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Waveguide cross-coupled silicon nitride microring resonators

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Abstract

Tunable three-dimensional silicon nitride racetrack resonators were experimentally demonstrated, with a microring resonator on a bottom layer and a feedback cross-coupled waveguide on a top layer. The filter performance such as the resonance wavelength and extinction ratio can be thermo-optically tuned based on the electrical control of a heater above the feedback waveguide. The presented device has a potential to be applied as a tunable modulator/switch as well as a highly-sensitive sensor.

1. Introduction

Silicon nitride (Si_3N_4) is a promising wave-guiding material for integrated photonics applications due to its wide transparency bandwidth, compatibility with the complementary-metal-oxide-semiconductor (CMOS) technology, and negligible nonlinear (two-photon) absorption [1]. Among various Si_3N_4 integrated devices, an optical micro-cavity is a versatile element and has been utilized in numerous linear and nonlinear optical applications [2]. Si_3N_4 platform is also favorable for realizing three-dimensional vertical integration [3, 4], which can increase integration density, enhance chip functionality, facilitate active-passive integration, and offer an improved fabrication tolerance.

It is desirable to enable active control on the resonance characteristics in order to advance the functionality of resonator filter. It has been shown that effective resonance control can be fulfilled by means of waveguide cross-coupling to the resonator, while a U-bend waveguide essentially acts as an external feedback to the resonator, which can also be used for phase-shift keying modulator. In the following, two three-dimensional cross-coupled Si_3N_4 racetrack resonators are fabricated and characterized, with the microring resonator on a bottom layer and the cross-coupled waveguide on a top layer [5]. The filter performance such as the resonance wavelength and extinction ratio can be tuned based on the thermo-optical control of the phase-shift of cross-coupled waveguide.

2. Device Fabrication and Characterization

Fig. 1 illustrates a schematic of the three-dimensional Si_3N_4 racetrack resonator with waveguide cross-coupling, while Fig. 1(a) shows a resonator with U-bend self-coupled waveguide and Fig. 1(b) presents a straight self-coupled waveguide case. The bottom layer resonator is cross-coupled to the top layer waveguide, with metal heaters placed above the waveguide or resonator to achieve an active phase-shift control. As a proof-of-concept, the three-dimensional silicon nitride resonators were fabricated based on the electron-beam lithography (EBL) and reactive ion etching (RIE). An InP substrate was adopted with consideration of the ease of wafer splitting, in order to obtain flat facets for a high coupling efficiency with the external fiber. A 4-µm-thick SiO_2 buffer layer was first deposited by plasma-enhanced-chemical-vapor-deposition (PECVD), then a 250-nm-thick Si_3N_4 was deposited by electron-cyclotron-resonance (ECR)-plasma-enhanced-sputtering, which is a room-temperature film deposition facility and can facilitate the potential integration of Si_3N_4 device with active semiconductor materials. Si_3N_4 thickness is chosen by a trade-off between a minimum value necessary for reducing waveguide bending-related loss and a maximum one in order to avoid the mechanical rupture caused by a high tensile stress. With a set of global alignment marks (consisting of 100-nm gold) formed by lift-off technique, the microring resonator was patterned by EBL and RIE, and electron-beam resist ZEP520 was used directly as an etching mask. After the wafer cleaned by using a wet chemical process and oxygen plasma, a 1.5-µm-thick gap SiO_2 layer was deposited. With the developed planarization technique by incorporating chemical-mechanical-planarization (CMP) and RIE, the gap SiO_2 surface was planarized to a thickness of about 750 nm. Then a second 240-nm-thick Si_3N_4 core was deposited and patterned, with the assistance of alignment marks. To check the control efficiency of metal heater, a thick 3.1-µm SiO_2 film was formed as cladding layer by PECVD, and Ti/Pt/Au heaters (40/10/10 nm thick, 5-µm wide) were fabricated by lift-off technique, placed above the feedback waveguide. Finally, the wafer was backside-polished and cleaved for measurement.

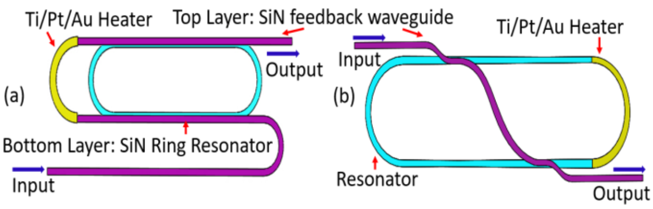

Fig. 1. Schematic of a three-dimensional silicon nitride racetrack resonator with a (a) U-bend and (b) straight self-coupled waveguide respectively.

The bottom layer racetrack resonator has a ring radius of 50 μm and a width of 1.5 μm with a trade-off between the single mode propagation condition and the bending-related loss. The top layer cross-coupled waveguide width was chose to be 1.7 μm, in order to realize a phase-matching with the bottom resonator. The coupling length between the resonator and waveguide is 30 μm. Fig. 2 shows the normalized static transmission spectrum of the vertically-coupled filter with a U-bend cross-coupled waveguide as in Fig. 1(a), recorded by a rapid spectrum measurement of an optical spectrum analyzer (OSA) with a 0.1-nm resolution. Fine spectrum measurement around 1560-nm wavelength was made with OSA resolution of 0.01 nm, as shown in Fig. 3. At 1559.3-nm, an extinction ratio of more than 14 dB and free spectral range (FSR) of 2.7 nm can be realized with a quality factor of about 1.88×10^4. For that of a straight waveguide coupled case (Fig. 1(b)), similar spectraum can be obtained (not shown here).

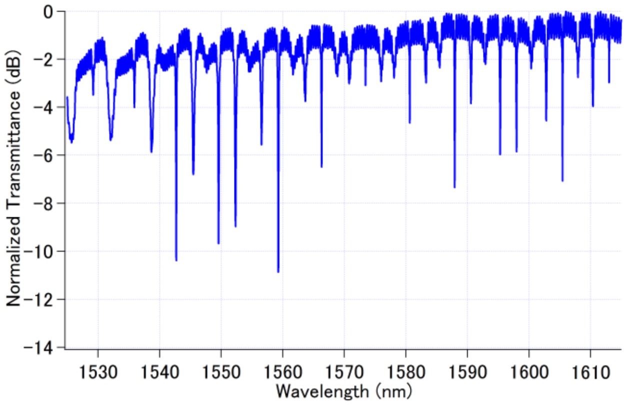

Fig. 2. Measured static transmission spectrum in the C+L band.

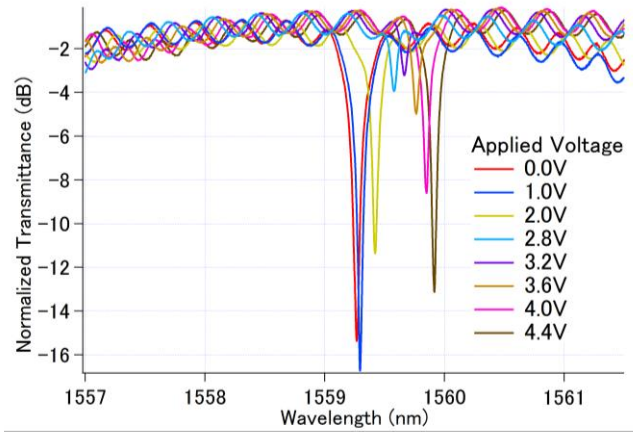

Fig. 3. Measured transmission spectra with varying voltage applied to heater above the U-bend cross-coupled waveguide.

The filter performance can be tuned effectively with applying voltage to heater. Fig. 3 shows the tuning effect for the U-bend cross-coupled waveguide case (Fig. 1(a)). With increasing the voltage, the resonance wavelength red-shifts, while the extinction ratio can be periodically tuned, which first increases to a maximum value, then decreases to an amplitude close to that of the ripples, and then increases again. The resonator can work as a notch filter while the spectral shape can be maintained during phase tuning. A 4.4-V voltage can roughly cause the resonance wavelength increase 0.8 nm while a 2.2-V voltage change (1 to 3.2 V) can cause an extinction ratio varying of about 14 dB. More efficiently tunable filter can be expected through optimizing the device design and fabrication process.

Fig. 4 shows the tuning effect for the straigth cross-coupled waveguide case (Fig. 1(b)). With increasing the voltage to the resonator, the resonance wavelength can be tuned and have a red-shift, with the extinction ratio changes little. But when applied voltage to the cross-coupled waveguide, little tuning effect can be observed, which is different from that with a U-bend couping waveguide.

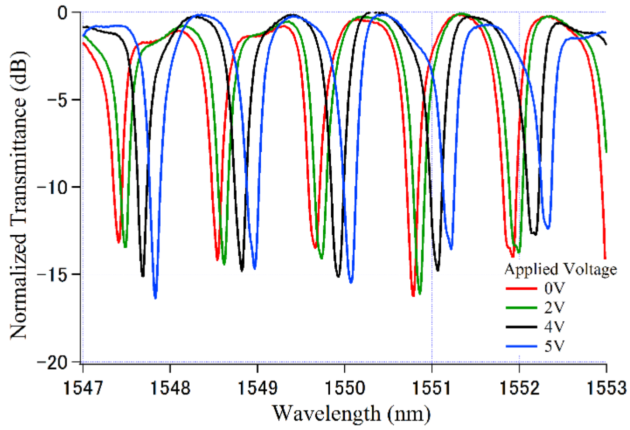

Fig. 4. Measured transmission spectra with varying voltage applied to heater above the resonator for a straight waveguide coupled case.

3. Conclusions

To summarize, two three-dimensional cross-coupled silicon nitride racetrack resonators were experimentally demonstrated based on the CMP planarization method. The filter performance such as the resonance wavelength can be tuned based on the thermo-optical control of the phase of feedback waveguide for the U-bend coupling case, but for the straight waveguide coupling case, only tuning the phase of the rasonator can work. These three-dimensional devices could be expected to have more application prospects such as constructing frequency comb, tunable modulator/switch, as well as highly-sensitive sensor.

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