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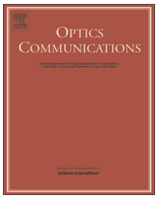

Tunable microring based on-chip interrogator for wavelength-modulated optical sensors

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ABSTRACT

An interrogation system for wavelength-modulated optical sensors based on tunable microring filter has been proposed and demonstrated both theoretically and experimentally. The wavelength shift of the sensors can be readout from the shift of the peak optical output of the system by scanning the resonant wavelength of the microring filter. We fabricate the interrogator on the silicon-on-insulator platform and a fiber Bragg grating sensor (FBG) is precisely interrogated. The Lorentz spectrum of the microring filter can de-flatten the output spectrum of the FBG and improve the interrogating resolution efficiently. Such a technique potentially provides a compact (only $50 \times 50\ \mu m^2$), low-cost, and high-performance (1 pm resolution) approach for the interrogation of the wavelength-modulated sensor and distributed sensor arrays.

1. Introduction

The wavelength-modulated optical sensors like the fiber Bragg grating (FBG) optical sensors are the most widely used optical sensors in the practical applications [1], such as strain and temperature sensing [2,3], biochemical and medical sensing [4,5], health monitoring of materials and structures [6], and refractive index sensing [7]. The sensors have growing importance given their simplicity, small size, low-losses, flexible design and the fact that the sensing information is encoded in an absolute parameter the optical wavelength. It implies the importance to interrogate this absolute wavelength information more suited to be handled using low-cost instruments [8]. However, the interrogation method for this kind of optical sensors is still pursuing, the main techniques include the interrogation by optical spectrum analyzers (OSA), and by the tunable filter with mechanical moving parts such as Fabry–Perot filter and fiber loop filter [9,10]. For the former, the drawback of the most of such systems is the high cost of the OSA, and for the latter the schemes usually cost space and the mechanical movements will limit the sensing speed. Thus the interrogation methods that can convert the wavelength into optical intensity using an optical filter based on planner lightwave circuit (PLC) without mechanical moving parts have attracted a lot of interests [11].

In order to expand the applied fields of the wavelength-modulated optical sensors, a simple and efficient on-chip interrogation system should be developed. The mostly used on-chip optical filters are arrayed waveguide grating (AWG) and etched diffraction grating (EDG) which have been proposed and studied as on-chip interrogator for the wavelength-modulated sensing applications [12–17]. The key advantages of using an interrogation system based on AWG or EDG are the compactness, low-cost and multichannel measurement capability. A multi-channel interrogator with 0.5 pm resolution can be achieved applying AWG [12] while the EDG based interrogator can also get a 1 pm resolution in 16 channels [15]. However, the AWG interrogator still has some issues need to be solved. For example, since the fixed and limited output channels, the sensing range and the number of the multiplexed channel are limited. And furthermore, the developments of the sensors will require more and more integrated sensing systems [18] and the on-chip integrated interrogator with more compact space will be needed.

Optical microring resonator, which is simpler, more compact and more flexible compared to the AWG or the EDG configuration, also has the potential of being used for the wavelength interrogation in wavelength-modulated optical sensing applications [19,20]. It has fast slopped Lorentz or box-like filtering spectrum [21] which is potential to get a high wavelength interrogation

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resolution [22]. The center wavelength of the microring filter also can be thermally tuned easily and exactly. So compared to the interrogating system that is constructed with AWG or EDG, the interrogator based on the microring filter will have higher integration, more flexible wavelength channels and the potential to make a higher resolution. As the thermally tunability, the microring based interrogator would not need external temperature controller which is essential in the AWG and EDG based systems. In this letter, an ultra compact on-chip interrogation system based on tunable microring resonator is proposed and demonstrated. The principle of the interrogation system is that by tuning the resonant wavelength of the microring resonator, the shifted wavelength of the wavelength-modulated optical sensor could be tracked by the shift of the corresponding tuning power of the maximum system output light intensity. Thus, we could correlate the center wavelength of the sensor to the tuning electrical signal applied on the microring resonator. The specific analysis of the microring based interrogator is demonstrated in this paper. By the complementary metal-oxide-semiconductor (CMOS) compatible process, a thermally tunable microring based interrogator is fabricated on silicon-on-insulator (SOI) platform, the footprint is about $50 \times 50\ \mu m^2$. We experimentally interrogate a FBG temperature sensor by using the thermally tunable silicon microring resonator based interrogator, the Bragg wavelengths of the sensor measured by the OSA show good consistency with the interrogated results, a high wavelength interrogating resolution of 1 pm can be achieved.

2. Design and principle

The optical sensor system with the on-chip microring interrogator is illustrated in Fig. 1. The system consists of a broadband light source (1520–1570 nm), a signal generator, a wavelength-modulated optical sensor (an FBG temperature sensor in our experiments), a photo-detector and an integrated thermal tunable optical microring add-drop filter. The -3 dB optical coupler is employed to couple the light from the broadband light source to the FBG sensor and couple the reflected light to the input port of the thermal tunable optical microring filter. The broadband light reflected by the FBG sensor is coupled into the input port of the microring filter with the integrated grating coupler. We detect the output light intensity of the drop port of the microring filter by the photo-detector. The signal generator is used to apply the scanning electrical signal on the thermal electrode of the microring filter for moving the resonant wavelength of the microring filter.

Like the interrogation principles of the tunable AWG as illustrated in the literature [12], assume the spectra distribution of the output light from the broadband light source, the reflection of the FBG sensor and the drop port transmission of the microring filter are $P_i(\lambda)$, $R_{FBG}(\lambda)$ and $T_D(\lambda)$, respectively. The system output light intensity, P, is

$$P = \int_{-\infty}^{+\infty} P_i(\lambda) \times R_{FBG}(\lambda) \times T_D(\lambda) d\lambda \tag{1}$$

suppose that P is initially tuned to the maximum with a bias heating power applied on the microring. If the Bragg wavelength of the FBG is shifted by λ_{shift}, we can track this shift by tracking the maximum output light intensity with tuning the resonant wavelength of the microring filter. Since the tuned resonant wavelength of the filter, $\Delta\lambda$, is related to the tuning power applied on the microring filter, the Bragg wavelength of the FBG sensor can be easily readout from the related tuning power applied on the microheater of the filter.

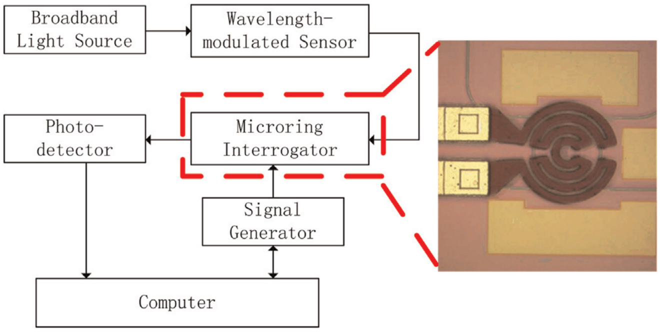

Fig. 1. Setup for the wavelength interrogation and the microscope picture of the thermal tunable microring filter.

An FBG usually has a flat peak about dozens of picometers wide that limits the interrogating resolution of the central wavelength. As the microring filter has a Lorentz spectrum with a small bandwidth, the output light can be de-flattened by the filter, thus the resolution can be increased. According to the analysis in [12], the sensitivity of the wavelength measurement depends on the 3-dB bandwidth of the FBG and the microring filter in inverse proportion to the factor $D = (\Delta\lambda_{FBG}{}^2 + \Delta\lambda_D{}^2)$. As is common knowledge, the bandwidth of the microring resonator is generally smaller than that of the AWG and EDG, our proposed microring based interrogator has the potential to achieve a higher resolution, and the resolution will be improved further by using the microring filter with higher quality factor.

3. Experiments and discussion

The microring add-drop filter with integrated TiN microheater is fabricated on a SOI wafer by the CMOS compatible process as described in Refs. [22,23]. Since the radius of the microring resonator is 10 μm, the free spectra range (FSR) of the microring is about 9.6 nm, which provides a wide interrogation range and a potential of multiplexing a large number of wavelength-modulated optical sensors. And with this compact ring size, the power consumption can also be reduced. The footprint including the ring, the heater and the thermal isolation trenches is about $50 \times 50\ \mu m^2$, as shown in Fig. 1.

We first characterize the heater efficiency of the filter by measuring the transmission spectra under different heating powers and the results are shown in Fig. 2(a). As the applied power increases, the resonant wavelengths of the microring filter red-shift due to the thermal-optic effect of silicon material and the thermal tuning range is wide enough to cover one whole FSR. The resonant wavelengths of the filter are extracted with different heating power as shown in Fig. 2(b).

The wavelength shift shows good linear dependence with the heating power, therefore, the resonant wavelength of the filter can be expressed as

$$\lambda_{res} = \lambda_0 + A \times P_{heat} \tag{2}$$

where $\lambda_0 = 1545.26$ nm, A is a constant (here is 0.104 nm/mW) which are obtained from the linear fitting in Fig. 2(b), and P_{heat} is the heating power applied on the ring. The 3-dB bandwidth of the drop port transmission is about 0.18 nm and the extinction ratio is higher than 20 dB. We can see from the figure that while the thermally tuning, the power loss of the microring filter almost stays the same, the non-uniformity of loss is less than 0.5 dB. It means the probable interrogating error which is caused by the loss fluctuation of the microring filter can be negligible, and even the 0.5 dB variation can also be compensated and normalized during the calculation after the optical intensity is detected.