams after DSP. (a) Activated +ch. from a single modulated carrier, (b) suppressed -ch. from the same modulated carrier, (c) and (d) +ch. and -ch. when two modulated carriers are transmitted

Conclusions

A novel WDM receiver concept which is capable of 1Tbps single-chip optical fiber communication has been proposed. An initial demonstration of a two-channel WDM receiver has shown good performance, indicating the promise of this approach. A six-channel receiver is now being tested.

Acknowledgements

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