Feedback-controlled resonance and temporal response modulations in silicon microring resonators

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Abstract: We report feedback-controlled electro-optically tunable resonances and time delay in silicon microring resonators. We demonstrate tunable extinction ratio of up to 25 dB and time delay modulation from 90 ps to 19 ps.

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Silicon microring resonators have been widely investigated for various applications including filters [1], modulators [2] and delays [3] due to their high quality factors and compact size. Conventionally, the resonance wavelength can be tuned by thermal-optical (TO), opto-optical (OO) and electro-optical (EO) effects. In order to control the resonance response, microring resonators with interferometric waveguide-coupled feedback has been proposed [4]. Over the past few years, various research groups have demonstrated different versions of interferometric feedback-controlled microring resonators but all adopted TO effect for tuning [5-7]. Compared with TO effect, EO effect by carrier plasma dispersion [8] enables faster speed and lower power consumption. Previously, our group demonstrated electrically-tunable silicon microring resonators with waveguide-coupled feedback for channel filter [9] and switch / modulator [10] applications. Here we report our latest progress in demonstrating feedback-controlled electro-optically tunable resonances and temporal response using silicon microring resonators with waveguide-coupled feedback.

![Feedback-controlled resonance and temporal response modulations in silicon microring resonators](image)

Figure 1 shows the schematic of the silicon microring resonator-based filter with waveguide-coupled feedback (U-bend) [9]. Both the microring and the U-bend waveguide are integrated with lateral p-i-n diodes and thus can be separately tuned by current injection upon free-carrier dispersion effect. Current injection to the microring resonator blueshifts the cavity resonance wavelength. Current injection to the U-bend waveguide modulates the feedback phase. The interference between the microring light field and the U-bend waveguide light field at the waveguide output-port yields the interferometric transmission that depends on the feedback coupling. Thus, both resonance wavelength and resonance transmission (intensity and phase response) can be electro-optically tuned using such waveguide-feedback coupled microring resonators.

We fabricated the device on a silicon-on-insulator (SOI) wafer with a 0.34-μm-thick silicon device layer on a 1-μm-thick buried-oxide layer. The rib waveguide and the microring have a designed waveguide width of 0.4 μm. The gap spacing between the waveguide and the microring is 0.35 μm. The racetrack microring is designed with arc radius of 15 μm and interaction lengths of 20 μm. The intrinsic region width of the embedded lateral p-i-n diode across the microring and the U-bend waveguide is 1 μm. The length of the U-bend waveguide is 180 μm with 87-μm of the waveguide integrated with a p-i-n diode. We define the device by i-line (365 nm) photolithography and etch by CF₃-based reactive-ion plasma etching. The fabrication process is therefore CMOS compatible. Figure 2(a) shows the optical micrograph of the fabricated device comprising the waveguide-feedback coupled microring resonator connected to an electro-optically tunable microring resonator notch filter without feedback waveguide. The two microring resonators are identically designed and this device was originally designed for clock recovery application [11]. Here we only use the waveguide-feedback coupled microring resonator to demonstrate our concept. Figure 2(b) shows the zoom-in view of the feedback-coupled device.
We measure the device optical intensity and temporal response spectra [4]. Figure 2(c) schematically shows the experimental setup. The laser output is modulated by a 1-GHz clock signal, which is generated by a network analyzer. An upstream erbium-doped fiber amplifier (EDFA) is used in saturation mode (~16 dBm saturation output power) to power-boost the modulated light before input-coupling to the bus-waveguide through a polarization-maintaining single-mode lensed fiber in order to compensate the fiber-to-waveguide insertion loss (~15 dB). We collect the device transmission by a lens system and amplify the light by another EDFA before the high-speed photodetector. We measure both the transmission intensity and phase response using the network analyzer. The temporal response is given as: 
\[ \Delta \tau = \Delta \phi / (2\pi f_{RF}) \]
where \( \Delta \phi \) is the phase change relative to the off-resonance wavelength and \( f_{RF} \) is the input radio-frequency (RF) signal frequency (1 GHz here).

Figure 3(a) shows the measured output transmission spectrum without any voltage supply. Resonance A at \(~1552.3\) nm belongs to the U-bend microring resonator, while resonance B at \(~1553.75\) nm belongs to the microring notch filter. We examine the resonance modulation by forward-biasing the p-i-n diode surrounding the U-bend waveguide. Figures 3(b)-(d) show the measured transmission spectra with voltage supply of 0.9 V, 1.0 V and 1.1 V. Depending on the bias voltage values, the resonance A lineshape and transmission intensity significantly vary. Notably, the resonance extinction ratio (ER) reduces from ~35 dB upon no bias to ~10 dB upon 1.1 V bias, while the resonance wavelength remains essentially intact.

Figures 3(e)-(h) show the corresponding temporal responses upon various bias voltages. For resonance A, we observe time delay for all the cases. The peak time delay reduces from ~90 ps upon 0-V bias to ~19 ps upon 1.1-V bias. This suggests that the feedback-coupled resonance is tuned from nearly critical coupling to under-coupling [12]. As references, the temporal responses for resonance B keep nearly unchanged for all the cases. We observe ~35-ps time advances, suggesting that the notch filter is over-coupled [12, 13]. Compared with our previous demonstration using only microring-based notch filters [12], where the carrier injection blueshifts the resonance wavelength, here our experiment reveals that the waveguide-feedback coupled microring resonator can modulate the resonance intensity and the temporal response, without resonance wavelength shifting. Moreover, we can modulate the resonance response from nearly critical coupling to other coupling conditions, which provides large response modulation upon relatively small bias voltages.

Another important merit of such U-bend waveguide-coupled microring resonators is that we can separately forward-bias the microring resonator to blueshift the cavity resonance wavelength and forward-bias the U-bend waveguide to tune the blueshifted resonance lineshape and temporal response. Figures 4 show the proof-of-concept demonstration of such wavelength-tunable feedback-controlled resonance lineshape and temporal responses. Figures 4(a)-(c) show the measured transmission spectra with different voltage supply schemes. With no voltage supply, the feedback-coupled microring cavity resonance is at ~1552.3 nm (resonance A). Upon a 0.8-V voltage supply to the microring resonator, the
resonance blueshifts by ~0.28 nm with an ER of ~50 dB. At the blue-shifted resonance wavelength C, we apply a 2-V forward bias across the U-bend waveguide and the resonance can be totally suppressed.

Figures 4(d)-(f) show the corresponding measured temporal responses. At resonance C, we observe ~85-ps time advance when we only bias the microring resonator. With the additional 2-V bias voltage applied across the U-bend waveguide, we obtain all-pass transmission without any time delay or advance.

Our demonstration shows two key advantages of the feedback-controlled microring resonator over the conventional microring notch filter: 1) given the waveguide-coupled feedback, we can modulate the resonance intensity and temporal response with large tuning range while upon relatively small bias voltage; 2) the intensity and temporal response modulation by current injection into the feedback waveguide and the resonance wavelength tuning by current injection into the microring resonator can be independently realized. Moreover, the EO effect by carrier plasma dispersion endows the feedback-controlled modulation with high speed. The research work on the modulation bandwidth is ongoing. It is conceivable that the feedback-controlled microring resonator can be a versatile building block for applications including reconfigurable filters, modulators, optical variable attenuators and tunable optical time delay and advance.

In summary, we investigated feedback-controlled electro-optically tunable silicon microring resonators with waveguide-coupled feedback. We demonstrated extinction ratio modulation from 35 dB to 10 dB and time delay modulation from 90 ps to 19 ps at a single wavelength. We also demonstrated at a blueshifted resonance wavelength we can totally suppress the resonance with a 50 dB modulation in extinction ratio and a modulation of 85 ps in time advance.

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