# Optical Generation of Nyquist-spacing Super-Channel Using a Ring Resonator-Based Flat-Top Interleaver

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**Abstract** *We experimentally demonstrate optical generation of a super-channel of 7 x 12.5 Gbaud QPSK-modulated subcarriers at Nyquist spacing, using a flat-top interleaver. The interleaver comprises a two-ring-resonator-assisted Mach-Zehnder interferometer with only an 8% excess bandwidth at 25-dB stopband suppression.*

## Introduction

Nyquist filtering is a promising technique for high spectral-efficiency optical communication systems[1,2]. It is usually applied at the transmitter side to generate a Nyquist signal spectrum. A Nyquist filter can be implemented in either the electrical or optical domains. Digital generation can provide near optimal Nyquist signals. However, this approach is power-hungry and its maximum producible symbol rate is limited by the sampling rate of the state-of-the-art digital-to-analog converter[3]. Optical Nyquist filtering, on the other hand, does not have these limiting factors.

In previous work, optical Nyquist filtering has been shown to be feasible using bulk optics[3-5]. However, implementation using a photonic integrated circuit (PIC) is beneficial in terms of device size, stability, control and fabrication cost[6]. Moreover, a PIC-based Nyquist filter allows for integration with other on-chip optical processing functions, and so could be of potential use in Nyquist-WDM transceivers.

In this work, we show experimentally that a flat-top interleaver circuit comprising a two-ring-resonator-assisted Mach-Zehnder interferometer (2RAMZI)[7] is a good candidate for Nyquist filtering. It is able to be configured to provide a filter shape approximating a root-raise-cosine (RRC) digital Nyquist filter with a 25-dB roll-off factor of 0.08. In contrast to a Nyquist-filtering multiplexer based on tapped-delay-line structures[8], the 2RAMZI implements an infinite-impulse-response filter[6] which features lower circuit complexity and therefore allows for smaller device size. Here we provide the first demonstration of the optical generation of a Nyquist-spacing super-channel from a RAMZI interleaver. The Nyquist filtering and interleaving functions of the 2RAMZI allows it to work with multiple transmitters simultaneously to generate a super-channel with 12.5 Gbaud sub-carriers with 12.5 GHz spacing. In our experiment, we show that the 2RAMZI-generated super-channel has comparable transmission performance to its counterpart generated by means of RRC digital Nyquist filtering.

## Principle of 2RAMZI

Figure 1a depicts a schematic of a 2RAMZI. It consists of an asymmetrical MZI having each arm side-coupled to a ring resonator (RR). The RRs have a roundtrip length twice as large as the inter-arm path length difference of the asymmetrical MZI, allowing for identically-shaped passbands for bar- and cross-ports. With a proper setting of the circuit parameters (Fig. 1a), the 2RAMZI provides the passband

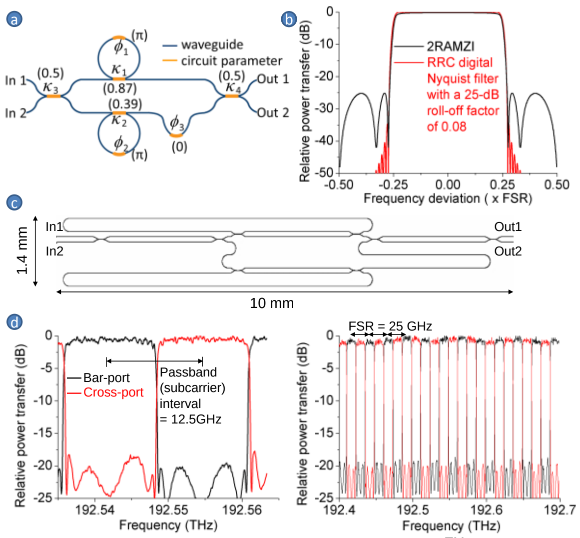


**Fig. 1:** A 2RAMZI chip fabricated in TriPleX™ waveguide technology: (a) circuit schematic and parameter indication: $\kappa$ for coupling coefficient and $\phi$ for phase shift, (b) calculated passband responses of the 2RAMZI and its digital-filter counterpart, (c) waveguide layout, (d) measured filter shape.

characteristics of a 5th-order Chebyshev Type II filter[7], which has a flat-top and a 25-dB-suppression bandwidth 8% in excess of the 3-dB bandwidth (interleaver channel spacing). As shown in Fig. 1b, this provides a good approximation to a RRC digital filter with a 25-dB roll-off factor of 0.08. In this work, we use a 2RAMZI fabricated in a commercial $Si_3N_4$ waveguide technology (TriPleX$^{TM}$)[7]. The device is designed with a passband interval of 12.5 GHz (a device FSR of 25 GHz). Its size is 10 × 1.4 mm$^2$ as shown in Fig. 1c. Figure 1d depicts the measured filter shape on different scales, showing the Nyquist filtering and frequency-interleaving functions.

**Nyquist-spacing super-channel generation**

The experimental setup for the 2RAMZI-based optical generation of a Nyquist-spaced super-channel is shown in Fig. 2a. We use a total of 7 tunable CW lasers to generate 7 subcarriers (limited by the available lasers in our lab). The frequency interval between the lasers is set to 12.5 GHz, matching the interleaver passband interval. The subcarriers are QPSK-modulated at a baud rate of 12.5 Gbaud, using 20-GHz complex Mach-Zehnder modulators. In principle, each subcarrier requires a modulator driven by an independent data sequence; the modulated subcarriers are multiplexed into two separate subcarrier groups—one with even-numbered subcarriers and the other odd-numbered—each having a subcarrier interval of 25 GHz and fed to a corresponding input of the interleaver circuit to undergo Nyquist filtering and subcarrier interleaving. For a proof of concept, we simplify our system of demonstration to the use of only two modulators instead, with one for even-numbered subcarriers and the other for odd-numbered as shown in Fig. 2a. The insertion loss over the chip is measured to be 8 dB. The subcarriers are frequency-aligned to the centers of the interleaver passbands and are set to equal powers. As the chip in this work has polarization-dependent fiber-chip coupling, polarization control is carried out before the chip's inputs.

Figure 2b depicts the measured Nyquist signal spectrum of one subcarrier at the output of the chip, compared to the original QPSK signal spectrum. It is clear that the subcarrier is reduced to a bandwidth matching the Nyquist spacing of 12.5 GHz. However, the spectrum still has residual sidelobes on both sides of the subcarrier. This is because the 2RAMZI provides periodic passbands (Fig. 1d) and the spectrum of the original QPSK signal extends over several FSRs. For super-channel generation, the residual sidelobes of one subcarrier may occur in the passbands assigned for other subcarriers, causing crosstalk. So, to optimize the system's performance, subcarrier sidelobe pre-filtering should be applied to minimize the in-band crosstalk. Figure 2c shows the chip output spectrum when only the odd-numbered subcarrier group is fed to the chip input; Fig. 2d when only the even-numbered group. These two results show the frequency periodicity of the Nyquist-filtering response of the chip. The complete output spectrum with all 7 subcarriers, Nyquist-filtered and interleaved, is depicted in Fig. 2e, demonstrating the generation of a Nyquist-spacing super-channel. For comparison, the subcarriers generated by means of RRC digital Nyquist filtering with a roll-off factor of 0.08 are also depicted in Fig. 2c through 2e, showing a good agreement with the optically filtered ones.

Further, to demonstrate the feasibility of our approach, we have performed a back-to-back transmission performance comparison between the optically-generated signals and their digital-Nyquist-filtering counterparts. In our experiment, we compared single-subcarrier transmission with 7-subcarrier-super-channel transmission. Figure 3 depicts the measured subcarrier Q-factors versus OSNR (0.1 nm noise bandwidth). For the single-carrier case, the 2RAMZI introduces an average penalty of 1 dB. This is

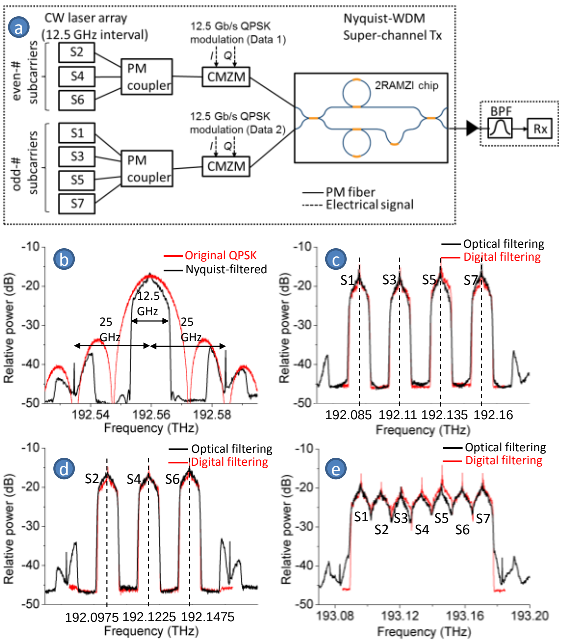


**Fig. 2:** Optical Nyquist-spacing super-channel generation. (a) experiment setup, (b-e) measured optical spectra at the output of the 2RAMZI chip, compared with their digitally-generated counterparts: (b) with only one subcarrier, (c) with only even-numbered subcarriers, (d) with only odd-numbered subcarriers, (e) with all 7 subcarriers.

mainly because the optically-generated signal waveform deviates from the ideal intersymbol-interference-free Nyquist pulse shape due to the non-rectangular-shaped spectrum. For the super-channel case, we received the subcarrier in the middle of the spectrum (S4), where the 2RAMZI gives an average penalty of 2 dB. We attribute this additional 1-dB penalty increase to the in-band crosstalk caused by the residual sidelobes of the other subcarriers. These residual sidelobes are mainly from the neighbouring subcarriers (S3 and S5) due to the limited stopband suppression of 18 dB (Fig. 1d) and from the two further subcarriers (S2 and S6) due to the passband periodicity as explained earlier (Fig. 2b). The effect of this on the Q factor is clearer at the higher OSNR values, where the noise plays a negligible role for the signal distortion. This result proves the principle of our super-channel generation approach. There are several methods to further optimize system performance. Subcarrier sidelobe pre-filtering can be used to reduce the in-band crosstalk, accurate setting the chip parameters should produce an interleaver response with a stopband suppression of 25 dB, and careful frequency-alignment between the subcarriers and the interleaver passband centers may also improve upon our current results.

In addition, we have recently theoretically shown that it is possible to further reduce the 25-dB-suppression bandwidth of the interleaver passband by coupling a third ring resonator to

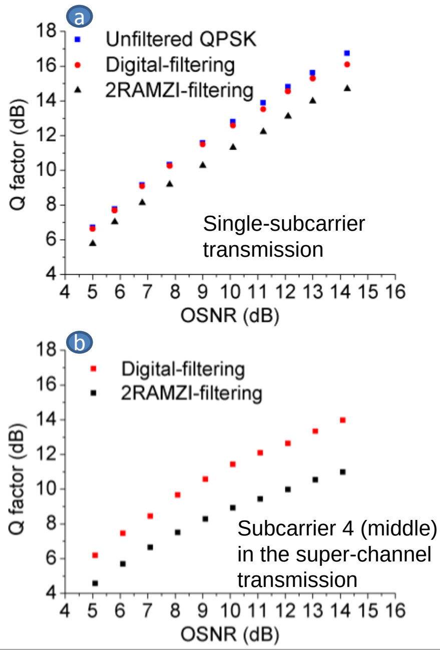


**Fig. 3:** Measurements of back-to-back transmission performance of Nyquist-filtered subcarriers. (a) single-carrier transmission, (b) 7-subcarrier superchannel transmission.

the MZI[9], which approximates more closely an ideal Nyquist filter shape.

In principle, the response of RAMZI interleavers should cover the entire C-band, and the flap-top passbands can be used to generate rectangular-shaped Nyquist channel spectrum when fed with modulated optical pulses having “white” spectrum[10]. As such, we expect RAMZI interleavers to enable the generation of multi-terabit Nyquist-WDM super-channels from a single PIC.

## Conclusions

We have demonstrated optical generation of a Nyquist-spacing super-channel of 7 x 12.5 Gbaud QPSK-modulated subcarriers, using a 2RAMZI chip with 12.5-GHz passband interval. This work opens a path towards Nyquist-WDM super-channel transceivers for high spectrum-efficiency optical communication systems.

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