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# Sub-wavelength silicon grating metamaterial ring resonators

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**Abstract**— We report on experimental results of silicon micro-ring resonators based on non-resonant photonic metamaterial waveguides. High extinction ratio up to 30 dB and loaded Q-factors in a range of 1500 to 6000 were achieved at a wavelength of 1550nm.

**Keywords**— Ring resonators, silicon photonics, silicon-on-insulator, sub-wavelength grating metamaterials, nanophotonics

## I. INTRODUCTION

Micro-ring resonators implemented on the well-established silicon-on-insulator (SOI) technology are recognized to be fundamental building blocks for multitude of complex photonic components [1-8]. This includes both passive and active devices such as filters [3], modulators [4], detectors [5], or sensors [6,7]. Most of ring resonators realized on conventional strip-like SOI waveguides can afford high quality factors (Q-factor) and low-loss propagation due to the high modal confinement, enabled by large index contrast of SOI platform. Conversely, this tight optical mode confinement imposes fundamental limitations to explore light-matter interactions with the surrounding environment (claddings).

In order to complementary combine a good mode confinement as well as a good mode interaction with the surrounding medium sub-wavelength grating (SWG) nanostructuring of regular Si waveguides can be developed [3,6-12]. SWGs, non-resonant nanophotonic structures of dimensions at a scale below the wavelength of light, allow local control of a variety of propagation properties. As demonstrated, this strategy opened up a promising way towards advanced Si photonic devices, typically achieving performances that substantially outperform their conventional counterparts [9-12]. More recently, only few research works have investigated the potential of SWG metamaterial waveguides to build micro-ring resonators [3,6-8], demonstrating promising prospects for enhanced on-chip functionalities.

Here, we report on experimental demonstration of SOI micro-ring resonators with SWG nanostructuring. The fabricated devices showed a high extinction ratio up to 30 dB and loaded Q-factors up to ~6000.

## II. DESIGN AND FABRICATION

The ring resonator based on SWG metamaterials is schematically shown in Fig. 1a. Devices are implemented on SOI platform, with 220-nm-thick Si and 2- $\mu$ m-thick

buried oxide (BOX) layers. The ring resonator geometry comprises nominal waveguide width  $W = 500$  nm. The SWG structure is formed by interlacing Si blocks of length  $L_b$  and fully etched trenches of length  $L_t$ . The SWG pitch  $\Lambda = L_b + L_t$  is sufficiently small, thereby frustrating the diffraction. The SWG duty cycle is defined as  $DC = L_b/\Lambda$ . The ring radius is denoted  $R$  and the coupling gap is  $G_c$ . For SWG pitch of 200 nm, and wavelength around 1.55- $\mu$ m, the structure operates at deep SWG regime and mimic optically equivalent strip waveguide of reduced refractive index. By alternating the geometry of SWG metamaterial waveguides, optical properties of this non-resonant photonic waveguides such as refractive index, modal confinement, mode profile as well as dispersion can be judiciously controlled.

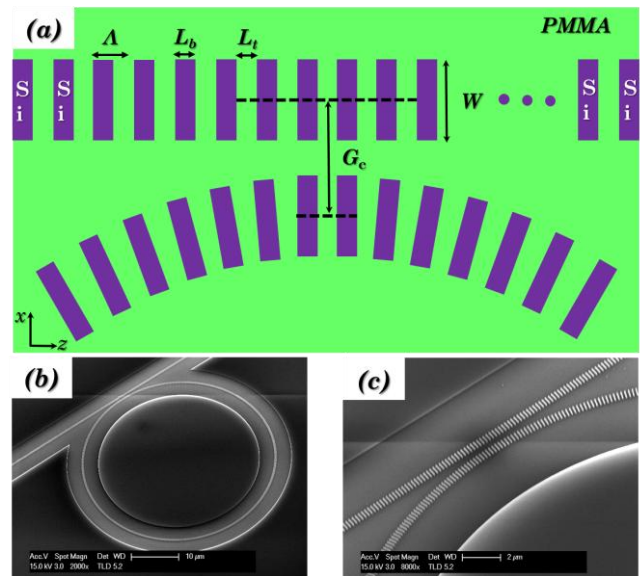


Fig. 1 (a) In-plane schematic view of the SWG-based micro-ring resonator and the bus waveguide. (b) and (c) Scanning electron microscopy images of fabricated device prior to the deposition of upper cladding (PMMA).

We estimated both effective and group indices of such SWG metamaterial waveguides used in ring resonators. Simulations were carried out using two-dimensional (2-D) mode solver, utilizing Finite Element Method (FEM). Figure 2a shows the evolution of the calculated free spectral range (FSR) as a function of wavelength for different ring radii ( $R = 10$ -;  $20$ -; and  $30$ - $\mu$ m) and its comparison with experimentally retrieved values. From Fig. 2a, it can be observed that the performed calculations and experiments

are in excellent agreement. This clearly confirms the expected trends of ring resonators based on non-resonant metamaterial waveguides.

Ring resonators were fabricated on standard SOI substrates, with 220-nm Si and 2- $\mu$ m BOX layers, using single-etch step process. The devices were first patterned by using electron beam lithography, with a 5 nm writing pitch. The pattern was then transferred onto the top Si layer using reactive ion etching. The PMMA was deposited on top of fabricated structures using spin coating to achieve a 3- $\mu$ m-thick overlayer. The scanning electron microscopy (SEM) images of fabricated SWG-based ring resonators before the deposition of the upper cladding are shown in Fig. 1b and c, respectively.

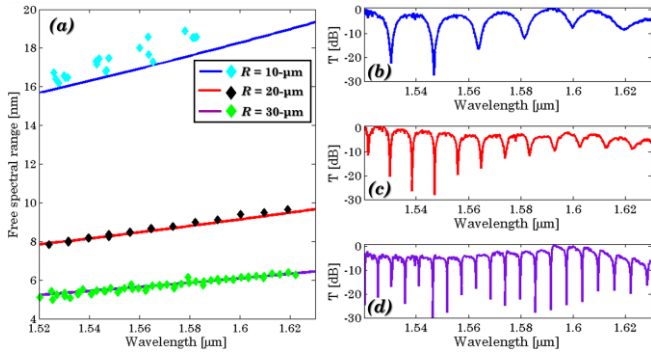


Fig. 2 (a) Simulated (lines) and measured (markers) free spectral range as a function of wavelength for SWG ring resonators of different radii. Normalized transmission spectral response of a SWG ring resonator, with (b)  $R = 10\text{-}\mu\text{m}$ , (c)  $R = 20\text{-}\mu\text{m}$ , and (d)  $R = 30\text{-}\mu\text{m}$ .

### III. OPTICAL PERFORMANCE

In order to facilitate optical testing, we performed back-to-back transmission characterization. The light coming from the tunable laser source (1520-1630 nm, swept with a resolution of 10 pm) was coupled via single-mode optical fiber to and from the Si chip using SWG-engineered surface grating couplers. These were optimized for transverse electrical (TE) polarization and operation near the wavelength of 1.55  $\mu$ m [12]. Mode size transformers were employed to provide smooth transition between the conventional Si strip waveguide and the patterned bus metamaterial waveguide [9]. The pitch and duty cycle of the converter were 200 nm and 50%, respectively. The width of the central strip was varied from 500 nm down to 150 nm, along the 45- $\mu$ m-long tapering section.

Figs. 2b-d show measured transmission spectra for different ring resonators of different radii based on SWG metamaterial waveguides. Here, the transmission spectral response was normalized to the response of SWG-engineered surface grating couplers. It can be seen that high extinction ratio was achieved, up to  $\sim 28$  dB. In order to determine the full width at half maximum, and subsequently, to estimate the Q-factor from the measured SWG ring resonators, the transmission spectral responses were fitted to a Lorentzian function using a least-square fitting approach. Different way of estimating FWHMs and Q-

factors was reported in Ref. [3,8], yielding a comparatively different value of those parameters. Figure 3a-c shows the normalized transmission spectral responses nearby the respective resonance wavelengths, for different SWG-based ring resonators, with ring radii of 10-; 20-; and 30- $\mu$ m. The estimated loaded Q-factor is in range of  $\sim 1700$  to  $\sim 6000$ .

Since, the SWG nanostructuring of Si waveguides affords additional design freedom to control all relevant propagation properties such as mode profile and confinement as well as refractive index and overall waveguide dispersion, we are working on improving both the ring resonator designs as well as fabrication fidelity to explore the true potential of SWG-based resonant components.

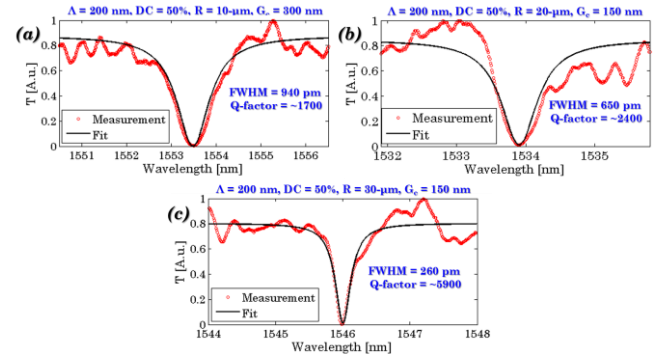


Fig. 3 Normalized transmission spectrum to the respective resonances of various SWG-based ring resonators. Resonance wavelength: (a)  $\lambda_0 = 1553.500$  nm, (b)  $\lambda_0 = 1533.900$  nm, and (c)  $\lambda_0 = 1546.020$  nm.

### IV. CONCLUSION

In this work, we experimentally demonstrated the SOI micro-ring resonators based on non-resonant SWG metamaterial waveguides. The fabricated devices shown a high extinction ratio as high as -30 dB and loaded Q-factors up to  $\sim 6000$ .

### ACKNOWLEDGMENTS

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