Compact multimode silicon-nitride waveguide micro-ring resonator with high-Q

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***Abstract*—A high Q racetrack micro-ring resonator (MRR) with ultralow propagation loss silicon-nitride waveguide is demonstrated by shaping the mode using a uniform multimode structure. They MRR is fabricated by the widely used LAT process. Results show that the Q factor of the specially designed MRR is significantly increased to more than 5 times higher order and reached 10.3 million for the first time.**

Keywords—Micro-ring resonator, high-Q, Silicon-nitride

I. INTRODUCTION

The silicon nitride (Si_3N_4) is an excellent photonic platform due to its wide transparency range, high refractive index, compatibility with large-scale semiconductor manufacturing, and ultra-low loss [1]. On-chip micro-ring resonators (MRRs) based on low propagation loss and large free spectral range (FSR) are important to many photonic devices, including microwave photonic filters (MPFs) [2], optoelectronic oscillators (OEOs) [3], and optical frequency combs [4]. However, due to the lithography and etching process in fabrication, the generated sidewall roughness induces high scattering loss and usually dominates the propagation loss of the waveguide. Therefore, the Q factors of the fabricated MRRs are usually limited by the scattering loss.

To increase the Q factors of MRRs, several approaches have been proposed. The ultra-high-Q MRRs can be achieved by using a weak optical confinement waveguide, which is less sensitive to the sidewall roughness. However, it relies on a large mode volume, weak constraint, and millimeter-scale bending radii [5]. For compact photonic routing or nonlinear applications requiring dispersion engineering, high confinement waveguides with low propagation loss are significantly desired. In parallel, thick Si_3N_4 of ultra-low loss are realized by introducing complex fabrication processes to reduce the scattering points at the interfaces, such as optimized etching [6], reflowing resist masks [7], and chemical mechanical planarization (CMP) [8]. So far, it is still challenging to develop an optimized fabrication process for different material platforms to achieve ultra-smooth interfaces, and all these reported high-Q MRRs are fabricated in laboratories.

Here, we propose and demonstrate an ultra-high-Q MRR based on high confinement Si_3N_4 waveguide. By using the multimode waveguide Euler-bends to achieve compact footprint and directional coupler (DC) to achieve adiabatic propagation, only the fundamental mode is excited with ultra-low loss. The MRR is fabricated by the widely used LIGENTEC-AN800 technology (LAT) and feature a footprint of only 2.226 mm, corresponding to the FSR of 65 GHz, and the intrinsic Q is more than 10 million. Compared with previously reported results, the Q factor is increased by more than five times higher order and reached 10.3 million for the first time. The ultra-low loss MRR is crucial for large-scale on-chip integrated devices.

II. PRINCIPLE

Fig. 1(a) shows the schematic diagram of the designed ultra-high-Q racetrack resonator based on a uniform multi-mode Si_3N_4 waveguide. The racetrack MRR is composed of two multi-mode straight waveguides (MSWs) and two multi-mode waveguide bends (MWBs) based on modified Euler curves. A DC is used to couple the light from the bus waveguide to the MRR. The wafer is with an 800-nm-thick Si_3N_4 layer and a 4-μm-thick buried-oxide layer. A 3.3-μm-thick silica thin film was deposited on the top as the upper cladding. We use $n-w$ model to analyze the scattering loss, which provides a comprehensive analysis of the fundamental role played by the sensitivity of the effective index of the optical mode to waveguide width variations [9]. From Fig. 1(b), we can see that the scattering loss decreases with the increase of waveguide core width W_{co}. When σ = 2.5 nm and Lc = 50 nm, the scattering loss are approximate 18 dB/m and 3.0 dB/m for the waveguide width of 0.8 and 3 μm, respectively. Therefore, the waveguide width W_{co} of MRR is designed to be 3 μm. Additionally, the DC-based multi-mode waveguides should also be carefully designed to ensure

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adiabatic coupling for the fundamental mode. From Fig. 2(c) we can see that the optical coupling only occurs for the fundamental mode, and higher-order modes are well suppressed, when the coupling length L_{DC} = 400 μm and the coupling gap w_{gap} = 0.8 μm. We choose the modified Euler-bend function for changing the bending radius to provide a high degree of adiabaticity and compact footprint. The Euler-bend is defined as [10]

$$\frac{d\theta}{dL}=\frac{1}{R}=AL+\frac{1}{R_{\max}}, \tag{1}$$

and

$$A=(\frac{1}{R_{\min}}-\frac{1}{R_{\max}})/L_0, \tag{2}$$

where θ is the center angle corresponding to the unit arc length, L is the arc length of the curve, R is the radius of curvature of the arc, A is a constant, L_0 is the arc length of the quarter Euler curve, $R_{\max}$ and $R_{\min}$ are the maximal and the minimal radii of the Euler curve, respectively. Fig. 2(d) shows the simulated light propagation field in the 180° Euler MWBs when $R_{\max}$ = 4000 μm and $R_{\min}$ = 100 μm. It can be seen that almost no multimode interference was observed, which indicates that the designed Euler MWBs work very well.

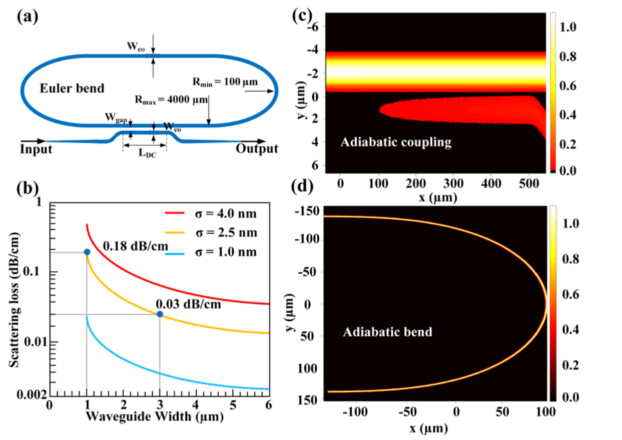

Fig. 1. Design of the compact ultra-high-Q micro-racetrack resonator. (a) Schematic diagram of the proposed compact ultra-high-Q MRR; (b) The relationship between the scattering loss and the waveguide core width based on $n-w$ model with differnet roughness σ and all the correlation length Lc = 50 nm; (c) FDTD simulations of the light coupling in the MSW DC; (d) Simulated light propagation in the designed 180° Euler MWBs.

III. Device Fabrication and Measurement

Fig. 2 shows the false color image of the fabricated compact ultra-high-Q racetrack resonator (LIGENTEC, Switzerland). Fig. 2(a) shows the global view of the resonator with a size of 0.27 × 0.98 mm^2. The microscopic images of the modified Euler-bend, the adiabatic taper, and the DC are shown in Fig. 2(b), (c), and (d), respectively.

Fig. 3 shows the experimental setup for characterizing the Q factor of the fabricated MRR. The optical carrier emitted by a tunable laser source (TLS, NKT Basik E15) is input into a phase modulator (PM, Covega Mach-40) via a polarization controller (PC1). Then the phase-modulated light is launched into an optical bandpass filter (OBPF). One of the first-order sidebands is suppressed by the OBPF and a single sideband (SSB) signal is achieved correspondingly. Then the light is amplified by an erbium-doped fiber amplifier (EDFA) and coupled into the device under test (DUT) via PC2. After being filtered by MRR, the output signal is routed to a high-speed photodetector (PD, SHF AG-Berlin) with a bandwidth of 40 GHz. At last, a microwave photonic notch filter (MPNF) is obtained. Therefore, the transmission of the ultra-high-Q resonator can be measured by a vector network analyzer (VNA, Anritsu MS4647B) precisely.

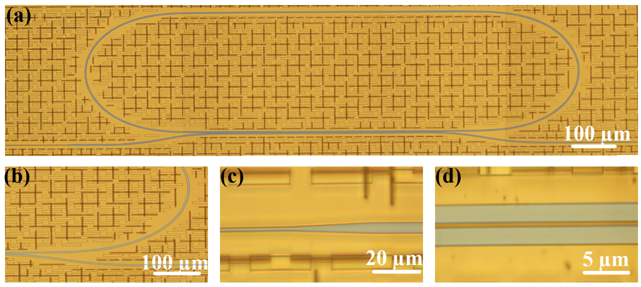

Fig. 2. False color images of the fabricated ultra-high-Q Si_3N_4 racetrack resonator. (a) The global view of the fabricated device; (b) The modified Euler bend; (c) Adiabatic taper; (d) Coupling waveguides of DC.

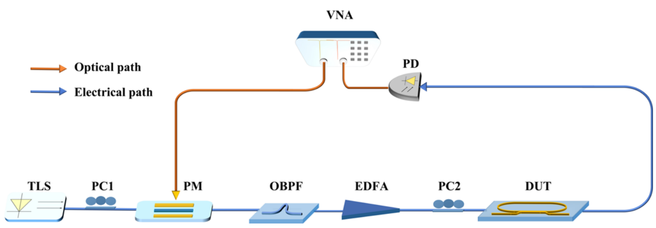

Fig. 3. Experimental setup for characterizing the Q factor of the compact ultra-high-Q Si_3N_4 racetrack resonator based on VNA. TLS: tunable laser source; PC: polarization controller; PM: phase modulator; OBPF: optical bandpass filter; EDFA: erbium-doped fiber amplifier; DUT: device under test; PD: photodetector; VNA: vector network analyzer.

The thickness of the Si_3N_4 waveguide is 800 nm, which also supports TM mode transmission. By adjusting PC2 to make the polarization state of input light to be aligned with the TE mode of the optical waveguide, we can obtain the transmission spectrum when only TE mode resonance exists. From Fig. 4(a), it can be observed that there are no obvious resonant notches of higher-order modes, which proves that the designed MRR can ensure adiabatic transmission for the fundamental mode. The measured FSR of TE0 mode is 65 GHz. A critically coupled resonance is shown in Fig. 4(b). The fitting curve indicates the full width at half maximum (FWHM) is 32 MHz, which indicates that a loaded Q of 6.3 × 10^6 is obtained. According to the data fitting, the highest probable propagation loss of the racetrack waveguide is 3.4 dB/m, which corresponding to an intrinsic Q of 1.03 × 10^7. Results show that by using the widely used LAT technology fabrication process, we boosts the Q factor to approximate 5 times higher than previously fabricated device [11].

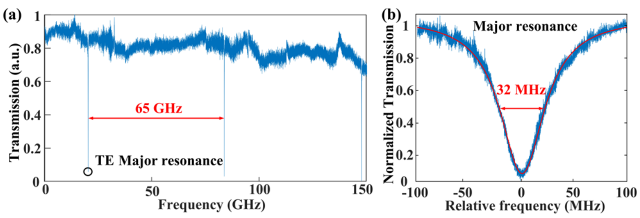

Fig. 4. Measured results of the micro-ring resonator (height 800 nm × width 3000 nm). (a) Measured transmission spectrum when only TE mode resonance exists; (b) A representative resonance with critical coupling.

IV. Conclusion

By using a highly multimode waveguide structure, we have achieved a racetrack MRR with a Q factor of 1.03×10^7 based on the widely used LAT fabrication process for the first time. The highly multimode design can be applied not only to Si_3N_4 but also to other different material platforms. The proposed approach opens widely opportunities for the applications of Si_3N_4 micro-resonators in many fields.

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