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A temperature sensor using cascaded microring resonators

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Abstract. A temperature sensor using cascaded microring resonator based on frequency beat system is presented and simulated in this paper. By changing bending radius of the inner ring, the relations between it and resonator wavelength spacing have been theoretically simulated. The simulation results show that the resonator frequencies of small microring transform to two frequencies and interval of these frequencies is very small which show this structure can be used as a sensor detector in beat frequency sensing system. Considering the thermal-optical effect of silicon, by changing the temperature, the output spectrum response is analysed in optical and microwave regime. The sensitivity is 7.2MHz/K.

1. Introduction

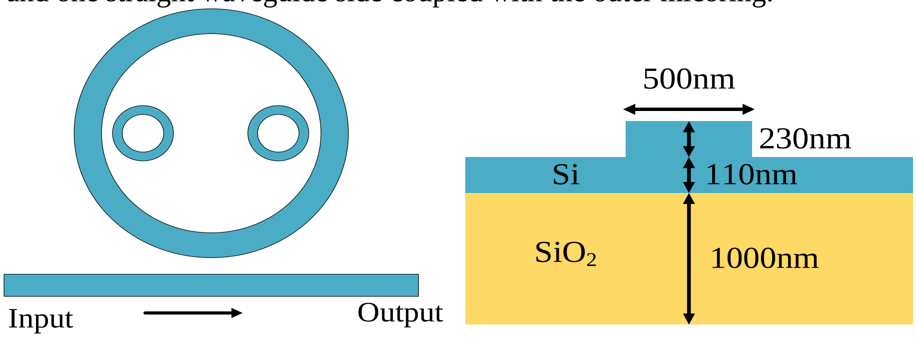
Microring resonator is attracted in recent years because it has excellent optical performance which can be applied in many areas, such as in high performance laser [1], low power optical switching [2], optical logic gate [3], optical modulators [4], and others [5-8]. Meanwhile, microring resonators (MRR) sensors can provide compact size and it can be flexible to fabricate an optical array for waveguides using material as silicon on insulator (SOI), which has high index contrast [9]. Baets fabricated a microring sensor to detect ethanol vapor concentrations [8] and Orghici demonstrated a detection of 1,3,5-trinitrotoluene (TNT) based on the combination of a silicon microring resonator and tailored receptor molecules [10].

The detection limitation of MRR will be improved by raise its Q factor. Many works were published to raise the Q factor of MRR in changing its structure, which has been reached to 139000 based on SOI MRR [11-13]. And many works were emphasized on fabrication processing to improve the Q factor [13,14]. However, Q factor is very high will induce the full width half maximum (FWHM) of resonator peak to very narrow which is very difficult to detect in optical regime. Beat frequency technology can be used to overcome this problem. Beat frequency technology can process the signal by transferring the signal frequency from optical regime to microwave regime, which has been applied in THz generation [15] and optical sensing [16]. In optical sensing system, the most application using beat frequency technology is applying perturbation on optical fiber grating with narrow bandwidth laser source to generate a beat frequency signal. This will limit its application because the narrow bandwidth laser is also expensive and the size of this type sensor cannot be compact enough.

In this paper, a temperature sensor using cascaded microring resonators (CMR) based on frequency beat system is presented and analyzed. The CMR has much higher Q factor with two neighbor resonator frequencies which is split from embedded MMR. According to these two neighbor resonator frequencies, a beat frequency sensing system has been designed and a microwave signal is produced according to the relations between the frequency shifting and temperature changing of embedded MMR are simulated and analyzed.

2. Structures

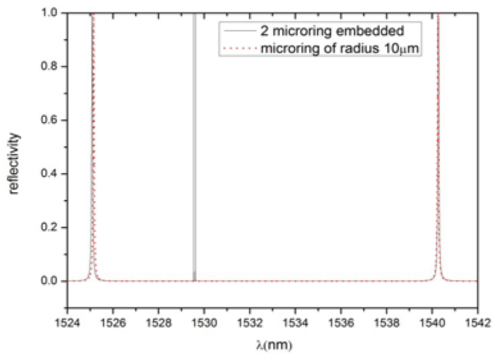
Fig. 1 shows schematic of our presented CMR. The CMR contains a large radius MRR embedded with two small radius MRR and one straight waveguide side coupled with the outer micoring.

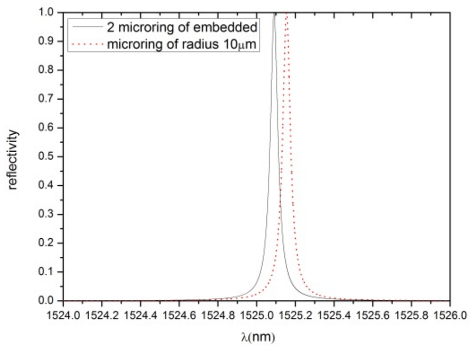


(a) (b)

Figure 1. cascaded microring resonator sturucture (a) top view; (b) cross view

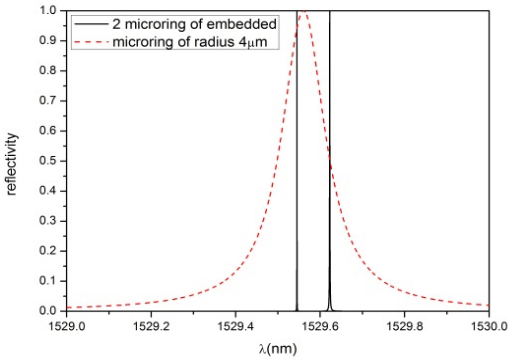
Lumerical 2015 is chosen as a simulation tool to compute the performance of MRR. In our structure, silicon-on-insulator (SOI) wafer is selected as optical material, where a Si layer with 340nm height deposited on SiO_2 insulator layer with 1μm height. The optical waveguide has a rib structure, where a 230nm rib height and a 500nm waveguide width, as shown in Fig. 1. The larger ring radius and small ring radius is 10μm and 4μm, respectively. The dielectric constant of Si is 3.45 and 1.45 for SiO_2 in 1.55μm band. Therefore, the effective index can be computed by Lumerical, where 2.4759 for large ring and 2.3735 for small ring.





(a)

(b)



(c)

Figure 2. The resonator spectrum of (a) CMR (black line), traditional MRR with 10μm radius (red line), (b) zoom out of (a) from 1524.0nm to 1526.0nm, (c) zoom out of (a) from 1529.0nm to 1530.0nm.

3. Simulation and analysis

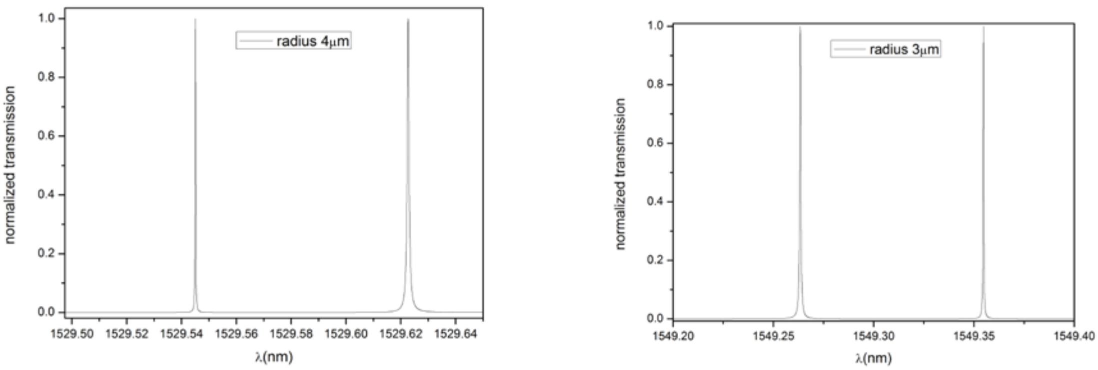
Fig. 2 gives the resonator spectrum of our CMR and those of traditional MRR only with larger ring. Resonator frequency of single MRR, whether large radius MRR, outer ring, or small radius microring, inner ring, are observed in our structure. The resonator wavelengths of CMR are left shift at 64.1 pm compared with resonator wavelength is 1524.991nm of single MRR, which is shown in Fig. 2 (b). As shown in Fig. 2(c), the two new resonator wavelengths of the small ring are split from the resonator frequency of single MRR which has smaller radius. Seen in Fig. 2(c), the resonator wavelengths of our MRR is left shift 0.0156nm and right shift 0.052nm compared with that of traditional MRR. These new resonator wavelengths are obviously narrower than that of single MRR. Therefore, our CMR has higher Q factor compared with that of traditional MRR.

As well known, radius of MRR affects its resonator wavelength and FWHM. In lossless circumstance, we can simulate the resonator spectrum with changing the radius of CMR. At 1.55μm wavelength, the effective index is 2.3014 and 2.2654 for 3μm radius and 2.5μm radius, respectively. The simulation results are shown in Fig.3. For embedded MRR of 4μm radius, first resonator peak is narrower than second peak, which is opposite in the structure of microring embedded with 3μm and 2.5μm MRR. The space distance between two split resonator wavelengths are 77.59pm, 91.30pm and 107.7pm with embedded microring's radius at 4μm, 3μm and 2.5μm, respectively. The highest Q value is 9.003e6 which is appeared with embedded microring's radius at 2.5μm. Obviously, the Q value increases with the embedded microring's radius decreases.

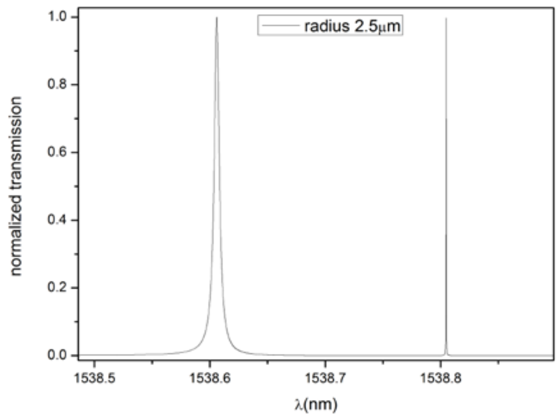
To the best of our knowledge, the wavelength precision below 1pm is very difficult to detect. Therefore, applying CMR in optical detection is not realistic. However, we can easily deal with this problem in microwave regime which use beat frequency technology to transfer optical wavelength to microwave frequency. The simulation results, depicted as Fig. 2, show that two resonator wavelengths are appearing and it is split from the original resonator wavelength of inner MRR. With this characterization, a beat frequency system can be designed and shown in Fig. 4. In this system, only broader laser is needed as a source, which will split to two neighbor peaks pass by CMR. And the two neighbor peaks can be coherent and produce a beat frequency signal on the receiver, which has changed from optical frequency to microwave frequency. The frequency of beat frequency signal can be detected as below:

$$\Delta f = -\frac{c}{\lambda_0^2}\Delta\lambda \tag{1}$$

where, Δf is the frequency of beat frequency signal and $\Delta\lambda$ is the wavelength spacing of two signals, c is the light speed in vacuum.



(a) (b)



(c)

Figure 3. The resonator spectrum of a CMR, where a 10μm radius MRR embedded with two (a) 4μm radius MRR, (b)3μm radius MRR and (c) 2.5μm radius MRR.

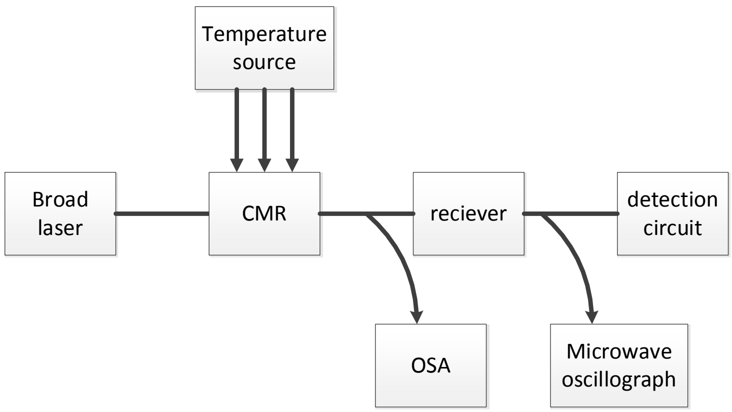
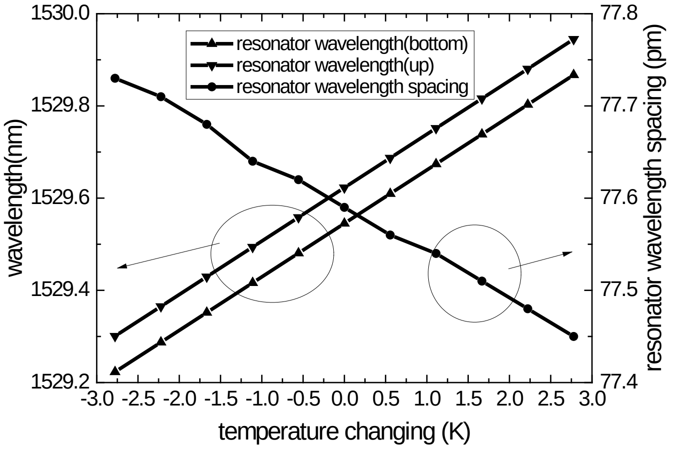
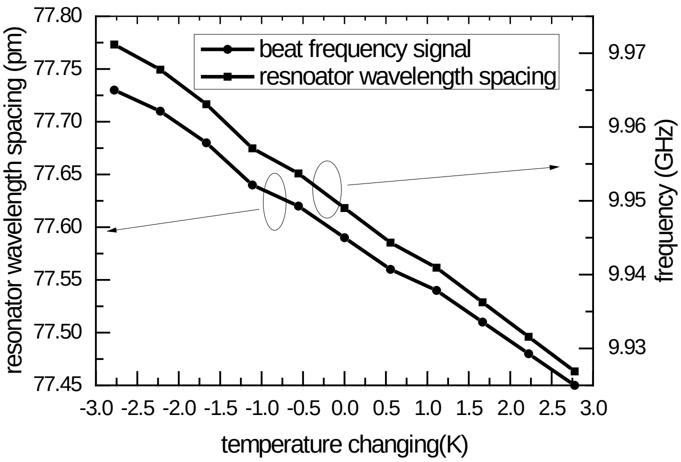


Figure 4. The schematic of beat frequency system based on CMR.

For the beat frequency system, the large MRR radius is 10μm with embedded MRR radius at 4μm. When it is not applying a perturbation, this beat frequency system produce a signal at 9.949GHz. When temperature is changing, the refractive index will change according to thermal-optical effect, assume the effective coefficient is 1.8e-4/K [17], this will produce a signal frequency shift, where is given in Fig. 5. Seen from Fig. 5, the frequency shifting is almost linear with temperature changing. When temperature changing 1K, the resonator wavelength spacing is shifted 0.54pm and the frequency shift of beat frequency signal is 7.2MHz. Therefore, the sensitivity of this beat frequency system is 7.2MHz/K.



(a)



(b)

Figure 5. The response of temperature changing (K), (a): two resonator wavelengths of CMR and their spacing. (b): the resonator wavelength spacing and the frequency of beat frequency signal.

4. Conclusion

A CMR temperature sensor based on frequency beat system is presented in this paper. The simulation of this structure has been obtained by Lumerical. The simulation results show that our CMR has higher Q factor compared with that of traditional MRR. Furthermore, the Q factor is increasing with decrease the radius of embedded MRR. To overcome the detection difficult below 1pm in optical regime, beat frequency system based on CMR is designed. Based on this, a sensor system is presented using beat frequency technology. By changing the temperature, the analytical descriptions of output spectrum response are derived and the relations between frequency of produced beat frequency signal and temperature changing are simulated, which show the sensitivity of beat frequency system is 7.2MHz/K.

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