Low-Loss Wide-FSR Miniaturized Racetrack Style Microring Filters for ≥1 Tbps DWDM

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Abstract: We demonstrate add-drop microring filters based on 180° varied-width hybrid Euler bends, suitable for supporting >Tbps DWDM. We measure FSR>40nm, 0.64nm/mW thermal tuning efficiency, and $IL_{off} \leq 0.02$ dB across the C- and L-bands. © 2023 The Author(s)

1. Introduction

The rise of cloud-based computing and high-performance data analytic applications, such as machine learning, has strained traditional data center and high performance computing architectures. Silicon photonic (SiP) interconnect architectures have been proposed as a bandwidth-dense and energy efficient solution to the problem of bandwidth bottlenecks in these systems. For achieving SiP interconnects with >Tbps aggregate data rates, architectures utilizing on-chip dense wavelength division multiplexing (DWDM) with massive parallelism provide an appealing path forward [1]. Add-drop resonant filters, typically micro-ring resonators (MRRs) or disks, are ubiquitous in DWDM SiP interconnect architectures as compact, low-loss, and tunable wavelength-selective filters. By cascading multiple resonant filters along a single waveguide, de-multiplexing of independently modulated carrier frequencies to independent detectors is possible [1]. Thus, the maximum aggregate data bandwidth of such a receiver is the data rate per channel (Gbps/ λ) multiplied by the number of wavelength channels (N_{λ}).

 N_{λ} is dominated by three factors: minimum channel spacing $(\Delta \lambda_{aggressor})$, resonator free spectral range (FSR), and off-resonance insertion loss (IL_{off}) . The feasibility of on-chip DWDM at 25 Gbps/ λ for channel spacing as low as 100 GHz (≈ 0.8 nm in the C-band) with minimal inter-channel crosstalk penalties has been demonstrated [2]. FSRs as large as 93 nm have also been demonstrated, but such large FSRs are achieved at the cost of significant IL_{off} due to excess bend loss of the phase-matched coupling geometry that enables the requisite resonator coupling [3]. For a cascaded resonator array, cumulative IL_{off} will strongly impact the channel corresponding to the last resonator, limiting N_{λ} before a full FSR of optical bandwidth can be utilized.

Here, we demonstrate a miniaturized racetrack-style MRR filter based on a pair of single-mode 180° variedwidth hybrid Euler bends. The devices were measured as having FSR > 40 nm, Lorentzian full-width half-max (FWHM) ≈ 50 GHz, and $IL_{off} \leq 0.02$ dB across the C- and L-bands, due to the straight coupling region. The thermal tuning efficiency was measured as 0.64 nm/mW. The same device is measured across 8 reticles over $\frac{1}{4}$ of a 300 mm wafer, showing the C-band resonance location varying with $1\sigma_{\lambda_0} = 1.1$ nm. To the best of our knowledge, this MRR supports the record for achievable $N_{\lambda}(IL_{limit} \leq 1 \text{ dB}, \Delta \lambda_{aggressor} \geq 0.8 \text{ nm}) = 50$, where IL_{limit} is the acceptable cumulative IL_{off} . As a result, a single array of these MRR filters, at 25 Gbps/ λ , is capable of supporting an aggregate DWDM receiver bandwidth up to 1.25 Tbps.

2. Low-Loss MRR Design & Simulation for Large N_{λ}

The maximum N_{λ} is limited by two key MRR factors, FSR and IL_{off} , and can be calculated as,

$$N_{\lambda} = \text{floor}\left[\min\left(\frac{FSR}{\Delta\lambda_{aggressor}}, \frac{IL_{limit}}{IL_{off}} + 1\right)\right].$$
(1)

min $(\Delta \lambda_{aggressor})$ should be set proportional to the data rate, affecting the target MRR FWHM [2,4]. For feasible DWDM applications, an IL_{limit} must be defined as the maximum threshold for the broadband cumulative loss contributed by each MRR prior to the last channel in the system's cascaded array. We set our design $IL_{limit} = 1 \text{ dB}$ to reduce the range of expected signal quality across the spectrum. To increase N_{λ} , both ratios in Eq. 1 must be maximized, but prior works have focused on the former, $FSR/\Delta\lambda_{aggressor}$. This has been achieved via reducing the MRRs' effective radius R_{eff} , which is inversely proportional to FSR [3]. Yet, IL_{off} is equally important and often not reported; in the case of $IL_{off} = 0.1 \text{ dB}$, max $[N_{\lambda}(IL_{limit} = 1 \text{ dB})] = 11$, regardless of FSR.

Prior work suggests that the resonator's FWHM $\ge 2 \times \text{Gbps}/\lambda$ to avoid spectral truncation negatively impacting signal quality [4]. For 25 Gbps/ λ this would correspond to FWHM ≥ 50 GHz, which requires the resonator power coupling for the through and drop waveguides to be $\approx 5\%$ in the C-band (in the case of negligible resonator round trip loss). For ultra-wide FSR resonators, this coupling strength is typically achieved using a phase-matched directional coupler, partially wrapped around the resonator body, matching the resonator curvature and engineered to optimally couple into the resonator's fundamental optical mode [1, 3]. As a consequence, all of the light must pass through a pair of S-bends in the through waveguide, introducing significant IL_{off} losses through bend and mode mismatch losses at the straight-to-bent and concave-to-convex bent waveguide interfaces [5]. These losses scale exponentially with $1/R_{eff}$, thus the larger the FSR, the larger the IL_{off} for a phase-matched coupling scheme.



Fig. 1. **a**) 180° hybrid Euler bend with varied waveguide width, $R_{eff} = 1.75 \,\mu$ m, $R_{min} = 1.63 \,\mu$ m, I/O Width = 480 nm, and Mid Width = 577 nm. The blue sections illustrate where the waveguide curvature (1/*R*) and width linearly vary and red sections signify where waveguide curvature and width is constant. **b**) Simulated field profile of optical transmission through the 180° bend. **c**) Simulated $IL(\lambda)$ /bend. **d**) Silicon layout of the miniaturized racetrack style MRR filter, with a ring shaped doped silicon heater included for thermally tuning the resonance location via the thermo-optic effect. Excess straight waveguide is added between the 180° bends to adjust the nominal resonance location. **e**) Simulated field profile of the MRR, with the fundamental mode launched from the input port. **f**) Simulated MRR $IL(\lambda)$ measured at the through port.

To overcome this, we propose utilizing a pair of 180° modified hybrid Euler bends (comprised of concatenated Euler and radial bends with varied-width), illustrated in Fig. 1a, to construct a MRR [6]. Figs. 1b and 1c show the FDTD simulation field profile and transmission of the bend measured from input to output, with less than 0.01 dB/bend at $R_{eff} = 1.75\mu$ m. The resulting MRR, shown in Fig. 1d, is quasi-ellipsoidal, with an approximately linear region at the top and bottom. This geometry permits an extended linear coupling region, similar to a larger race-track style MRR. Removing the tight S bends from the through waveguide also removes the off-resonance bend and mode mismatch losses, drastically reducing IL_{off} . Figs. 1e and 1f illustrate the FDTD simulations for this MRR, which are in good agreement with our expectation of low IL_{off} and FSR> 40nm.

3. Experimentally Measured MRR Characteristics

MRRs were fabricated with the excess length varied from 0 to 250 nm and their measured normalized through port transmission is plotted in Fig. 2a, showing consistent critical coupling, FSR > 40 nm, and FWHM \approx 50 GHz for each variation. The thermal tuning efficiency is measured as 0.63 nm/mW, shown in Fig. 2b, and a single MRR variation (L = 0) is measured on 8 reticles, sampled across $\frac{1}{4}$ of a 300 mm diameter wafer, as having a $1\sigma_{\lambda_0} = 1.1$ nm variation in resonance location. This suggests 99.7% of fabricated devices should fall within ± 3.3 nm of the nominal target λ_0 , and the average per device thermal tuning energy $P_{\text{th}} = 5.24$ mW to compensate for fabrication variation (210 fJ/bit at 25 Gbps/ λ). A series of cascaded resonator cutback measurements of both the proposed MRR with linear coupling and a resonator with a phase-matched coupling scheme confirms the former results in reducing IL_{off} by more than a factor of 4 over the full C- and L-bands, as seen in Fig, 2d. The resonator with the phase-matched coupler also has a 63% lower FSR, corresponding to a much larger R_{eff} and lower bend losses. We extrapolate that for equivalent FSR resonators, our IL_{off} improvement relative to a phase-matched coupler geometry would be much greater than the factor of 4 measured here.



Fig. 2. **a**) Measured transmission of multiple MRRs with the *L* parameter varied to adjust nominal resonance wavelengths. FWHM \approx 50 GHz, with negligible change over $0 < L < 0.25 \,\mu\text{m}$. **b**) Thermal tuning response using the integrated heater, as shown in Fig.1d, tuning efficiency measured as 0.63 nm/mW. **c**) Variation of the same device over multiple reticles, sampled across $\frac{1}{4}$ of a 300 mm wafer. $1\sigma_{\lambda_0} = 1.1 \text{ nm}$. **d**) Subset of the cutback measurements made for different resonators. 30 cascaded MRRs with a bent phase-matched coupler ($R_{\text{MRR}} \approx 4.4 \,\mu$ m) show $IL_{off} \approx 0.09 \,\text{dB}$, compared to our miniaturized racetrack coupled MRR, which shows $IL_{off} \leq 0.02 \,\text{dB}$. Insets are microscopic images of adjacent cascaded resonator arrays.

4. Conclusion

We design and experimentally demonstrate an add-drop MRR filter capable of supporting up ≥ 1 Tbps along a single cascaded resonator array. To the best of our knowledge, the MRR demonstrated in this work is capable of supporting the largest feasible N_{λ} , as well as the largest feasible aggregate bandwidth, for a single array of cascaded add-drop MRR filters. This work supports the next generation of energy-efficient and bandwidth dense on-chip DWDM interconnects.

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