Optical nonlinearity enhancement in a silicon-organic hybrid slot microring resonator

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***Abstract*—Silicon photonic integrated devices that rely on optical nonlinear effects play a vital role in all-optical signal processing, optical computing, optical routing and so on. However, the practical use of these devices is limited due to the low Kerr nonlinear index of silicon and high nonlinear loss associated with two-photon absorption (TPA) and TPA-induced free carrier absorption (FCA) in the near-infrared band. In this paper, we propose and numerically demonstrate the optical nonlinear enhancement of silicon-organic hybrid slot microring, which consists of an ultra-narrow slot micro-ring coated with highly nonlinear organic material MEH-PPV. The degenerate four-wave mixing (DFWM) spectra show that the FWM conversion efficiency is improved by 12 dB compared to a silicon microring of the same size. This improvement further indicates that the nonlinear coefficient of the proposed device is up to 1.45 × 10^{6} W^{-1}km^{-1}. We show that this device's nonlinear enhancement capability has great potential for applications in all-optical signal processing, high-performance optical switching and optical computing.**

***Keywords*—silicon photonics, optical nonlinear device, organic material, slot microring, four-wave mixing, optical signal processing**

I. Introduction

Optical nonlinearity plays a critical role in the rapid development of information and communication applications, such as in all-optical signal processing, optical routing, and non-reciprocal devices [1]. Highly nonlinear devices are essential to improve the performance of these applications. Among the many nonlinear devices, silicon photonic integrated devices have attracted considerable attention due to their small size, low cost, high integration density, and compatibility with conventional metal oxide semiconductor (COMS) platform. Particularly, microring resonators (MRR) based on silicon-on-insulator (SOI) enable flexible resonant wavelengh, Q-factor, and free-spectral range (FSR), which can offer intensive optical nonlinearity associated with the high-quality resonance.

While silicon microring has been a widely used device for nonlinear processes, the inherent low Kerr index and high loss caused by TPA and FCA limit the operating speed of the devices [2]. The use of highly nonlinear organic polymers, which have high nonlinear Kerr indices and negligible nonlinear absorption coefficients, in conjunction with silicon has recently gained popularity as a solution to improve the nonlinear effect of silicon devices [3]. Consequently, silicon-organic hybrid (SOH) nanostructures offering enhanced third-oder nonlinear effect, such as four-wave mixing, make the ultrafast signal processing or large-capacity optical computing highly feasible. In our previous work[6], we experimentally demonstrated a SOH slot waveguide for 40 Gb/s all-optical logic operations. With a length of 3 mm, the proposed device exhibited a DFWM conversion efficiency improvement of more than 5 dB compared to that of the bare waveguide with the same length. Such high nonlinearity primarily benefits from the nonlinear organic material 2-methoxy-5-(2-ethylhexyloxy)-1,4-phenylvinyl (MEH-PPV) [4], whose Kerr index almost 20 times the value of silicon, and the 50 nm ultra-narrow slot which intensively confined the optical field in the polymer filled gap. However, there is still potential for further optimization of the device size and nonlinear characteristics.

In this work, we propose and numerically demonstrate a highly nonlinear silicon-organic hybrid slot microring resonator (SOHSMRR) with a nonlinear coefficient of 1.45 × 10^{6} W^{-1}km^{-1}, which is slightly higher than that of our previous work, but the radius of the SOHSMRR is only 30 μm. Compared to a bare MRR of the identical radius with a strip waveguide, the DFWM conversion efficiency obtained from the proposed SOHSMRR is increased by over 7.5 dB. These results suggest that the device's ability to enhance nonlinear effects has significant potential for use in high-performance optical signal processing, optical routing systems and optical computing.

II. Device Design And Theory

A. Devices design

The device model of our SOHSMRR is presented in Fig. 1(a). The SOHSMRR, fabricated on a SOI wafer with a top silicon thickness of 220 nm (h_{si}), features an ultra-narrow slot that allows for highly efficient light confinement. In comparison, a common bare all-pass microring is shown in Fig. 1(b). Fig. 1(c) illustrates the electric field of the SOHSMRR with a 300 nm thick (h_{poly}) nonlinear polymer

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layer, where most of the light is confined in the organic slot, resulting in weak TPA and FCA within the silicon waveguide.

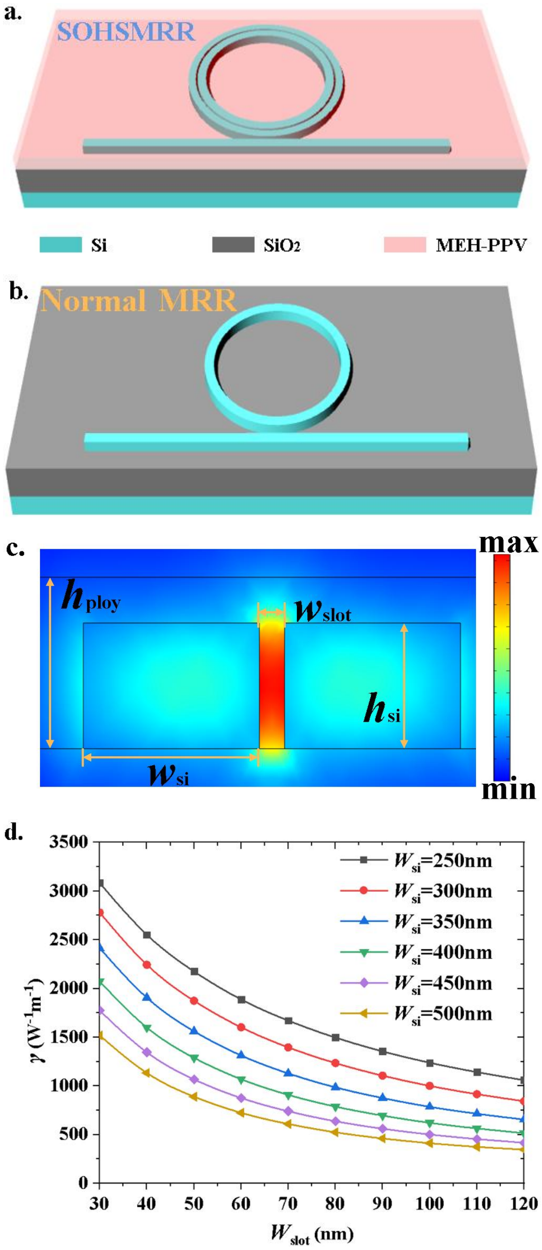


Fig.1. (a) Schematic diagram of the highly nonlinear SOHSMRR and (b) common bare all-pass MRR. (c) Normalized electric field distribution of SOHSMRR. (d) Evolution of the nonlinear coefficient γ with various slot widths for different waveguide widths.

The nonlinear coefficient γ of SOHSMRR can be calculated for each material and scaled by the respective fractional energy $E_{f,q}$ of the corresponding material. Thus, γ can be expressed as:

$$\gamma=\sum\gamma_q\cdot E_{f,q} \qquad (1)$$

with γ_q defined as:

$$\gamma_q=\omega n_2/(cA_{eff}) \qquad (2)$$

where ω is the angular frequency of the incident light, n_2 is the nonlinear Kerr index of the material, and A_{eff} denotes the effective mode area corresponding to each material of the device.

As depicted in Fig. 1(d), the evolution of γ is calculated as a function of the slot width (w_{slot}) with various waveguide widths (w_{si}) ranging from 200 nm to 500 nm. It is evident that γ strongly relies on w_{slot} for all waveguide widths, where γ shows a nearly exponential decay with the increasing w_{slot}. Notably, the enhancement of γ is more pronounced when the w_{slot} is less than 60 nm, which is attributed to the tighter optical field confinement in the slot. Additionally, the magnitude of the entire curve rises as the waveguide width decreases. This is ascribed to the relatively higher fractional energy in the MEH-PPV cladding associate with the lower total energy in the device as the silicon waveguide becomes narrower. Considering the practical fabrication conditions, the SOHSMRR is designed to be w_{si}=350 nm, w_{slot}=50 nm and h_{poly}=300 nm.

B. *Numerical mode*

The nonlinearity enhancement in SOHSMRR is numerically analyzed through the conversion efficiency of the DFWM with two continuous waves. Based on the DFWM, the nonlinear coefficient γ of the MMR resonator can be determined as follows [5]:

$$\eta=\gamma^2P_p^2L_{eff}^2F_p^4F_s^2F_c^2exp(-\alpha L) \qquad (3)$$

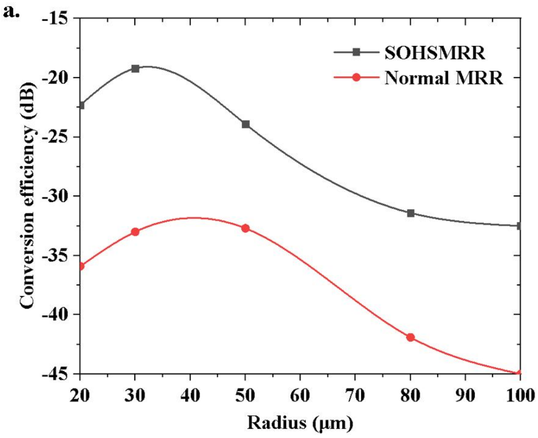
where η denotes the conversion efficiency of DFWM, which is defined as the power ratio of converted idler to the input signal. α is the transmission loss, including both linear and nonlinear losses. P_p is the pump power coupled into the microring. $F_{p,s,c}$ are the field enhancement factors of the pump, signal and converted idler, respectively. L and L_{eff} are the respective actual and effective MRR lengths. L_{eff} is further expressed as:

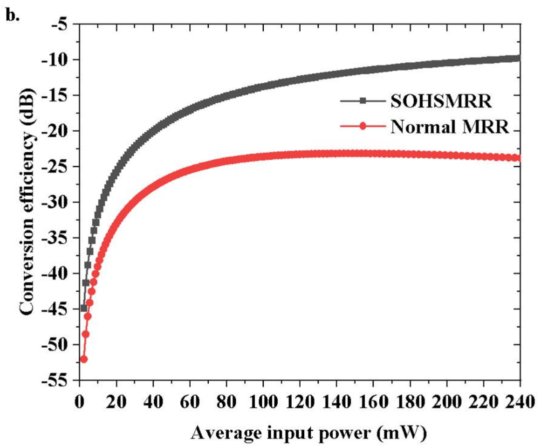
$$L_{eff}=|(1-exp[-(\alpha+i\Delta\beta)L])/(\alpha+\Delta\beta)| \qquad (4)$$

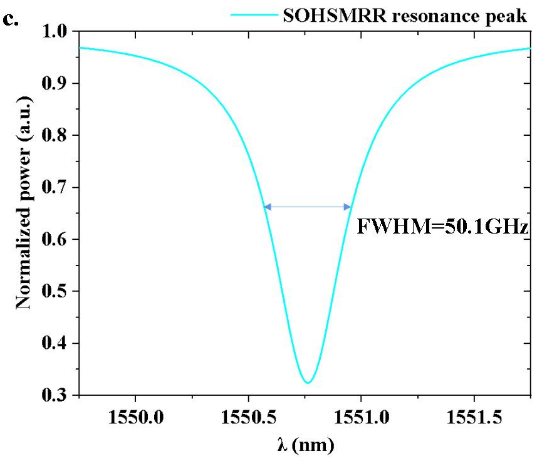
where $\Delta\beta$ is the total phase mismatch between the signal and idler, which can be calculated applying the vector finite difference modesolver [4]. Parameters used to calculate the DFWM conversion efficiency of SOHSMRR and bare common MRR can be found in our previous work [6].

III. Simulation Results And Discusion

Fig. 2 displays the simulation results. In Fig. 2(a), the conversion efficiency is shown as a function of the ring radius, which ranges from 30 to100 μm in the simulation. At a fixed input power is 20 mW (13 dBm), the conversion efficiency of the device exhibits a non-monotonic dependence on the radius. This is because of the interplay between light-matter interaction and loss mechanisms. Based on practical constraints such as device footprint, FWM efficiency and design feasibility, the results suggest that the optimal radius of 30 μm can be adopted. Fig. 2(b) depicts the DFWM conversion efficiencies of both nanostructures with various average input powers . For the normal MRR, the FWM conversion efficiency initially increases with the input optical power, but then decreases due to the dominant nonlinear loss caused by TPA and FCA. On the contrary, the conversion efficiency of the SOHSMRR keeps rising within the tolerable optical power range, which should be less than 19 dBm according to our previous work. The robust nonlinearity improvement in SOHSMRR is attributed to the optical field enhancement at the resonant wavelengths of the ring, of which the optical field is concentrated in the polymer-filled slot and the nonlinear loss can be safely ignored. With the average input power of 19 dBm, the FWM conversion efficiency of SOHSMRR is up to -13 dB, exhibiting an increase of 12 dB compared to the normal MRR. Fig. 2(c)-2(d) reveal that the full width half maximum (FWHM) of the resonances for both structures is equal to or more than 50 GHz, rendering them well-suited for the high-speed optical signal processing applications exceeding 40 Gb/s.







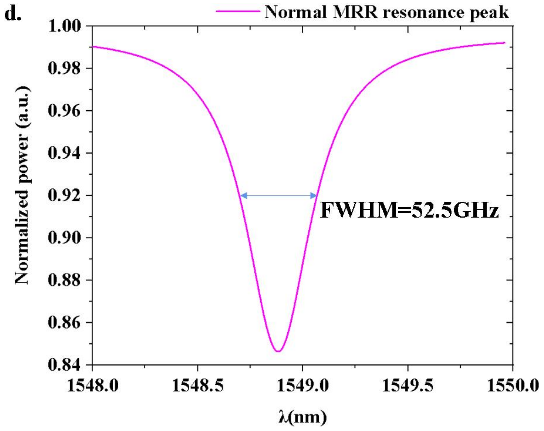


Fig.2 FWM conversion efficiency as a function of (a) different ring radiuses and (b) various average input powers of SOHSMRR (red curve) and normal bare MRR (black curve). Resonance spectra of the (c) SOHSMRR and (d) normal bare MRR.

IV. CONCLUSION

In summary, we propose and numerically demonstrate a highly nonlinear silicon-organic hybrid slot microring resonator. The simulation results show that the SOHSMRR significantly enhances the nonlinear effect of the device. The ultra-strong light confinement achieved through the polymer-filled slot allows for an efficient light-matter interaction. Additionally, the microcavity nanostructure results in field enhancement at the resonant wavelengths, further improving the nonlinear property. Compared to a normal bare MRR with the same radius, our device yields a 12 dB increase in the DFWM conversion efficiency. The proposed SOHSMRR has potential applications in high-speed optical signal processing, optical communications, and high-performance computing.

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