Bandwidth tunable filter based on silicon microring-MZI structure

Yunhong Ding[1,2], Xinliang Zhang[1], Dexiu Huang[1],
[1]Wuhan National Laboratory for Optoelectronics,
School of Optoelectronics Science and Engineering,
Huazhong University of Science and Technology,
Wuhan, 430074, Hubei, People's Republic of China
hustdyh@smail.hust.edu.cn

Minhao Pu[2], Liu Liu[2], Jing Xu[2], Christophe Peucheret[2], Haiyan Ou[2]*
[2]Department of Photonics Engineering,
Technical University of Denmark,
2800 Kgs. Lyngby, Denmark
*haou@fotonik.dtu.dk

Abstract—**A novel bandwidth tunable bandpass filter based on a silicon microring-MZI structure is proposed and demonstrated. By thermally tuning the resonance offset between the two microring resonators, and adding the two drop transmissions together, the bandwidth of the microring-MZI filter can be easily linearly tuned with low in-band ripples.**

Key words—bandwidth tunable; thermal tunable; optical filter; microring; optical signal processing.

I. INTRODUCTION

Optical filters are one of the basic components in modern optical applications, especially in wavelength division multiplexing (WDM) optical networks. An optical filter is typically applied to filter out the required channel from a WDM signal. A bandwidth tunable filter is much more flexible since it can adapt to the bit rate of the selected channel, or select several channels simultaneously. To obtain such tunability, many approaches have been proposed and demonstrated so far. For example, a bandwidth tunable filter based on a single microring resonator has been demonstrated by micro-electronic-mechanical-system (MEMS)-tuning the coupling coefficient of the resonator [1, 2]. However, to realize MEMS tunability, a high actuation voltage of nearly 40 V should be applied. In another demonstration, the coupling of the microring resonator was tuned with a Mach-Zehnder interferometer (MZI), resulting in bandwidth tunability of the through transmission [3]. However, for the single microring resonator scheme, the tunability is limited, and as the bandwidth is tuned, the extinction ratio (ER) of the drop transmission is deteriorated. To improve the tunability and ER, high order microring resonators have also been used [4]. However, those are relatively complex and hard to control.

In this paper, we propose and demonstrate a simple and novel bandwidth tunable bandpass filter based on a silicon microring-MZI structure. The drop transmissions of the two identical microring resonators are combined together in the MZI structure. By thermally tuning the resonance offset between the two microring resonators, the bandwidth of our device can be easily linearly tuned over a large range with nearly constant ER and small in-band ripples.

II. FILTER PRINCIPLE

The proposed device is illustrated in Fig. 1. The drop

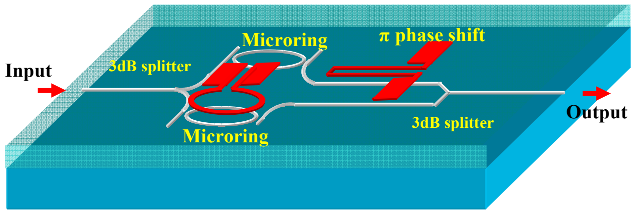

Figure 1. Structure of the microring-MZI bandwidth-tunable filter. It consists of two 3 dB splitters and two identical microring resonators. One heater is added on top of one microring resonator for resonance offset tuning. Another heater is added on top of one straight waveguide for phase tuning of the MZI.

transmission of a single microring resonator can be expressed as

$$t = -\frac{\kappa^2\sqrt{a\exp(-j\theta)}}{1-a(1-\kappa^2)\exp(-j\theta)} \tag{1}$$

where κ is the field coupling coefficient of the coupling region of the microring resonator, and θ and a are the roundtrip phase shift and transmission coefficient, respectively. As shown in Fig. 2(a), the wavelength-dependent phase shift induced by a single microring resonator over one free spectral range (FSR) is π. The two drop transmissions of the two microring resonators are partly overlapped by tuning the resonance of one ring. At the wavelength corresponding to the crossing point between the two drop transmissions (see Fig. 2(a)), a phase shift difference close to π is obtained between the two propagation paths in the MZI. Thanks to the additional π phase shift induced by the heater over the straight section of one MZI arm, the phase shifts in both arms can be made nearly equal, resulting in constructive interference and addition of the two drop transmissions, as shown in Fig. 2 (b). The bandwidth of the filter can then be tuned by adjusting the resonance offset between the two drop transmissions. At the same time, outside the combined passband of the two drop transmissions, the induced extra π phase shift will lead to a destructive interference and subtraction of the two drop transmissions, which further improves the ER of the proposed filter.

An optical filter is normally characterized by its 3 dB bandwidth, in-band ripple and ER, as defined in Fig. 2(b). For our application, a device with large tunability, high ER and small in-band ripples is preferred.

This work was supported by the National Natural Science Foundation of China (Grant No. 60577007), the National Basic Research Program of China (Grant No. 2006CB302805) and the Chinese Scholar Council (CSC).

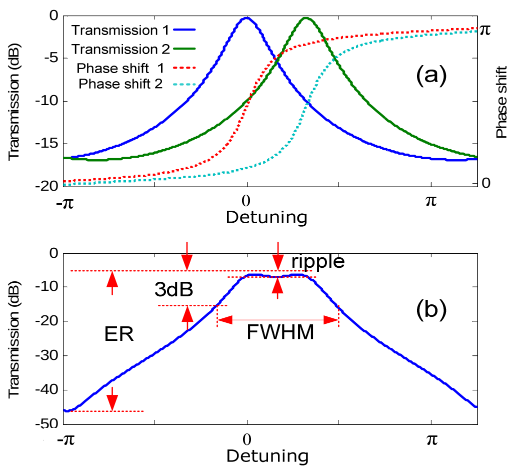

Figure 2. Principle of the bandwidth tunable filter. (a) Transmission and phase shift of the two microring resonators. (b) Characteristics of the bandwidth tunable filter. Here, we assume $\kappa = 0.5, a = 0.99$.

III. FILTER FABRICATION AND CHARACTERIZATION

Fig. 3 shows the fabricated device. The device is fabricated on a SOI wafer with top silicon thickness of 250 nm and buried silicon dioxide of 3 µm. Diluted (1:1 in anisole) electron-beam resist ZEP520A is spin-coated on the wafer to form a ~110 nm-thick mask layer. The microring-MZI structure is then defined using electron-beam lithography (JEOL JBX-9300FS). After that, the sample is etched by inductively coupled plasma reactive ion etching (ICP-RIE) to transfer the patterns to the top silicon layer. Afterwards, a top cladding layer of 550 nm benzocyclobutene (BCB) is spin-coated for planarization, and a layer of 400 nm ZEP520A is spin-coated in sequence as the mask layer for the heaters. Electron-beam lithography is used again to define the patterns of the heaters and pads. Finally, 100 nm thick titanium heaters and pads are formed by evaporation and lift-off techniques. The radii of the microring resonators are 10 µm, with the waveguide width of 430 nm and coupling gap of 97 nm for both through and drop coupling regions, as shown in Fig. 3(a).

Due to fabrication uncertainties, the transmissions of the two microring resonators may not coincide initially. Since the thermal tuning will lead to a red-shift in the resonance of the microring resonator [5], one of the resonators is slightly blue-shifted by design. To ensure equal loss in the two arms of the MZI, and since heaters may cause excess loss, they are implemented on top of both straight sections. However, only one of them is used, with a heating electrical power of 88 mW, in order to introduce the desired π phase shift.

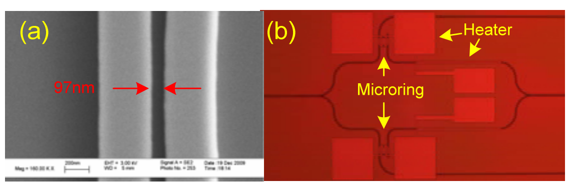

Figure 3. (a) Scanning electron microscope (SEM) top view image of the coupling region of the microring resonator. (b) Optical microscope picture of the fabricated device. Two identical add-drop microring resonators with micro-heaters are inserted in the two arms of the MZI structure. The straight sections of the two arms are also both implemented with heaters.

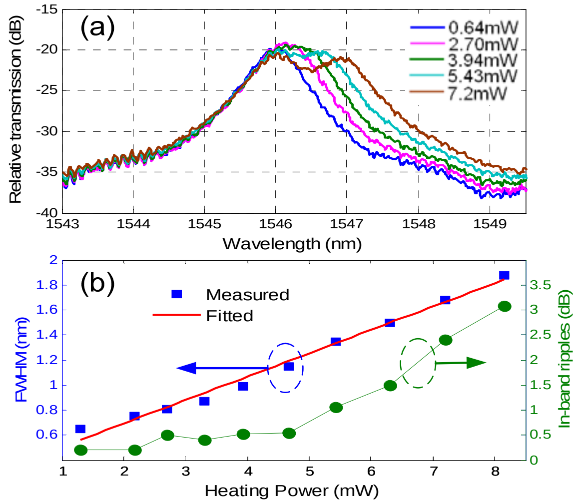

Figure 4. (a) Measured transmissions of the filter with different microring heating powers for the TE mode of the filter. (b) Measured bandwidth and in-band ripples versus microring heating power.

Fig. 4(a) shows the measured transmissions for the TE mode of the fabricated device, with the microring heating power from 0.64 mW to 7.2 mW. A clear bandwidth broadening can be observed. Fig. 4(b) illustrates the further measured tunability and the in-band ripples. The bandwidth linearly increases with the heating power. The in-band ripples remain below 1 dB when the heating power is under 5.43 mW. In this range, the 3 dB bandwidth can be linearly tuned from 0.65 nm to 1.35 nm. However, if the heating power further increases, the in-band ripple gradually increases. The ER of the filter is always larger than 15 dB, as shown in Fig. 4(a), which makes it practical in real applications.

IV. CONCLUSION

We have proposed and demonstrated a bandwidth tunable filter based on a silicon microring-MZI structure. An effective bandwidth tuning range from 0.65 nm to 1.35 nm, with nearly constant ER and small in-band ripples below 1dB, is obtained with a microring heating power between 1 mW and 5.43 mW. Based on the proposed structure, further improvement of the tunability can be realized by combining more microring resonators.

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