Wavelength Monitoring using a Thermally Tuned Micro-ring Resonator

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***Abstract*—In this work, we describe a system in which a thermally tunable micro-ring resonator filter is applied to monitor spectral shifts in a FBG sensor. The system was simulated using the time interval method with a simple ring resonator thermo-optical model with experimental values. For 2.56 nm scan range at 1 Hz we predicted a time interval sensitivity of 124 $\mu s/pm$.**

I. INTRODUCTION

Many applications in spectroscopy, optical sensing and laser monitoring rely on the accurate determination of any optical spectrum shift. There are a variety of methods and systems for wavelength monitoring such as power ratiometric measurements, Fabry-Perot filter and spatial grating spectrometry [1]. We propose using a micro-ring resonator as a tunable filter to convert spectral shifts from an optical sensor into a time interval measurement [2]. This technique potentially allows reading a group of optical sensors at different wavelengths which can be demultiplexed and processed by an array of micro-ring resonators. Also, by thermally tuning a micro-ring resonator resonance, it is possible to cover a reasonable wide wavelength range with low power and precision [3][4]. Although the thermo-optical effect is slow, this system can be enhanced by applying a carrier injection scheme obtaining sub-nanosecond optical time response [5]. In this work, the effect of source noise and detector noise though important, were not taken into account.

II. METHODOLOGY

The proposed system is shown in Fig. 1 and it consists on a Si ring resonator buried in SiO2 with a micro-heater on top of the structure to thermally tune the ring spectral response [4]. As denoted in Fig. 2, a sinusoidal current signal applied to a micro-heater will induce a temperature change in an area which eventually will reach the Si micro-ring waveguide. Due to Si large thermo-optic coefficient, any differential change in temperature will induce a differential change in the effective refractive index of the waveguide, which will in turn detune and tune the ring resonance.

To better understand this system, we employ a numerical simulation. From reported values [4], a micro-ring (10 μm radius) with quasi-TE resonance had a linear resonance shift coefficient (a) of 0.095 $nm/°C$. In addition, the line-shape of the drop port transmittance of the ring resonator can be fitted as a Lorentzian curve [4]. Therefore, an approximation of the resonance wavelength is expressed as:

$$\lambda(t) = \lambda_0 \left[1 + a\Delta T(t)\right] \tag{1}$$

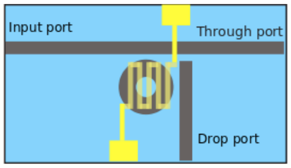

Fig 1. Ring resonator Si structure with two waveguides buried in SiO2 and a micro-heater on top.

Where λ_0 is the ring resonator resonance at room temperature and $\Delta T(t)$ is the temperature change in the ring waveguide. To obtain the resonant shift $(a\Delta T)$ is necessary to solve a thermo-optical problem. However, for qualitatively assessment, we assumed an uniform temperature distribution which varies in time due to a sinusoidal electrical current applied to the heater with a frequency $\omega = 2\pi f$.

A lumped capacitance thermal model was assumed for the micro-heater [6]. The transient response is similar to a RC circuit with a thermal resistance and capacitance. A simple although not so rigorous model was to assume $\Delta T(t) = A(1 - \cos(2\omega t))$. At low frequency the DC and AC thermal amplitudes are very similar thus $A_{DC} \approx A_{AC} = A$ (thermal amplitude for joule heating).

The maximum wavelength shift is expressed as $\Delta\lambda = 2aA$, therefore our ring resonance wavelength in time can be rewritten as: $\lambda(t) = \lambda_0 \left[1 + \frac{\Delta\lambda}{2}(1 - \cos(2\omega t))\right]$. As observed in Fig. 2 the micro-ring's drop port transmission is modulated accordingly, when an optical signal from a sensor (fiber Bragg grating) pass through the micro-ring, an overlap of the two spectra occurs and a periodic signal can be measured with a photo-detector. The time interval between consecutive peaks will depend on the heating period $(T/2)$. If t is the time when a first peak is measured then at $\frac{T}{2} - t$ a second peak occurs, thus the time interval is $\Delta t_{pp} = \frac{T}{2} - 2t$. A relationship between this time interval and the wavelength difference between a FBG center wavelength and micro-ring initial resonance can be derived as:

$$\Delta t_{pp} = \frac{T}{2}\left\{1 - \frac{1}{\pi}\arccos\left[1 - \frac{2(\lambda_{FBG} - \lambda_0)}{\Delta\lambda}\right]\right\} \tag{2}$$

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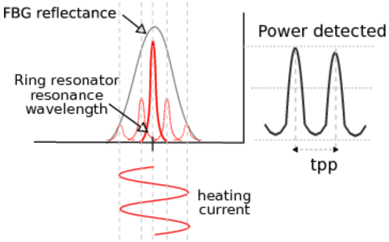

Fig 2. Time interval measurement concept

In our simulation, starting at room temperature (25 °C), ring temperature varies from 0 °C to 26.9 °C which implies a maximum wavelength shift of 2.56 nm. The sinusoidal current signal frequency was $f = 1\ Hz$, thus the temperature rate was twice that frequency. The FBG reflectance was modeled as Gaussian spectrum at 10 different center wavelengths. By applying a Lorentzian model for our ring resonator transmission, then a numerical integration was done between those spectra. The time interval between peaks was obtained by a peak search algorithm.

III. RESULTS AND DISCUSSION

Fig. 3 shows the overlap intensity of our ring resonator filter and FBG spectrum. In the picture there are three intensity curves which corresponds to events when the FBG Bragg resonance have a spectral shift. Fig. 4 shows how a measured peak to peak time interval could be converted into FBG spectral shift. The dots correspond to results of the peak search algorithm obtained from simulated FBG spectral shift scenarios while the red line comes from (2).

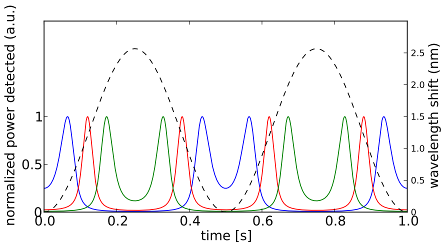

Fig 3. Ring resonator wavelength variation and time interval measurement results at three different FBG wavelength shifts (0.4, 1.2 and 2.0 nm).

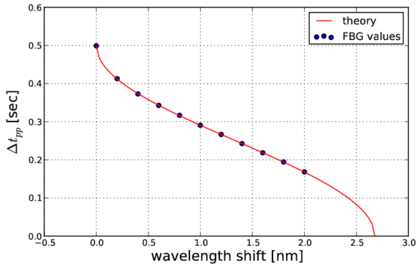

Fig 4. Results from time interval between peaks detection for 10 wavelength shifts of a FBG.

We can obtain the maximum sensitivity of the time interval measurement due to a fractional change of the center wavelength of a sensor. By calculating the slope of (2), the maximum sensitivity is proportional to the time period of the heating current and inversely to the wavelength scanning range. A sensitivity value of 124 $\mu s/pm$ was obtained for a current frequency of 1 Hz and 2.56 nm of wavelength range.

In reference [4], a ring resonator of the same dimensions as this simulation had a maximum average rise time of 78 μs for a 6.4 nm tuning and 14 μs for 0.2 nm tuning. This simulated scenario employs 2 Hz wavelength tuning, which can be increased accordingly to hundreds of Hz. Therefore a compromise must be made between scan rate and wavelength tuning range in order to maintain an acceptable timing sensitivity which will also depend on the oscilloscope time settings.

Based on these results, and a FBG sensor at 1574 nm with strain and temperature responsivities of $0.78 \times 10^{-6} \mu\varepsilon^{-1}$ and $6.67 \times 10^{-6} {}^{\circ}C^{-1}$[1], using a 2 nm of wavelength range for this system, will imply approximately 1.6 $m\varepsilon$ and 190 °C strain and temperature measurement range. These values show that this sensor reading system can be used for civil engineering applications.

Noise performance while is important for comparison among other interrogation methods, was not considered in this analysis. We will extend our research by introducing noise sensitivity and how this affects wavelength resolution.

CONCLUSION

We have shown an optical sensor demodulation system based on a ring resonator tunable filter. To extract the wavelength shifts of a sensor's spectral response, we employed a time interval between detected peaks. This system was simulated based on ring resonator published data and a simple thermal model. A sensitivity of 124 $\mu s/pm$ was obtained which depends on the scan rate and wavelength tuning range of the ring resonator. This approach has the potential of high scalability due to small footprint of the Si device, and large demultiplexing capabilities by employing an array of ring resonators that can read many optical sensors distributed in a fiber.

REFERENCES

[1] A. D. Kersey, "Fiber grating sensors," *Journal of Lightwave Technology*, vol. 15, no. 8, pp. 1442– 1463, 1997.

[2] J. Mora, J. L. Cruz, M. V. Andres, and R. Duchowicz, "Simple High-Resolution wavelength monitor based on a fiber bragg grating," *Applied Optics*, vol. 43, pp. 744–749, Feb. 2004.

[3] P. Rabiei, W. Steier, Z. Cheng, and L. Dalton, "Polymer micro-ring filters and modulators," *Journal of Lightwave Technology*, vol. 20, no. 11, pp. 1968–1975, 2002.

[4] X. Wang, J. A. Martinez, M. S. Nawrocka, and R. R. Panepucci, "Compact thermally tunable silicon wavelength switch: Modeling and characterization," *Photonics Technology Letters, IEEE*, vol. 20, no. 11, pp. 936–938, 2008.

[5] Q. Xu, S. Manipatruni, B. Schmidt, J. Shakya, and M. Lipson, "12.5 gbit/s carrier-injection-based silicon micro-ring silicon modulators," *Optics Express*, vol. 15, no. 2, pp. 430–436, 2007.

[6] B. Jayaraman, N. Bhat, and R. Pratap, "Thermal characterization of microheaters from the dynamic response," *Journal of Micromechanics and Microengineering*, vol. 19, no. 8, p. 085006, 2009.