On-Chip Programmable MZI-Based Fourier Synthesizer for Ultra-Broadband Kerr Comb Equalization

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Abstract: We equalize non-uniform Kerr comb line power using a single-chip programmable multi-arm MZI filter that synthesizes arbitrary passbands, and experiments show a path to lower DWDM receiver dynamic-range requirements by $\geq 16\,$dB.

1. Introduction

Silicon photonics has become a leading platform for dense wavelength-division multiplexing (DWDM) to meet rapidly growing artificial intelligence/machine learning bandwidth demands. Kerr frequency combs are especially attractive DWDM light sources because they provide precise channel spacing, inter-channel coherence, and broadband multi-line generation from a single device [1–3]. However, the inherent line-power non-uniformity, most notably the power asymmetry between the pump line and distant channels, forces receiver circuitry to accommodate large dynamic ranges often exceeding 10 dB, while transmitter resonators must navigate bistability and self-heating–induced operating-point shifts and nonlinearities [4]. A prior mitigation strategy operates the resonator devices at different driving voltages and/or detuning distances [5], which can ease receiver constraints. However, these approaches introduce per-channel optimization loops and result in suboptimal operating points on the transmitter side.

Here, we demonstrate an on-chip programmable filter placed immediately after the comb source to shape its envelope and flatten the line-power profile before entering the transmitter. Building on Mach-Zehnder interferometer (MZI)-based finite impulse response filter concepts [6] and application agnostic designs [7], we propose a multi-arm MZI-based Fourier synthesizer architecture whose passband shape can be controlled by a small set of coefficients. Fabricated on a commercial 300 mm silicon photonics platform, our 4-tap filter prototype comprises 6 custom MZI elements that function as tunable couplers and 4 arms with incrementally increasing delay lengths, consisting of 20 heaters in total and offering practical programmability with reasonable complexity. We program several different transmission spectra to validate arbitrary passband synthesis, and then demonstrate ultra-broadband Kerr-comb equalization that lowers DWDM receiver dynamic-range requirements by $\geq 16\,$dB.

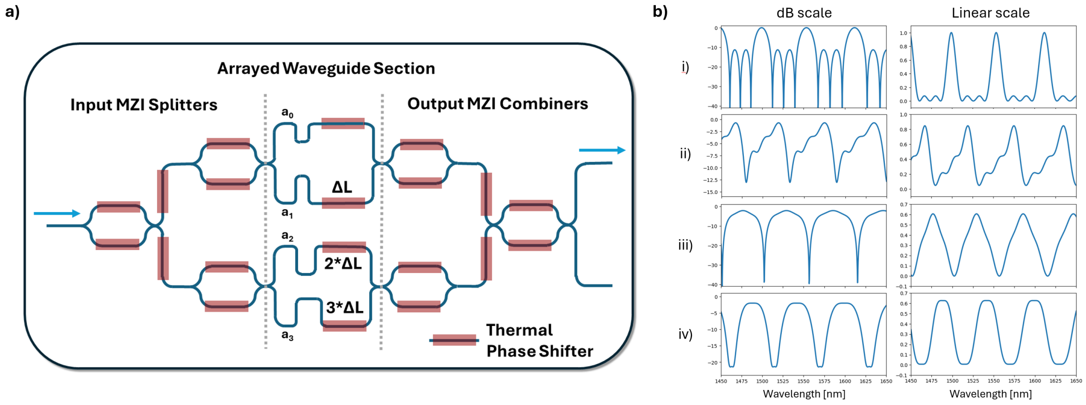

Fig. 1: (a) Schematic of the 4-tap programmable filter. The four arms of the filter are denoted as a_0, a_1, a_2 and a_3, respectively. (b) Simulation results of the target waveforms: impulse (i), sawtooth (ii), triangle (iii), and flat-top (iv) passbands. The left side is in decibel scale and the right side is in linear scale.

2. Programmable Filter Architecture

The proposed programmable filter realizes a Fourier synthesizer using a multi-arm MZI structure. As illustrated in Fig. 1(a), an MZI splitter tree fans-out the input light into N parallel arms (N-tap) with incremental delay lengths (0, ΔL, $2\Delta L$, $3\Delta L$, $\cdots$) and independent thermal phase shifters. All arms then recombine coherently through an MZI combiner tree to form a periodic transfer function with a free spectral range set by ΔL. The interference between each pair of arms can be expressed as the basic sinusoidal functions: (a_0, a_1), (a_1, a_2) and (a_2, a_3) contribute to $sin(\beta\Delta L)$; (a_0, a_2) and (a_1, a_3) contribute to $sin(2\beta\Delta L)$; (a_0, a_3) contributes to $sin(3\beta\Delta L)$. In this way, the recombined field can be expressed in the form of a Fourier series; for a 4-tap filter the transfer function consists of the fundamental plus the second- and third-order harmonics. By configuring the power ratio between the branches and adjusting their phases through thermal phase shifters, the amplitude and phase of the Fourier coefficients can be controlled accordingly, enabling the creation of arbitrary periodic passbands. Instead of using 3 dB couplers plus attenuators, cascaded MZI tunable couplers are used to control the power ratio between the four branches, realizing the minimum loss for the target transmission waveform. Any power combination can be achieved by tuning the power splitting ratio of each MZI element. It should be noted that the output phase of the MZI coupler will also change with the internal thermal phase shifters, so phase compensation heaters are added between the first stage and the second stage MZIs for the sake of an easy control scheme. Fig. 1(b) demonstrates simulated 4-tap examples of several featured waveforms.

Kerr comb power equalization can be achieved by first measuring the comb spectrum and fitting a smooth power envelope across the usable band, and then computing the inverse envelope as the target periodic passband and finding the corresponding Fourier series. By comparing the Fourier series between the target waveform and the filter transfer function and solving a set of coupled equations, the required splitting ratio of the MZI couplers and the phase of the filter arms can be determined. Finally, the power required for each heater can be calculated from the measured heater I-V curve and heater thermal efficiency.

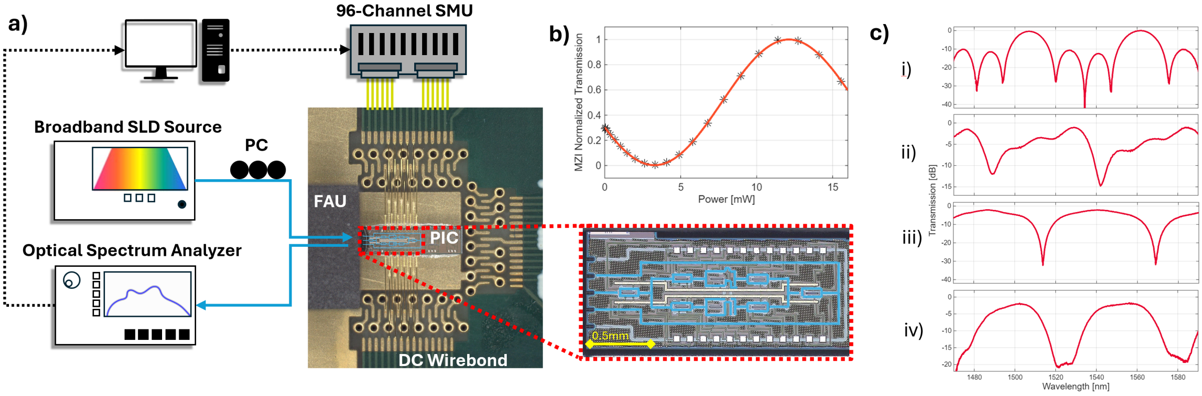

Fig. 2: (a) Schematic of experimental setup. A broadband superluminescent diode source is sent to the packaged PIC via a fiber array unit after apolarization controller. The spectrum of the filter is measured by an optical spectrum analyzer and is recorded for each tuning step programmed through Python to a 96-channel DC controller. (b) Calibration of the thermal tuning efficiency measured from a reference test MZI structure demonstrating a P_π of 8.8 mW. (c) Programmed filter states to produce the impulse (i), sawtooth (ii), triangle (iii), and flat-top (iv) responses.

3. Experimental Validation

We validate our programmable filter on a packaged photonic integrated circuit (PIC) in a setup shown in Fig. 2(a). The zoomed-in microscope image shows the fabricated PIC containing a 4-tap filter, fabricated through TowerJazz foundry and optically packaged and wirebonded at Optelligent (Costa Mesa, CA). A broadband SLD source (EXFO FTB-2250) passes through a polarization controller and is coupled through a fiber array unit (FAU) into the PIC, and the output is monitored by an optical spectrum analyzer (OSA) (Yukogawa AQ6375). All heaters (20 in total) are wire-bonded to a PCB and driven by a 96-channel DC controller (Qontrol Q8iv modules) for thermal tuning.

To increase thermal tuning efficiency, three-folded waveguides are placed under the metal heaters. Fig. 2(b) shows the MZI metal heater characterization result from the bare die testing, demonstrating a P_π of 8.8 mW. Isolation trenches are placed between the heaters to minimize thermal crosstalk. A trimming power of 1.15 mW is also extracted from Fig. 2(b) result, corresponding to a 0.13π phase mismatch between the balanced MZI arms due to fabrication variations. Therefore, a series of calibration steps is required to extract splitter set points and per-arm phase offsets prior to passband synthesis, revealing phase mismatch across all six MZIs ranging from 0.12π to 0.42π. After applying the required corrections to the phase mismatch, we program several representative passbands as shown in Fig. 2(c), demonstrating a reasonable match to simulation results in Fig. 1(b). Finally, we place the filter immediately after a Kerr comb source and apply the workflow described in Section 2 to flatten the comb profile. Fig. 3(a) and Fig. 3(b) show the comb spectra before and after equalization, respectively. The flattened comb exhibits only ±0.9 dB power variation from 1525.2 nm to 1553.9 nm, significantly compressing the original 18 dB power disparity between the pump residue and the edge line. This flattening thereby reduces DWDM receiver dynamic-range requirements by ≥ 16 dB.

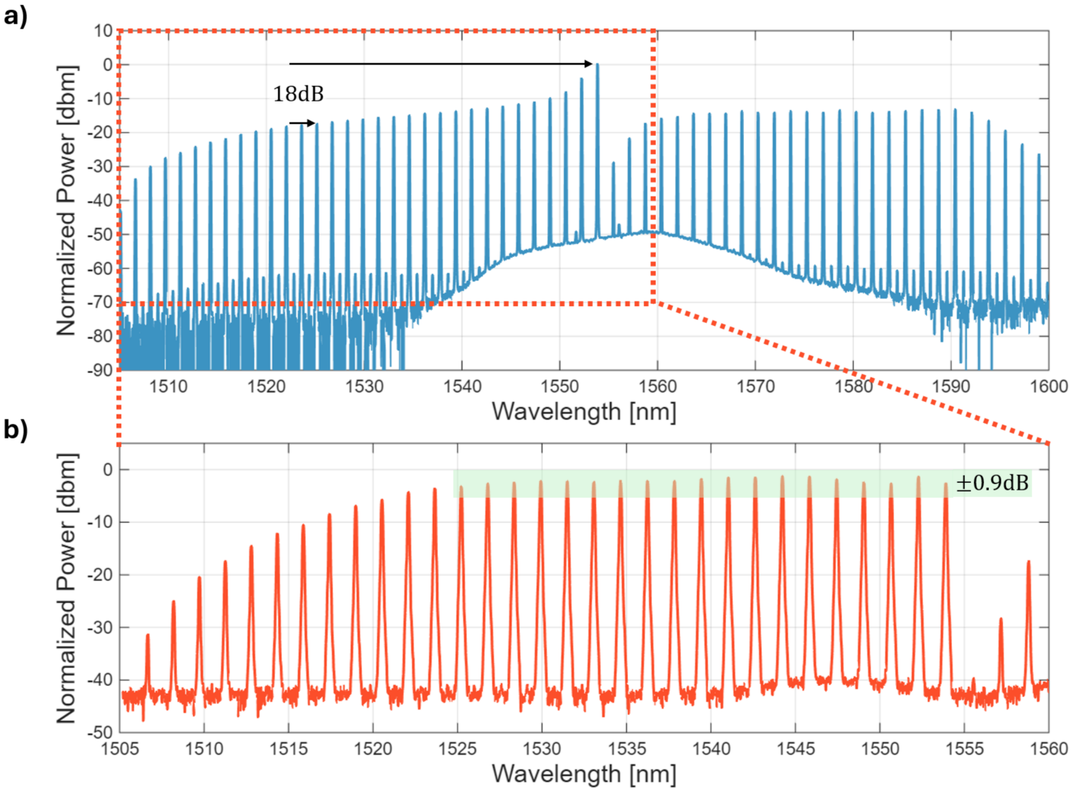

Fig. 3: (a) The original Kerr comb spectrum with 200 GHz channel spacing. The power difference between the pump residue and the comb line at 1525.2 nm is 18 dB. (b) The flattened comb spectrum, showing ±0.9 dB power variation between 1525.2 nm and 1553.9 nm (pump wavelength).

4. Conclusion

We presented an on-chip, multi-arm MZI-based Fourier synthesizer that programs arbitrary periodic passbands for ultra-broadband Kerr comb equalization. A fabricated 4-tap device demonstrated accurate spectral synthesis and ≥ 16 dB reduction in receiver dynamic-range requirements across ≥ 28 nm with ±0.9 dB residual ripple. This architecture is compact and expandable to higher tap counts, positioning programmable MZI filters as a scalable, source-side solution for comb equalization in next-generation DWDM links.

References

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