Novel Ring Resonator Combining Strong Field Confinement With High Optical Quality Factor

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***Abstract*— Slot waveguide ring resonators appear promising candidates for several applications in silicon photonics. Strong field confinement, high device tunability, and low power consumption are beneficial properties compared with strip waveguides. Slot waveguide ring resonators suffer, however, from rather low optical quality factors due to optical losses. This letter proposes and experimentally demonstrates a novel concept based on a partially slotted ring and a strip-to-slot mode converter. An exceptional high quality factor of ~10^5 has been measured.**

***Index Terms*— Silicon photonics, nanophotonics, optical waveguides, semiconductor waveguide, optical resonators, resonator filters.**

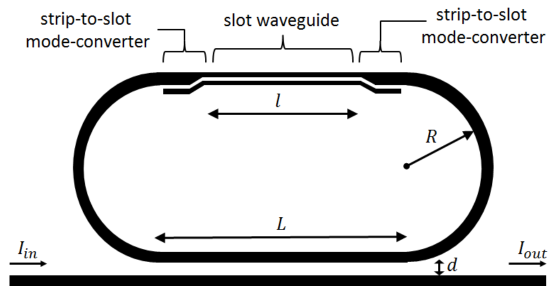

Fig. 1. Schematic of a partially slotted ring resonator.

I. INTRODUCTION

SILICON based micro-ring modulators have high potential in the field of optical switching and modulation. They are known to exhibit high-speed operation [1], [2], small bending radii and accordingly small footprints [3], [4]. The phase shift in such ring resonators is primarily induced by exploiting the plasma dispersion effect since the Pockels effect, Kerr effect, and Franz-Keldysh effect are too weak in silicon [5], [6]. For several applications higher optical field confinement and higher tunability with low power consumption are desirable. Perhaps the most important limitation of free-carrier plasma dispersion based ring resonator modulators is the device tunability. Therefore a different approach based on slot waveguide structures has been proposed and experimentally demonstrated [7]. This silicon-organic hybrid technology [8], [9] allows the use of electro-optical polymers with large Pockels coefficients and hence higher device tunability.

However, slot waveguide structures suffer from relatively high losses, mainly caused by sidewall roughness and Free Carrier Absorption (FCA) [10], [11]. As a consequence, slot waveguide ring resonators have typically small optical quality factors (Q-factors) [7], [12], [13].

To overcome this deficiency we propose a novel concept where the ring resonator is only partially slotted. To demonstrate the potential of the concept we present a suitable design, realized on 200 mm silicon-on-insulator wafers using 248 nm DUV lithography.

II. DEVICE FABRICATION AND OPTICAL CHARACTERIZATION

A scheme of the partially slotted ring resonator geometry is shown in Fig. 1. Strip-to-slot mode-converter are used to couple the light from the strip waveguide into the slot waveguide [14]. The length of the strip-loaded slot waveguide is $l = 12$ μm and the length of the strip-to-slot mode-converter is 8 μm. A detailed cross sectional view of the strip-loaded slot waveguide structure is shown in Fig. 2. The strip-loaded slot waveguide consists of two silicon rails with a standard silicon-on-insulator height of $h_r = 220$ nm. Both silicon rails are located on top of a 2 μm buried oxide substrate. The coupling length, coupling distance, waveguide width, slot width, and silicon strip-load height are $L = 28$ μm, $d = 200$ nm, $w = 500$ nm, $s = 60$ nm and $h_l = 50$ nm, respectively. With the ring radius $R = 20$ μm the total circumference results in $C = 182$ μm which is comparable with pure silicon rib waveguide based ring resonator modulators [15]. The slot waveguide structure is located inside a trench as illustrated

Manuscript received May 12, 2015; revised June 19, 2015; accepted July 10, 2015. Date of publication July 14, 2015; date of current version September 17, 2015. This work was supported by the German Federal Ministry of Education and Research under Contract 03FH086PX2.

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Digital Object Identifier 10.1109/LPT.2015.2456133

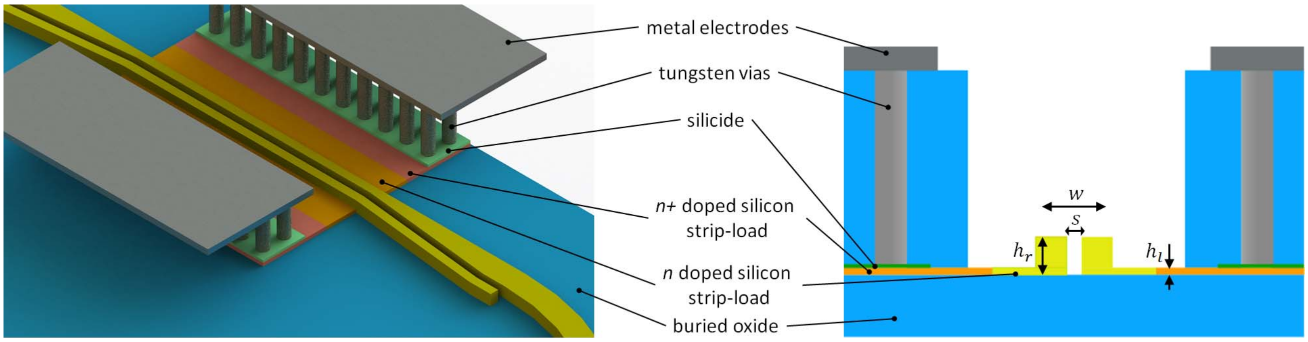

Fig. 2. Detailed schematic of the strip-loaded slot waveguide part of the ring resonator and cross sectional diagram including electrical contacts (not to scale).

in Fig. 2. This allows the functionalization of the slot with an organic electro-optic material [16]. For the purpose of optical characterization of this resonator structure we used air as cladding material.

The slot waveguide is electrically connected to ground-signal-ground aluminium electrodes through doped silicon strip-loads and tungsten contacts (see Fig. 2). In order to improve connectivity and conductivity, a thin silicide intermediate layer was used to connect the tungsten contacts to the doped silicon for an ohmic contact.

The silicon strip-loads were etched remaining a silicon slab height of $h_l = 50$ nm and additionally n^+-implanted to decrease the electrical sheet resistance. In order to avoid excessive FCA losses, the doping concentration was reduced close to the slot waveguide structure (n-implanted). Scanning-electron microscopic images of the top view of the fabricated ring resonator are shown in Fig. 3.

The transmission spectra of the fabricated devices were obtained by a testing platform using a tunable external cavity laser (ECL) as light source with a bandwidth of < 1 pm and maximum output power of 14 dBm. During the measurements, the temperature of the photonic chip was stabilized to 35 °C using a hot plate in order to avoid changes in the transmission due to temperature fluctuation. Laser light was coupled into the silicon-on-insulator waveguides through a grating coupler [17]. The polarization of the input light was controlled using a paddle style fiber polarization rotator.

III. Results and Discussion

Fig. 4 shows the observed transmission spectrum of the ring resonator. The ECL was swept from 1520 nm to 1580 nm. The gradual increase of the peak intensity reflects the wavelength dependent coupling efficiency. From the spectra we derive a free spectral range of ~ 3.4 nm and a line width (Full Width at Half Maximum) at the center wavelength $\lambda_c = 1573.58$ nm of $\delta\lambda = 15$ pm (± 2 pm). The Q-factor is determined by $Q = \lambda_c/\delta\lambda$, yielding a value of $\sim 10^5$. It drastically exceeds the values for conventionally slotted waveguide ring resonators, reported so far [12]. Instead it is close to the Q-factors, published for strip ring resonators, suggesting that the induced losses are rather small for the partially slotted ring design, presented here.

Using electro-optic chromophores or organic crystals as cladding material instead of air, the wavelength shift and therefore the device tunability is expected to be higher compared to free-carrier plasma dispersion based phase shifters [18], [19]. In order to give an estimate on the expected device tunability using organic materials as cladding instead of air we calculate the wavelength shift by

$$\Delta\lambda = \frac{n_{clad}^3}{2} \cdot r_{33} \cdot U \cdot \frac{l}{s} \cdot \Gamma_{slot}, \qquad (1)$$

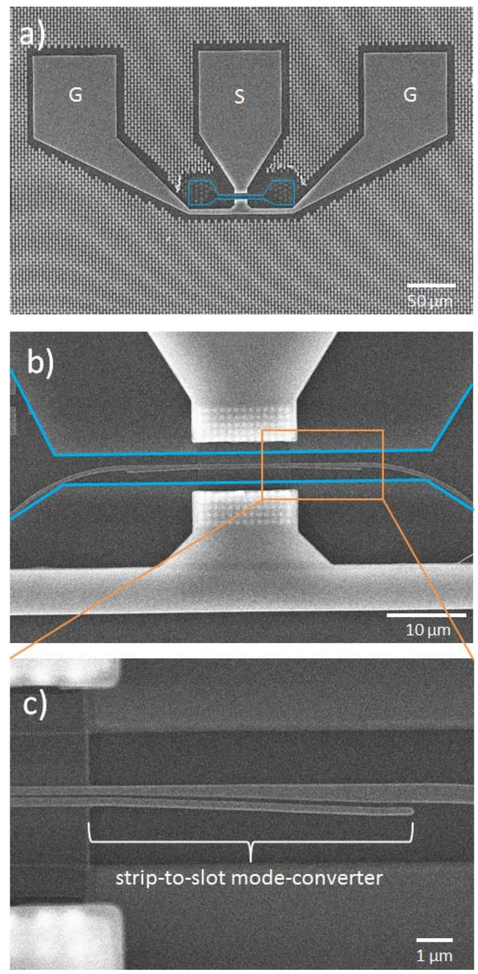

Fig. 3. Scanning-electron microscopic images: a) Ground-Signal-Ground (GSG) aluminium electrode from the top view with a trench (highlighted in blue) for the possibility to functionalize the slot waveguide with an organic cladding material. b) Part of the ring resonator with strip-to-slot mode-converter and strip-loaded slot waveguide. c) Magnification of the strip-to-slot mode-converter for the 60 nm slot waveguide.

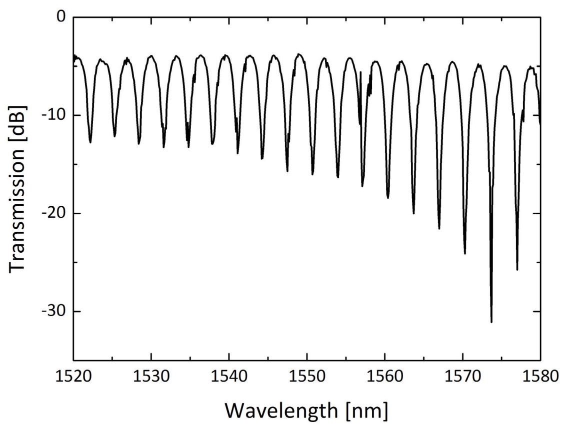

Fig. 4. Transmission spectra of a partially slotted ring resonator with air cladding. The free spectral range is $\sim$ 3.4 nm and the line width at $\lambda_c = 1573.58$ nm is $\delta\lambda = 15$ pm (± 2 pm).

where U is the applied voltage, n_{clad} is the cladding refractive index, and Γ_{slot} is the field confinement factor of the slot region [20]. The field confinement factor is usually defined as the ratio of the time averaged power flow in the slot area (A_{slot}) to the time averaged power flow in the total area (A_{tot})

$$\Gamma_{slot} = \frac{\displaystyle\int\int_{A_{slot}} Re\{[\mathbf{E} \times \mathbf{H}^*] \cdot \mathbf{e}_z\}\, \mathrm{d}x\mathrm{d}y}{\displaystyle\int\int_{A_{tot}} Re\{[\mathbf{E} \times \mathbf{H}^*] \cdot \mathbf{e}_z\}\, \mathrm{d}x\mathrm{d}y}. \quad (2)$$

E and H are the electric and magnetic field vectors, respectively, and e_z is the unit vector in z direction [21]. We employed a full-vectorial 2D finite element method based mode solver to calculate the field confinement factor. For the slot waveguide geometry presented here the field confinement factor is $\Gamma_{slot} \approx 0.2$ [22]. Assuming a moderate Pockels coefficient of $r_{33} = 10$ pm/V, a refractive index of $n_{clad} = 1.5$ and a voltage of $U = 1$ V, a wavelength shift around $\Delta\lambda = 675$ pm can be expected for the ring resonator presented here.

This estimate fits reasonably well preliminary experiments, using Poly[(methyl methacrylate)-co-(Disperse Red 1 acrylate)] as cladding material. With DC driving voltages ranging from -7 V to $+7$ V we obtained an approximately linear wavelength shift of ~ 480 pm/V.

It should be mentioned that the current resonator design was chosen with intent to achieve the maximum slot waveguide length compatible with the device geometry. Although the presented data are promising, it must not necessarily be optimal. Smaller slot waveguide lengths would result in increased Q factors at the expense of tuning range and driving voltage. The best compromise depends on the intended use.

The proposed concept can also be adopted for on-chip sensor applications. Slot waveguide ring resonators are shown to be suitable for biosensing because the guided light can interact directly with the analyte [13]. Since the partially slotted ring resonator has a high Q-factor, it improves the sensitivity of such sensors because the impact of noise on the determination of the resonance wavelength will be reduced [23].

IV. Conclusion

In summary, we have proposed, fabricated, and characterized a novel resonator design based on a partially slotted ring. As demonstrated here, our design provides advantages compared to existing slot waveguide technology in terms of high Q-factors, small bending radii and accordingly high compactness. This approach appears to be promising for various fields of applications like integrated optoelectronics and on-chip sensor technology. In particular, the proposed design will be useful for integrated silicon-organic hybrid photonic devices such as optical switches, modulators, and tunable filters by using electro-optical polymers as cladding material.

Acknowledgment

The authors thank F. Nanni, P. Prosposito, F. De Matteis, and R. De Angelis from the University of Rome Tor Vergat, Italy, and A. Al-Saadi from the Technical University Berlin, Germany, for their encouragement. Furthermore, they thank J. Katzer, H. Silz, L. Zimmermann, B. Tillack and W. Mehr from the Institute of High-Performance Microelectronics (IHP), Germany, for their support in the framework of the Joint-Lab IHP/TH Wildau.

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