Full C-band Nyquist-WDM Interleaver Chip

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Abstract: We experimentally demonstrate full C-band coverage of a Nyquist-filtering interleaver for super-channel multiplexing. We show N-WDM super-channel multiplexing with zero guard-band, 12.5-GHz spacing, 0.08 roll-off, and a Q fluctuation <0.3-dB across C-band.

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1. Introduction

Nyquist wavelength division multiplexing (N-WDM) is a promising candidate for increasing the spectral efficiency of optical systems. To gain a high spectral efficiency, N-WDM requires optical filters with sharp passband-stopband transitions [1, 2]. Optical filters can be implemented with tapped delay lines and ring resonators. Goh *et al.* reported an on-chip Nyquist-filtering multiplexer with tapped delay lines, in which the maximum delay line length is 56 times of the circuit unit delay [3]. Wang *et al.* reported a ring-resonator based interleaver with simpler circuity and smaller size, with a pass-band width of 100-GHz [4]. For super-channel generation, a narrower pass-band (*i.e.* 12.5-GHz) is desired, necessitating tighter fabrication tolerances due to the longer waveguide delays.

In this work, we report a RAMZI interleaver implemented on a Si_3N_4/SiO_2 platform. It features full C-band coverage (1530 nm-1565 nm), small size (1.2 mm×0.4 mm), sub-GHz spectral resolution, and a 0.08 RRC roll-off transition-band. We have previously shown that a photonic integrated circuits (PICs) using a ring-resonator-assisted Mach-Zehnder interferometer (RAMZI) can be used to shape and de-interleave N-WDM channels, with narrow or zero-guard bands, and nearly-flat pass-bands [5].

Full C-band coverage is always challenging to achieve due to the wavelength dependence of the material. For the first time, full C-band coverage of the RAMZI based Nyquist-filtering WDM multiplexer is experimentally demonstrated. The maximum Q variation over the C-band is less than 0.3-dB at the 7% hard FEC limit (@ BER= 3.8×10^{-3}). The presented RAMZI interleaver is an important building block for C-band N-WDM super-channel transmitters that are integrated on a photonic chip.

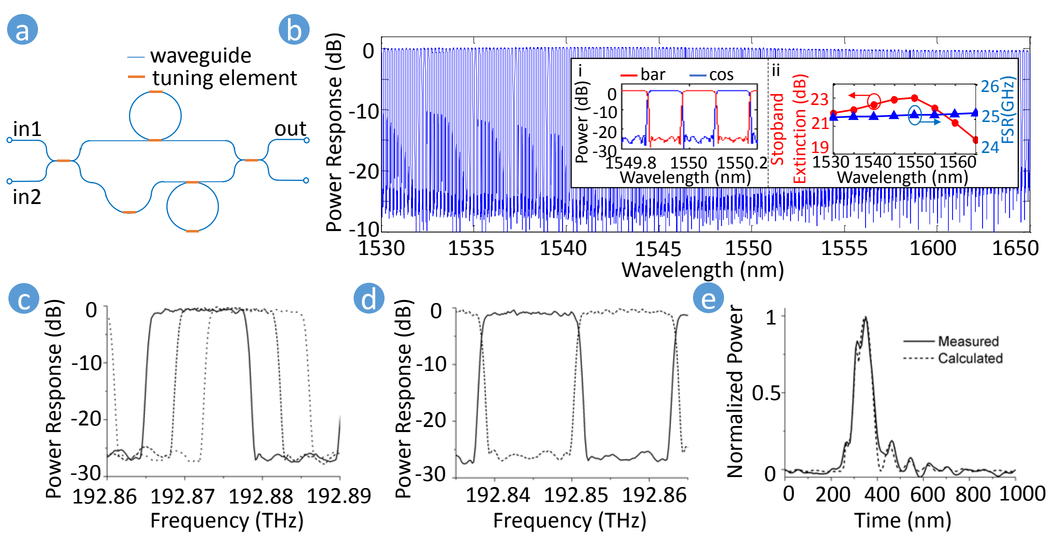

Fig. 1. (a) Chip topology; (b) Full C-band response (Insets: *i*. power response of bar and cross; *ii*. FSR and stop-band extinction); (c) demonstration of tuning; (d) demonstration of swapping; (e) Power envelope of the impulse response of the circuit.

2. Device Characterization

Figure 1a shows the topology of the RAMZI interleaver, which comprises an asymmetric Mach-Zehnder interferometer (MZI) with one ring resonator coupled to each arm. The tuning elements can adjust optical phase or coupling ratios to obtain a flat-top filter response [6]. The response of the interleaver depends on whether the signals pass horizontally through it (e.g. from top port to top port), which we call the *bar* response, or diagonally across it (the *cross* response).

Figure 1b also plots the bar response over the entire C-band, measured with an optical vector analyzer (Luna System OVA5000). The inset plots the stopband extinction measured at eight frequencies. The stopband extinction is larger than 20 dB at all points across the C-band. The inset also plots the free spectral range (FSR) variation across the C-band. The variation is less than 120 MHz, measured with 19 MHz wavelength accuracy.

Figures 1c and 1d demonstrate the programmability of the interleaver circuit. In Fig. 1c, the phases of the two ring resonators and phase of the asymmetric MZI were tuned. This shows the passband's central frequency can be tuned without changing its shape, which is a useful function for flexible channel allocation in N-WDM. In Fig. 1d, the passbands and stopbands swap positions, simply by introducing a phase change of π to one arm of the MZI.

Figure 1e is the power-envelope of the impulse response of the interleaver. It shows a deviation from a sinc-shaped response that would be required for a true Nyquist-WDM signals. This is because the ring-resonators have decaying responses, so it is difficult to synthesize an overall response that is more symmetrical in time (in addition to the usual considerations of non-causality with sinc-shaped signals). This means the interleaver may introduce inter-symbol interference.

The filter has a total insertion loss of 9-dB, which is dominated by the fiber-chip coupling losses of 4 dB/facet. However, in principle, the coupling loss can be reduced to 1 dB/facet by waveguide facet optimization [7].

3. Experimental System

Figure 2 shows the experiment to test the performance of the RAMZI as an interleaver/shaper in a multi-channel system. Seven QPSK or OOK channels are generated at a 12.5-GHz spacing, using seven tunable lasers coupled through two modulators, to give three odd and four even channels. This number is sufficient to assess the inter-channel interference due to close neighbors. The tunable lasers were tuned across the C-band. The QPSK channels were spectrally shaped by the interleaver to approximate to N-WDM channels [1]. The output signal of the interleaver was loaded with white noise (amplified spontaneous emission) then band-pass filtered with a Finisar WaveShaper to select one channel. The receiver was either a single photoreceiver (Finisar XPRV2021A) with a 40-GHz bandwidth for the OOK eye diagrams, or a coherent receiver (U2T). The oscilloscope was a Keysight DSO-X 95004Q with a 50-GHz bandwidth and 160-GSamples/s rate.

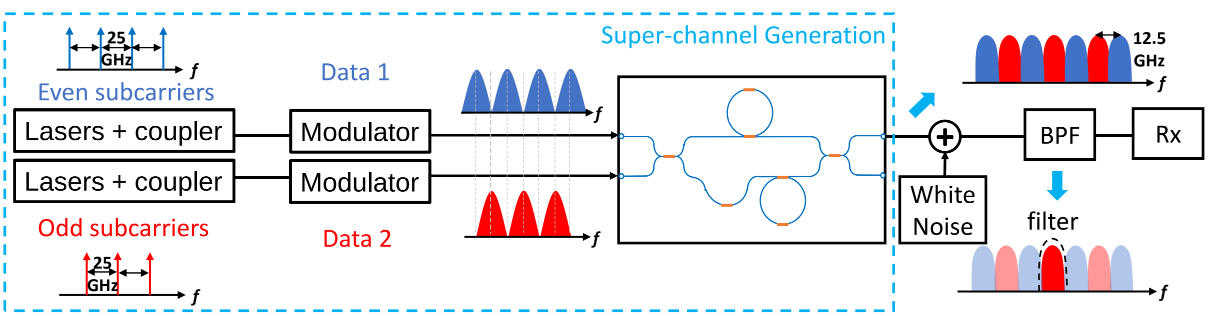

Fig. 2. Experimental setup of N-WDM generation using RAMZI Nyquist interleaver; CMZM: complex I/Q modulator.

4. Results and Discussion

Figure 3a shows the eye-diagrams of OOK signals at four different baud-rates. Both the 5-Gbaud and 7.5-Gbaud cases show clear open eyes, which indicate little distortion. In the 10-Gbaud case, the eye-diagram shows some ringing causing broadening of the 0-1-0 transitions, possibly originating from the 120-ps separation of the main peak and the second peak of the impulse response (Fig. 1e). The 12.5-Gbaud signal has significant eye closure, possibly because it excites the 12.5-GHz resonances of the ring resonators.

Figures 3b and 3c demonstrate the uniformity cross C-band. Figure 3b plots the quality factors of the on-chip interleaved N-WDM QPSK signal measured over the full C-band, with OSNR = 25 dB (12.5-GHz resolution bandwidth). Since the chip was optimized at 1550 nm by adjusting the heaters, the maximum quality factor (Q = 16.5 dB) is observed at 1550 nm. The quality factor degrades away from this wavelength due to a reduced stopband extinction, as was shown in Fig. 1b—the lowest Q (15.2 dB) occurs at 1565 nm. The difference in quality factors between the best-case and the worst-case wavelengths is 1.3 dB. Figure 3c plots QPSK quality factor versus OSNR for central wavelengths of 1530, 1550 and 1565 nm, which are the best and the worst wavelengths in Fig. 3b. The Q factors differ by 0.3 dB at the error-free threshold for 7% forward-error-correction (FEC) (Q = 8.53 dB).

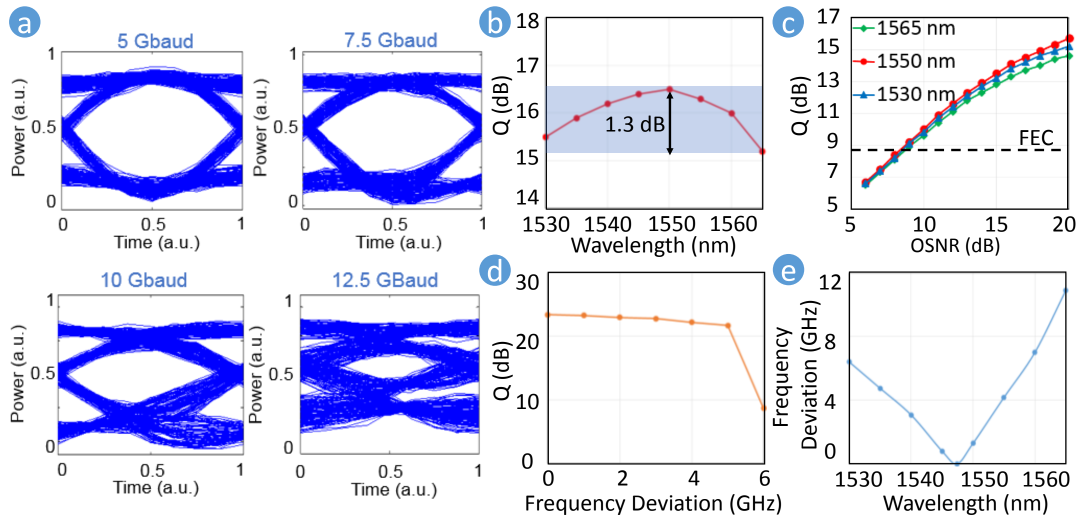

Fig. 3. (a) Eye-diagrams of OOK signals filtered by RAMZI; (b) Quality factor of QPSK signal at different wavelengths over the C-band; (c) Q *vs.* OSNR for QPSK signals centered at 1530 nm, 1550 nm, and 1565 nm; (d) Q degradation due to frequency misalignment; (e) Frequency deviation of the central frequencies compared with a 50-GHz grid.

In Fig. 3d, the center frequency of the single-channel 12.5-Gbaud QPSK signal has been detuned away from the center of the filter passband. For frequency deviations less than 5-GHz, the data can be decoded with less than a 1.7-dB penalty. If the deviation is larger than 6.25 GHz (half of the passband-width), the signal cannot be recovered.

The FSR of the chip is 25.1-GHz, so there will be an accumulated frequency deviation from the chip's grid and the 50-GHz PTC grid over the C-band. As shown in Fig. 3e, when the chip is aligned at 1547.4 nm, a 10.9-GHz frequency deviation is measured at 1565 nm. Frequency errors can be reduced by optimizing the filter design.

5. Conclusions

We have experimentally demonstrated that a single RAMZI based filter can cover the C-band with little variation of its amplitude characteristics. For multiple wavelengths over the C-band, the difference in Q factor of QPSK signals that are shaped and multiplexed by the chip is <0.3 dB at 7% FEC hard limit, and the difference in Q is <1.3 dB at OSNR = 25 dB.

The reported chip overcomes conventional challenges, which include having broad-band coverage, small size, sub-GHz spectral resolution, tenability, and sharp transition simultaneously. Full C-band coverage is essential for building highly compact, low-cost and high-speed optical communication systems. The RAMZI interleaver shows the possibility of fabricating chip-scale N-WDM multiplexer. In addition, the RAMZI interleaver can be made as a standard building block, so as to integrate with other circuits for multiple complex functions.

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