Miniature interrogator for multiplexed FBG strain sensors based on a thermally tunable microring resonator array

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Abstract: We present a high-resolution and miniature multi-wavelength Fiber Bragg Grating (FBG) interrogator based on a thermally tunable microring resonator (MRR) array. A phase detection method using dithering signals is exploited to generate an antisymmetric error signal curve, which is utilized for the feedback locking of the MRR with the FBG sensor. Dynamic strain sensing of both single FBG and multiple FBGs are experimentally demonstrated, with a dynamic strain resolution of 30 nε/√Hz over 100 Hz to 1 kHz. The proposed interrogator shows the great improvements in both resolution and wavelength accuracy compared with the reported MRR-based interrogators and is promising for scalable multiplexed sensing applications.

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1. Introduction

Fiber Bragg Gratings (FBGs) have shown the great potential as a monitoring solution in research and industrial fields, which are used ranging from geological tectonic process and seismic research to structure health monitoring and energy production such as oil and gas [1, 2]. Due to the advantages of compactness, low cost, immunity to electromagnetic interference, and multiplexing capability, the FBG sensors have become very competitive compared with the conventional electronic sensors. However, the superior of FBG sensors has been weakened both in size and cost by the bulky bench-top optical components used in the readout units, i.e., the interrogation systems. The problem would become more severe under the multiplexing scenes where multiple readout units are required in order to monitor different wavelengths indicating the corresponding channels. The miniature and economical interrogators thus become desirable in order to achieve the large-scale deployments of FBG sensors.

Recent advances in photonics integration provide the possibility to embrace ultra-compact and cost-effective FBG interrogators. Silicon photonics (SiP) could provide a complementary metal oxide semiconductor (CMOS) compatible platform that enables monolithic integration of photonic components such as optical waveguides, grating couplers, modulators and photo-detectors (PDs) on a single silicon chip. It has been initially applied to meet the requirements of data communications in data centers and overcome the input/output (I/O) bandwidth limitation of the processors and memories. To date, there has been an increasing amount of research that applies SiP technology to specific applications in various areas [3–5]. More recently, several works of photonic-integrated FBG interrogators give encouraging examples of such on-chip interrogation systems with balanced performance in terms of size, power consumption, resolution, dynamic range and multiplexing capabilities [6–12].

Various interrogation approaches have been investigated to implement on-chip FBG interrogators, including spectral analysis based on diffraction gratings and photo-detector arrays [6–8], phase demodulation based on the unbalanced Mach-Zehnder interferometers (MZIs) [9, 10], and frequency discrimination based on tunable filters such as microring resonators (MRRs) [11, 12].
Interrogators using integrated spectrometers such as arrayed waveguide gratings (AWGs) have been proposed to acquire spectral information in parallel from a large array of high-speed PDs, which enables fast and simultaneous interrogation of multiple FBG sensors. However, this solution comes with the cost of relatively high system complexity and a large device footprint. It has been demonstrated that MZI-based phase demodulation interrogators can achieve wavelength resolution less than 1 pm, while the footprints of the photonic components remain incompact since that the large phase difference is required in the two arms of the MZI for the phase detection [10]. The large footprint has constrained its application in the multiplexing scenarios with the cascaded MZIs. Besides, microring resonators could work as the tunable filters by thermal tuning to determine the peak wavelength of the FBG sensors, and also allow the dense integration and scalable multiplexing [11, 12]. However, the resolution of the wavelength to time interval demodulation approaches, typically several tens pm in the reported works [11, 12], are limited by the linewidth of the MRR filter and the curve fitting accuracy of the resonant spectrum. Therefore, more sophisticated approaches need to be investigated in order to achieve compact on-chip interrogator with high resolution.

In this paper, we present an integrated FBG interrogator based on a SiP MRR-array to achieve dynamic strain measurements of the multiplexed FBG sensors. In order to improve the resolution, we propose a demodulation method that is similar to the Pound-Drever-Hall (PDH) scheme, by taking advantage of phase detection for the determination of the Bragg wavelength. Furthermore, frequency multiplexed dithering signals are utilized to lock multiple wavelengths simultaneously by monitoring a single output signal. The proposed interrogation system is featured with high-resolution and compactness for dense integration and scalable multiplexing.

2. Principles and interrogation method

In our system, FBGs are used as the sensors which have a high reflective band that is sensitive to both strain and temperature. The basic thought is to measure the shift of the Bragg wavelength of the FBG by monitoring amplitude or phase fluctuations at specific wavelength. The wavelength-selective characteristic of MRRs can be suitable to interrogate the wavelength by using either method. For the phase detection, PDH scheme is widely used in laser frequency stabilization and high resolution sensing systems, where the phase of the cavity outside the resonance is sampled through phase modulation and thus an error signal can be obtained in order to lock the laser with the cavity [13]. A phase detection method utilizing dithering signals that is similar to the PDH method, has been demonstrated in order to generate an antisymmetric error signal, which can be utilized to lock the MRR to the laser [14]. Here, we use the PDH-like method to identify drifting direction of the Bragg wavelength.

The intensity of the reflected light reaches the minimum at the through port of the MRR filter when the Bragg wavelength is aligned with the resonant wavelength. If the Bragg wavelength drifts out of the resonance, the reflected intensity will increase regardless of the drifting direction. Thus, wavelength locking or the disturbance measurement cannot be achieved only by monitoring the optical intensity. Fortunately, the derivative of the transmission is antisymmetric which can be utilized for wavelength locking and interrogation. When a dithering signal is applied to the MRR at a frequency $f_d$, a small modulation of the optical signal is generated and thereby the output signal would contain the frequency components at the fundamental and harmonics of $f_d$. Therefore, the error signals can be recovered through phase detection to indicate the offset direction of the Bragg wavelength.

The transmission spectrum at the through port of the MRR usually has a Lorentzian lineshape, which can be represented as Eq. (1), where $\lambda_R$ is the resonant wavelength, and $\omega$ is the full width at half maximum (FWHM). Therefore, the output optical power $P_{out}$ can be calculated by
\[ P_{\text{in}} \cdot T_R, \text{ where } P_{\text{in}} \text{ is the input power.} \]

\[ T_R(\lambda) = \frac{(\frac{\lambda R - \lambda}{w/2})^2}{1 + (\frac{4 \lambda R - 4 \lambda}{w/2})^2}. \tag{1} \]

The resonant wavelength \( \lambda_R \) is modulated by the dithering signal, which satisfies

\[ \lambda_R = \lambda_0 + \Delta \lambda \cdot \cos(2\pi f_d t), \tag{2} \]

where \( \lambda_0 \) is the initial resonant wavelength, and \( \Delta \lambda \) is the range of resonance shift. For the convenience of derivation, we assume that modulating the resonance is equivalent to modulating the wavelength of the input optical signal. Hence, the output optical power \( P_{\text{out}} \) can be expressed as Eq. (3) using Taylor series expansion,

\[ P_{\text{out}} = P_{\text{in}} \cdot [T_R(\lambda) - T_R'(\lambda) \Delta \lambda \cos(2\pi f_d t + \phi) + \frac{1}{2} T_R''(\lambda) \Delta \lambda^2 \cos^2(2\pi f_d t + \phi) + \cdots]. \tag{3} \]

where \( \phi \) is the phase difference between the received electrical signal and reference of the mixer.

Therefore, the fundamental harmonic component \( P_{f_d} \) of the dithering frequency \( f_d \) is

\[ P_{f_d} = -P_{\text{in}} T_R'(\lambda) \Delta \lambda \cos(2\pi f_d t + \phi). \tag{4} \]

The amplitude of the fundamental component serves as an error signal which can be obtained by mixing \( P_{f_d} \) with the dithering signal and low-pass filtering, as shown in Eq. (5). The first term of the Taylor series expansion, also known as the DC component, is relatively large compared with the higher order harmonics, especially in the scenes of weak input signals. It can drift over time and temperature, resulting in a decrease of the sensitivity and accuracy of measurements. Therefore, the DC component should be removed from the received signals before the mixer in order to obtain the correct error signal.

Figure 1 illustrates that the error signal has an antisymmetric center at the resonant wavelength, due to the anti-symmetry of the derivative of the modulated optical signal.

\[ P_{f_d} \cdot \cos(2\pi f_d t) = -\frac{1}{2} P_{\text{in}} T_R'(\lambda) \Delta \lambda [\cos(2\pi \cdot 2 f_d t + \phi) + \cos(\phi)]. \tag{5} \]

The resonance of the MRR is locked with the Bragg wavelength through a feedback control loop using the error signal. Consequently, the control voltage would carry the disturbance information sensed by the FBG and thereby the dynamic strain signal interrogation would be achieved.

![Fig. 1. Principle of proposed demodulation scheme using dithering signals.](image-url)
3. Experimental setup

The experimental setup of the proposed MRR-based interrogation system is illustrated in Fig. 2(a). An erbium-doped fiber amplifier (EDFA, Amonics AEDFA-23-B-FA) is used as a broadband light source (BBS) to launch optical signals into the FBG sensor via a three-port optical circulator. The FBG characterized by a Bragg wavelength of ~1550 nm is longitudinally strained by using a piezo-electric actuator (PZT). The reflected optical signal is vertically coupled into the MRR through a grating coupler after a polarization controller (PC), and then coupled out at the output port. A DC bias and a sinusoidal signal are combined by a bias tee to drive the MRR for aligning the FBG and the MRR. The photo-diode (PD, Thorlabs PDA10CS-EC) output is then mixed with the reference signal and amplified by a lock-in amplifier (Stanford SR844) with a 10 kHz output analog bandwidth to generate the error signal. In addition, the lock-in amplifier would chop the mixer reference signals in the range of 2-12 kHz and operate in the range of 25 kHz to 200 MHz. Therefore, the frequency of the dithering signal must be higher than 25 kHz. A data acquisition card (DAQ, NI USB-6281) is used for data acquisition with the sampling rate of 200 kHz.

The acquired error signals are sent to the computer for digital signal processing as shown in Fig. 2(a). Instantaneous variation of the error signals are converted to strain signals by multiplying the voltage to strain conversion factor. Meanwhile, average variation of the error signals in each feedback cycle is used to update the bias of the MRR by the feedback loop.

As shown in Fig. 2(b), the MRR is made of the 220 nm × 450 nm single mode optical waveguides on an SOI platform, consisting of a 10 µm radius microring and two bus waveguides 0.2 µm away from it. A thin titanium film is deposited directly above the MRR by 1 µm of oxide as a heater for the thermal tuning, which is utilized to compensate the resonance deviation due to the fabrication error and ambient temperature fluctuations. Figure 2(c) is a four-channel MRR array for multiplexed FBG interrogation, which is consisted of four same MRIs, with each having a heater for thermal tuning. The MRR-array chip is wire-bonded to a printed circuit board (PCB) for the convenience of applying electric signals.

The measured 10% – 90% rise time of thermal tuning is 7.1 µs while the 90% – 10% fall time is 1.6 µs as shown in Fig. 3(a). Therefore, dithering signals up to several hundred kHz can be applied to the heater of the MRR. Figure 3(b) is the modulation signal received by the PD when 400 kHz dithering signal is applied.

Two FBGs are used in the following experiments. The first FBG sensor has an FWHM of 0.155 nm while the other one has an FWHM of 0.272 nm. Both FBGs have a reflectivity of 99%.

Fig. 2. (a) Experimental setup of the multiplexed FBG interrogation system based on a MRR-array; (b) Photography of the MRR used in single FBG interrogation; (c) Photography of the MRR array used in multiple FBG interrogation.
4. Single FBG interrogation

The drop-port transmission of the MRR and the reflective spectrum of the FBG is illustrated in Fig. 4(a). The center wavelength of the FBG sensor is 1553.85 nm with the pre-strain applied to it. It is clearly shown that the Bragg wavelength and the resonance are initially misaligned. As the preliminary operation, bias scan of the MRR is performed by applying a 20 Hz sawtooth signal to the heater of the MRR in order to align the resonance of the MRR with the FBG, denoted as wavelength locking. Meanwhile, the dithering signals with the 2 V peak-to-peak amplitude and 400 kHz frequency are also applied to the heater. The slope of the linear range of the error signal curve is affected by the amplitude of the dithering signal. Therefore, the amplitude should be optimized in order to obtain an error signal curve with a maximum slope. With the bias voltage increasing, the resonance of MRR overlaps with the FBG reflective spectrum, and the antisymmetric error signal curve can be observed. The voltage corresponding to the antisymmetric center of the error signal is used as the operating voltage, i.e., the operation point, of the MRR for wavelength locking.

The result of the bias scan is shown in Fig. 4(b). The bias voltage at the center of the error signal curve is around 5.1 V. Theoretically, the error signal is 0 V at the center. However, the shape of the error signal curve can be influenced by the instrument configuration such as the phase parameter of the lock-in amplifier. The non-zero parameter would not affect the strain measurement once the MRR is locked with the FBG at the same position.
However, the MRR suffers from resonant wavelength drift during the measuring process due to ambient temperature fluctuations. Therefore, we set up a feedback loop in order to compensate for the slow temperature change and maintain the wavelength locking state of the interrogation system. The feedback speed is 100 Hz, and thereby the operation point is updated every 0.01 s. The feedback signal is proportional to the average variation of the error signals in each feedback cycle. It should be noted that the averaging process results in the filtering effect and partial power of the error signal is depressed at the frequencies lower than 100 Hz. By operating in the wavelength locking state, the variation of the error signal would represent the fluctuations of the strain signal. A 100 Hz sinusoidal signal is generated to drive the piezo stage, which longitudinally strains the grating region and causes a shift of the Bragg wavelength. This method is also applied for the strain with a particular frequency distribution.

![Figure 5](image-url)  
Fig. 5. Single FBG sensing results. (a) Feedback signals during the measurement; (b) The power spectral density of the feedback signals; (c) Measured strain signals in time domain, inset is zoomed signals; (d) The power spectral density of the measured signals in (c).

Figure 5(a) is the feedback signal during the measurement and Fig. 5(b) is its power spectral density. The envelope of the feedback signal indicates the tuning condition of the MRR whose trend is opposite to the drifting direction of the resonant wavelength. The measured error signals and the corresponding wavelength shift are illustrated in Fig. 5(c). It is estimated that a peak-to-peak value of 32.2 $\mu$ε strain signal has been applied to the FBG sensor. No obvious drift can be observed in the traces, indicating that the locking state is well maintained by the feedback loop. Figure 5(d) illustrates the power density spectrum of the strain signals. The sharp peak at 100 Hz is well agreed with the applied strain signals. The dynamic strain resolution at 100 Hz is about 30 nε/\sqrt{Hz}, limited by the noise floor of the system. Moreover, the noise floor in Fig. 5(d) at low frequencies is much lower compared to that in Fig. 5(b), which proves the filtering effect of the feedback loop. The harmonics of 100 Hz observed in the spectrum is due to the non-linear response of the piezo stage.

The interrogation range is determined by the linear range of the error signal curve. In order to recover the strain signal without distortions, the system needs to operate within the range that the error signal voltage variation is linear to the wavelength shift. Otherwise, the interrogation results would be smaller than the actual value if the Bragg wavelength shifts to near or even out...
of the margin of the error signal peak or valley, as shown in Fig. 4(b). We find that the error signal voltage to wavelength shift relation has an excellent linearity within the half intermediate range between the error signal curve and peak. The coefficient of determination $R^2$ of the linear fitting is 0.998 so that we define this range as the linear interrogation range. The corresponding maximum detectable amplitude of the strain signal is about $\pm 38 \mu e$. The shape of the error signal curve is determined by the first-order derivative of the MRR transmission. Therefore, the interrogation range is determined by the FWHM of the MRR.

For the assessment of the wavelength accuracy of the interrogation system, no strain signal is applied to the PZT to conduct a static measurement. The wavelength accuracy is determined by the error of the measured Bragg wavelength, which can be represented by the root-mean-square error (RMSE) of the measured values. As shown in Fig. 6, the RMSE of measured static FBG Bragg wavelength is 0.9 pm with a 10 kHz bandwidth of the measurement. The wavelength accuracy can also be estimated by the noise of the error signal curve. The estimated wavelength error of the system is 0.84 pm. It is close to the measured value and the slight difference could be caused by the environmental noise. The noise of the interrogation system is consisted of two parts, the optical noise and the electric noise. The optical noise is mainly the spontaneous emission noise of the EDFA and power fluctuation caused by the fiber coupling, while the electric noise including the noise in the amplifying circuits of the PD and the lock-in amplifier. Both optical and electrical noise would have a contribution to the error of measurements.

Fig. 6. Static measurement of the MRR-based interrogator with no strain variation applied to the FBG.

5. Multiple FBG interrogation

In order to verify the scalability of the proposed interrogation system, we designed an MRR array (illustrated in Fig. 2(c)) as a wavelength-division-multiplexing (WDM) device for multiple FBG interrogation. It is capable of distinguishing the reflected optical signals of four FBGs with different Bragg wavelengths. The received optical signal is coupled out to the PD from the through port shared by all the four MRRs. Therefore, only one PD is needed for optical signal receiving. Otherwise, four PDs would be needed which would greatly increase the system complexity and cost.

Limited by the number of channels of the lock-in amplifier, we use two channels of the MRR array for multiplexed FBG interrogation. The center wavelengths of both FBGs are 1551.345 nm and 1552.477 nm as shown in Fig. 7(a). Multiple signals from different FBG sensors should avoid wavelength overlapping to prevent inter-channel crosstalk. Meanwhile, the dithering signals should be orthogonal and the dithering frequencies should be properly chosen so that lock-in detections would not be interfered by the high order harmonics of other channels. Frequencies of the dithering signals for both channels are 400 kHz and 492 kHz respectively, with the same peak-to-peak amplitude of 2 V. Due to lack of thermal isolation on the chip, the thermal
crosstalk can be another concern. Thus, we choose the first and the third MRR for interrogation, considering the spacing and resonance difference between the two MRRs. A thermal isolation structure, for example an air-trench, can be used to reduce the thermal crosstalk [15].

The experimental results are shown in Fig. 7. Figure 7(a) are the reflective spectra of the FBGs and transmission spectra of the MRRs. Despite the same structural parameters of the four MRRs, resonances of the four channels are separated from each other due to the random resonance deviation caused by fabrication errors. The four drop-port transmission spectra are measured in order to identify the corresponding MRR in the through port transmission spectrum.

Similar to the scene of single FBG interrogation, the bias scan is performed to both MRRs respectively for the wavelength alignment of the MRRs and the FBGs. The error signal curves are shown in Fig. 7(b). Each curve has two antisymmetric centers indicating the Bragg wavelengths of the two FBG sensors. The first FBG has a smaller bandwidth than the second one, which results in smaller optical power of the reflective signal of the first FBG. This explains the amplitude difference between the two peaks in each error signal curve. The two FBG sensors are locked to the first and the third MRR by feedback loops respectively.

The measured time-domain strain signals of the two FBGs are illustrated in Fig 7(c). The measured multiplexed strain signals have smaller SNRs compared with the demodulated signals in single channel interrogation, since that the optical power is decreased by using the 3 dB coupler. The power density spectra of the strain signals are shown in Fig. 7(d). The peak in the spectra of the first channel at 100 Hz and the one of the second channel at 200 Hz are agreed with the applied strain signals. The dynamic strain resolution of both channels is about 30 $\text{n}\varepsilon/\sqrt{\text{Hz}}$ over 100 Hz to 1 kHz. We also estimate the linear range of both error signal curves. The results show that the maximum range of measurements for the first channel is $\pm 26.6 \mu \text{m}$ while it is $\pm 40.9 \mu \text{m}$ for the second channel.

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Fig. 7. Multiple FBG sensing results. (a) Transmission spectra of the FBG sensors and the MRRs; (b) Bias scan results and error signal curves; (c) Measured strain signals in time domain; (d) The power spectral density of the strain signals in (c).
6. Discussion

The key component in our proposed interrogation system is the tunable MRR filter. As shown in Fig. 8, our system is much more compact than the MZI-based and AWG-based ones while maintaining a relatively high static wavelength resolution of 0.9 pm. A dynamic resolution of 30 \( \text{nm/}\sqrt{\text{Hz}} \) has been achieved. Meanwhile, benefiting from the wavelength selective characteristic of MRRs, our interrogation approach is promising for scalable multiplexing. A WDM multi-channel FBG interrogation is realizable with appropriately designed resonance and free space range (FSR) of the MRRs. All the MRRs are coupled to the same waveguide. Therefore, the WDM signals can be detected by a single PD from the through port of the MRRs and the strain signals can be recovered using dithering signals of different frequencies. The scalability of the multiplexed interrogation system is determined by the FSR of the microring resonator. Resonance overlapping of different microring resonators should be avoided for the detection. Meanwhile, it is of great significance to eliminate the spectrum overlapping of the harmonics of the dithering signals. In future, time division multiplexing (TDM) can be used to further extend the number of multiplexing channels.

We envision that the interrogation system can be achieved by a single chip. Apart from the light source, all the other optical components are now ready to be integrated on a signal chip, including the optical input and output (I/O), the MRR and the photo-detector. As for the light source, an off-chip broadband light source is used in our demonstration. However, light source such as heterogeneous integrated semiconductor laser diode (SLD) is still an option with the technical progress of the on-chip light source. Furthermore, high power light emitting diode (LED) might be another choice considering its broadband spectral characteristic. The frequency mixing, filtering and the rest of calculation procedures can be accomplished by CMOS electronic circuits or an FPGA chip. Thus, interrogator chips with fiber pigtails would possibly be ready for sensing applications in the future.

Fig. 8. Comparison of the static wavelength resolution of the integrated FBG interrogators using different demodulation approaches (horizontal axis: the size of the optical component for single channel interrogation).

7. Conclusion

In conclusion, we demonstrate a novel on-chip interrogation system based on a thermally tunable microring resonator array using a phase detection method. Feedback control loops are used for temperature fluctuation compensation for the MRRs and maintaining the function of the
interrogator. Interrogation of multiple FBG strain sensors is achieved, with a dynamic strain resolution of 30 nε/√Hz over 100 Hz to 1 kHz and a static wavelength accuracy of 0.9 pm. The proposed MRR-based interrogation system is promising for scalable multiplexing.

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