

Fast-Tuning Adiabatic Microrings for CROW Filters and Athermal WDM Receivers in a 45 nm SOI CMOS Process

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Abstract: Adiabatic microrings with opposing p/n contacts achieve full carrier sweepout in reverse bias and energy-efficient carrier injection in forward bias, exhibiting 200GHz/V peak shift in C-band for athermal tuning over a 220 GHz range. © 2022 The Author(s)

Monolithic integration of CMOS electronics and photonics is a leading approach to realizing next-generation chip-to-chip optical IO at Tbps speeds due to dramatically reduced interconnect parasitics and packaging costs as compared to heterogeneous integration [1]. Moreover, this technology can enable large-scale quantum optical communication and computing systems, where many photon-pair sources and associated high-order filters must be aligned and locked to the same operating wavelengths via active feedback control [2,3]. We present an adiabatic microring filter, depicted in Fig. 1, that can serve as a core building block in such CMOS-photonics systems and is implemented in GlobalFoundries' next-generation silicon photonic process in 45nm CMOS [4]. In contrast to previous adiabatic microring devices [5], this device utilizes the entire microring as the active intrinsic region in a PIN diode, providing full carrier extraction in reverse bias and efficient carrier injection in forward bias, while maintaining high intrinsic Q -factor. The main tradeoff is slower transit-time-limited bandwidth, which is acceptable in reconfigurable optical filters (as opposed to high-speed data modulators). Fig. 2 summarizes the key performance metrics of the device.

High-bandwidth chip-to-chip optical links are designed with several microrings operating in wavelength division multiplexed (WDM) fashion on the same optical waveguide, both as modulators on the transmit end and drop filters or photodetectors on the receive end [1], to achieve better energy efficiency than aggregating the same bandwidth into a single modulator and receiver [6]. Adding optical switches to the path to increase the connectivity radix, future architectures will dynamically switch different modulator and receiver banks together, creating a need for channel-dropping microring filters that can quickly retune to a new grid of laser wavelengths to compensate for thermal and manufacturing variations between different transmitter-side lasers. Under forward bias the adiabatic microring filter injects carriers that traverse the entire circumference of the ring and overlap strongly with the confined optical mode. This creates a fast plasma-dispersion resonance shift strong enough to replace or augment thermal tuning, achieving up to 200 GHz/V shift over a 220 GHz range while being 100× faster, important for increasing overall data throughput. The tuning range is ≈ 150 GHz with ≤ 2 V forward bias, enabling direct interfacing to thick-gate-oxide transistors in this process. Compared to forward-bias operation of interleaved-junction devices [7], adiabatic microrings exhibit higher intrinsic Q -factor because the doped regions are designed not to overlap the optical mode, reducing losses

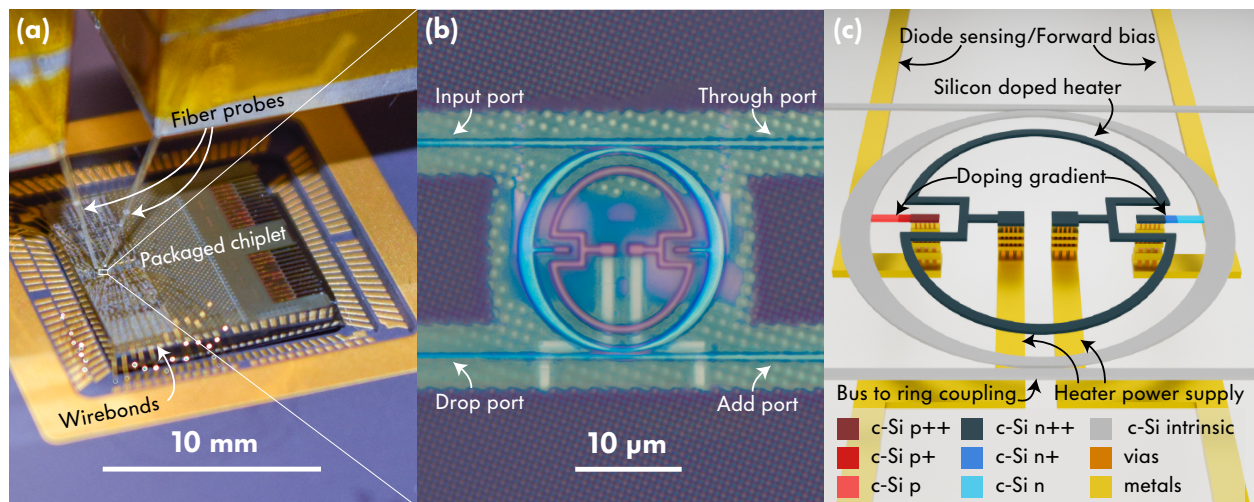


Fig. 1: (a) Wirebonded chip, (b) adiabatic add-drop ring micrograph (back side), and (c) device design and doping profile.

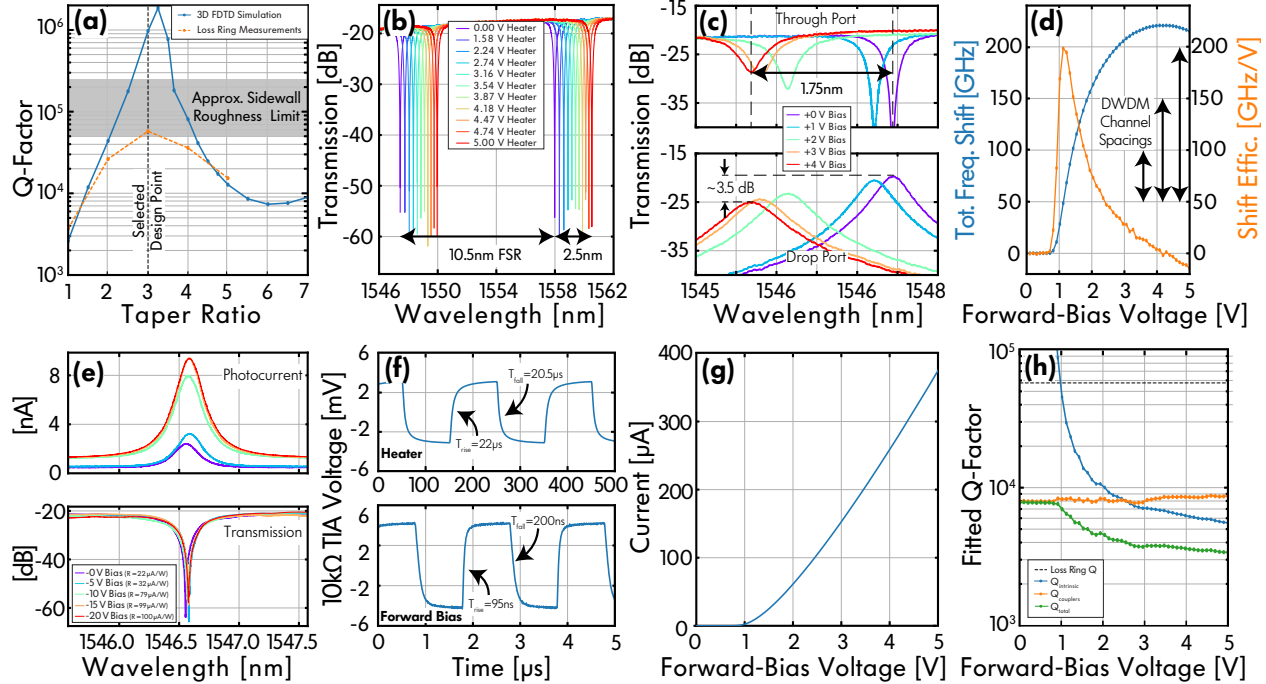


Fig. 2: (a) Device geometry optimization and measurements of intrinsic Q , (b) thermal tuning resonance shift via 450Ω microheater, (c) forward-bias-shifted transmission spectra on through and drop ports, (d) forward-bias total shift and shift efficiency, (e) reverse-bias responsivity, (f) large-signal time-domain electrical responses ($500\text{mV}_{\text{pk-pk}}$, $+1\text{ V}$ offset), (g) forward-bias IV curve, and (h) Q -factors fitted to add-drop resonator coupled-mode theory model vs. forward-bias shift.

from free-carrier absorption at low to moderate forward-bias voltages ($Q_{\text{intrinsic}}$ is limited by effects such as sidewall roughness rather than scattering losses at the contacts). They also achieve better mode confinement than rib waveguide microrings, allowing tighter bend radius and wider free spectral range. Additionally, our device reaches the same carrier density with much lower forward-bias current and power owing to the parallel direction of current flow relative to the propagation of the optical mode, resulting in more energy-efficient operation. A high-speed linear photodetector can be coupled to the drop port to create a receiver channel in a WDM link — Ge PDs with 0.9 A/W responsivity in O-band, 50 GHz bandwidth, and sub- 40 nA dark current are available in this process [4].

The two opposing single-mode coupling regions allow multiple adiabatic rings to be cascaded into coupled resonator optical waveguide (CROW) structures used for high-order pump cleanup and pump rejection filters in scalable integrated quantum photonics [8]. Under reverse bias they exhibit full carrier sweepout and achieve enough responsivity in C-band (up to $100\text{ }\mu\text{A/W}$ in add-drop configuration) to be useful for feedback-controlled filter alignment. The p-n junctions are designed with long, graded dopings to avoid punch-through at high reverse bias and reduce dark current by preventing high electric fields from developing in the heavily-doped contact regions where defect-assisted dark current mechanisms are exacerbated. This photosensing scheme is preferable to tapping off some light into linear photodetectors because it prevents free-carrier oscillations from developing at higher optical powers [9] while also improving the insertion loss to the drop port. We anticipate such adiabatic microring devices to find applications in future classical and quantum CMOS-photonics systems.

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References

1. M. Wade, *et al.*, “An Error-free 1 Tbps WDM Optical I/O Chiplet and Multi-wavelength Multi-port Laser” OFC, OSA, paper F3C.6 (2021).
2. J.W. Silverstone, *et al.*, “Silicon Quantum Photonics”, IEEE J. Sel. Top. Quantum Electronics 22, 390-402 (2016).
3. J. Carolan, *et al.*, “Scalable feedback control of single photon sources for photonic quantum technologies”, Optica Vol. 6, No. 3 (2019).
4. M. Rakowski, *et al.*, “45nm CMOS - Silicon Photonics Monolithic Technology (45CLO) ...” OFC paper T3H.3 (2020).
5. E. Timurdogan, *et al.*, “Adiabatic resonant microring (ARM) modulator”, OIC paper TuC6 (2012).
6. M. Georgas, *et al.*, “Addressing Link-Level Design Tradeoffs for Integrated Photonic Interconnects”, CICC, IEEE, pp. 1-8 (2011).
7. J.M. Shainline, *et al.*, “Depletion-mode carrier-plasma optical modulator in zero-change advanced CMOS”, Opt. Lett. 38, 2657-2659 (2013).
8. J.M. Fargas-Cabanillas, *et al.*, “Tunable Source of Quantum-Correlated Photons with Integrated Pump Rejection...”, FiO paper FTu2E.1 (2021).
9. Johnson, T. J. *et al.*, “Self-induced optical modulation of the transmission through a high-Q silicon microdisk resonator”, Opt. Express (2006).