Two-pole microring weight bank

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Received 29 January 2018; revised 5 April 2018; accepted 7 April 2018; posted 11 April 2018 (Doc. ID 319497); published 7 May 2018

Prior research in MRR circuits has focused on single-bus, multi-wavelength MRR devices [Fig. 1(b)], such as demultiplexers [18,19]. In demultiplexers, a WDM channel partially coupled through a neighboring filter exits the wrong output port, resulting in inter-channel cross-talk (Xtalk), which limits minimum channel spacing [20,21]. Extensive research has also been directed towards double-bus, single-wavelength MRR devices [Fig. 1(c)], including series/parallel-coupled ladders [22,23], 1-pole and 2-pole (a.k.a. twisted) SCISSORs [24–26], and more generalized circuits [27,28]. In these cases, all MRRs within a filter act on a single wavelength channel, each resonating at or near a common wavelength. These single-wavelength filters are often used within demultiplexers, in which case subsequent channel filters (each containing multiple MRRs) are cascaded via a single bus WG.

In a MRR weight bank, parallel-coupled 1- or 2-ring filters act on different WDM carriers. In this respect, they are similar to demultiplexers; however, unlike demultiplexers, a weight bank does not separate WDM channels into individual WGs. A WDM channel partially coupled through a neighboring filter exits the same two output ports. This crucial difference results in (1) the breakdown of inter-channel Xtalk as a meaningful concept and (2) the presence of two-bus WGs between filters that act upon different WDM channels. The minimum channel spacing is limited by the ability to weight neighboring channels independently, rather than inter-channel Xtalk [16]. Furthermore, the path taken through the neighboring filter interferes coherently with the path taken through the nominal filter. This coherent phenomenon has a pronounced impact on channel density limits.

The nature of inter-filter interference is fundamentally different for MRR filters that are odd-pole vs. even-pole because signals are dropped in opposite directions [Fig. 1(a)]. The number of poles is equal to the number of series-coupled MRRs per channel filter. In an odd-pole bank, a channel partially coupled through a neighboring filter returns through the opposite bus WG to complete a resonator-like feedback path. In an even-pole bank, the partially dropped channel continues in the same direction to complete an interferometer-like feed-forward path instead. Interferometer-like interference depends on a path length difference, rather than a sum, so changes that affect both bus WGs equally will not change the interferometric phase condition. While the group velocity of WGs as fabricated varies significantly over the chip area, this variation is spatially correlated [29,30]. Dynamic variation due to thermal tuning can be made congruent using the designs introduced in this Letter.

In this Letter, we demonstrate that the inter-channel phase condition is tolerant to dynamic tuning only in 2-pole weight banks. Furthermore, we show that 2-pole banks can be tailored to exploit this effect for deeper isolation between channels, even in the presence of fabrication variation. Using the parametric scaling analysis developed in Ref. [16], we estimate that these properties represent a $3.4\times$ improvement in channel scalability.

Three silicon MRR weight banks, pictured in Fig. 1(i, ii, and iii), are fabricated to study inter-filter effects: type (i) is a 1-pole bank; type (ii) is a 2-pole bank with identical bus WGs; and type (iii) is a 2-pole bank with a bus WG asymmetry. A bus length asymmetry of 95 nm is designed to give a $\pi/2$ phase shift, given the TE group index of $n_g = 4.2$ on this platform [31] ($\Delta\phi = 2\pi n_g \cdot 95\ \mathrm{nm}/\lambda_0$). Heating filaments provide independent resonance control and indirectly heat the bus WGs. The indirect MRR-to-bus thermal Xtalk (different from inter-channel signal Xtalk) is desirable in this experiment as a way to effect bus WG index shifts. Filament symmetry is critical to ensure that index shifts are applied equally to both MRRs within a 2-pole filter and both surrounding bus WGs. A 1-pole bank with bus length asymmetry is not fabricated because it is expected to behave the same as device (i).

Silicon-on-insulator samples have a silicon thickness of 220 nm and a width of 500 nm with fully etched WGs, a 3 μm oxide passivation layer, a Ti/Au heating filament layer, and an Al routing layer [32]. The measured WG loss is 7 dB/cm for the TE mode. In each bank, the MRRs have a short 2 μm straight coupling region with arcs of slightly different radii near 10 μm. Exact layout perimeters are $L = [68.0, 68.1, 68.2]\mu\mathrm{m}$. This design is intended for approximately equal FSRs of 9.1 nm and inter-channel resonance offsets of 2.3 nm. The actual offset is affected by fabrication variation. These 1- or 2-pole MRR channels are arranged in a parallel add/drop configuration with symmetric bus coupling gaps of 100 nm. The MRRs in each 2-pole filter are separated by a gap of 300 nm, optimized to critically couple the two MRRs. The critical coupling gap was d-1.1-8.3result(a)-262.6(parallel)-2

within 10k–20k with an FSR of 9.1 nm (finesse, $\mathcal{F} \approx 133$), so it could potentially yield MRR weight bank channel limits of 32 (1-pole) and 110 (2-pole).

The performance gain represented by designing 2-pole versus 1-pole filters in MRR weight banks is unexpectedly high compared to the same design change in conventional MRR demultiplexers. This means the MRR weight bank's inter-channel interference effects can be exploited, not just tolerated. In both types of devices, the steeper roll-off of the 2-pole filter allows for denser channel spacing. This impact is expected. In demultiplexers, it represents a 70% channel density improvement [20]. However, in this Letter, we calculate the corresponding improvement in MRR weight banks to be 240%. This discrepancy is achieved by exploiting inter-channel interference within the two-bus circuit.

This Letter calls for further study in weight bank control strategies. Feedforward control techniques have been shown [15], but only in the coarse WDM regime where each channel is affected by only one MRR filter. With dense WDM, this assumption is violated, so the approach would have to also model inter-filter interference, as well as variable ring-to-bus thermal Xtalk. The repeatability of 2-pole weight bank spectra hint at simplified algorithms for dense WDM weight control. We have shown here that the bus phase condition does not change with tuning, so, for example, it could be considered a fixed parameter, rather than a tuning-dependent variable.

We have compared in experiment 1-pole and 2-pole silicon MRR weight banks. As opposed to other WDM devices based on MRRs, weight banks are sensitive to coherent interactions between neighboring filters, and the character of this interaction is fundamentally different for odd-pole and even-pole filters. By tuning banks of three weights together to effectively sweep their inter-channel interferometric phase conditions, we have shown that 1-pole weight banks are not tolerant to tuning-related thermal Xtalk, while 2-pole weight banks are tolerant. The coherent inter-channel effects in 2-pole banks can be exploited for greater isolation between channels. A bus length asymmetry (here, 95 nm), designed lithographically and robust to fabrication variations, was seen to increase isolation by 5 dB. This isolation translates to a channel density increase over baseline designs, found here to be 3.4×. Channel count improvements in MRR weight banks directly impact proposed analog signal processing approaches in silicon photonics, particularly neuromorphic photonics and multivariate photonics.

Funding. National Science Foundation Enhancing Access