High precision measurement of intensity peak shifts in tunable cascaded microring intensity sensors

Prashanth R. Prasad,1 Shankar K. Selvaraja,2 and Manoj M. Varma1,2,*

1Department of Electrical Communication Engineering, Indian Institute of Science, Bangalore 560012, India
2Centre for NanoScience and Engineering, Indian Institute of Science, Bangalore 560012, India
*Corresponding author: mvarma@ece.iisc.ernet.in

Received 18 May 2016; accepted 5 June 2016; posted 9 June 2016 (Doc. ID 265380); published 5 July 2016

We demonstrate a method to precisely track intensity peak shifts in tunable cascaded double-microring based refractive index sensors. Without modifications, width of the intensity peak of a tunable cascaded microring device limits the precision of peak-shift measurements and thereby the limit of detection of the sensor. We overcome this limitation by using dual harmonic lock-in detection for precisely determining the position of the intensity maximum. Using this modification, we have demonstrated a reduction in the full width at half-maximum (FWHM) of the intensity peak by a factor of over 1300. We show that such a reduction in FWHM of the peak curve can significantly improve the detection limit of a tunable cascaded microring-based sensor. © 2016 Optical Society of America

OCIS codes: (130.0130) Integrated optics; (130.6010) Sensors; (230.5750) Resonators.

http://dx.doi.org/10.1364/OL.41.003153

Silicon-photonics-based evanescent field optical sensors have been studied extensively in the past for potential applications in the field of biomedical research, food processing, health care diagnostics, and other areas [1,2]. One of the main factors driving the research on silicon-photonics-based sensors is the possibility of high-volume production by leveraging the well-established CMOS technology, used for manufacturing semiconductor electronics. Among various sensor configurations in silicon photonics, microring resonators have attracted great interest because of their simple design and well-studied operation [3,4]. In the recent past, a highly sensitive refractive index measurement device configuration based on cascaded microring resonators was demonstrated [5]. In this scheme, wavelength shifts are converted to intensity variations by using two microrings in a series cascade. This enables low-cost operation by sensing changes in the output intensity instead of spectral shifts. Although this detection scheme offers high sensitivity owing to the Vernier effect [6], it suffers from a limited range of detection [5]. To extend the detection range, we had previously described and implemented thermo-optically tunable cascade microring sensors that track the intensity peak, instead of measuring the intensity changes around the maximum slope [7]. While the tunable microring sensor provides an extended range beyond 0.02 RIU of analyte index, the detection limit in this case is constrained by the width of the intensity peak.

In this article, we overcome this limitation from intensity peak width by implementing a dual harmonic lock-in-based detection to reduce the FWHM of peak widths by nearly 3 orders of magnitude. This technique is used extensively in a wavelength-modulated laser absorption spectroscopy for precise measurement of absorption peaks for detection of trace amounts of gases [8]. A similar technique has been implemented with a single microring-resonator-based sensor using electro-optical tuning [9]. In this Letter, we describe a method in which the position of intensity peak of a cascaded double microring sensor is precisely determined by obtaining the ratio of the second- and first-order derivative of the intensity curve by thermo-optic modulation and lock-in detection. Using this method, we have achieved a reduction in the FWHM width of intensity peak over a factor of 1300 and an instrument noise constrained detection limit of $8.7 \times 10^{-6}$ RIU of analyte index.

A basic schematic of a tunable cascaded microring sensor device is shown in Fig. 1. It consists of two microrings, a filter ring and a sensor ring, in a cascade series. The filter microring is thermo-optically tunable by means of a microheater, while the sensor microring probes the analyte. Broadband light is input to

![Fig. 1. Schematic of the thermo-optically tuned cascaded microring resonator.](image-url)
the device through grating couplers. The drop port output of the sensor microring is coupled to the filter microring. The output of the filter microring, at its drop port, is detected by a photodetector. Because we aim to demonstrate the proof-of-concept device in this Letter, we use thermo-optical tuning to induce changes in the spectrum of the sensor microring to emulate variations in analyte index. In an actual device, the sensor microring could interface with the analyte liquid through a window opened in an overlying polymer layer such as PDMS.

The optical power at the drop port output of a single microring can be written as [10]

\[
P_{d_i} = |E_{d_i}^2| = \frac{\alpha_i |k_{f_i}|^2 |k_{s_i}|^2}{1 - 2 |r_{f_i} r_{s_i}|^2 |\alpha_i \cos(\theta_i) + \alpha_s^2 |r_{f_i} r_{s_i}|^2|^2}.
\]

Here, the subscript \(i\) can be interchanged for either the sensor or filter microring, \(k\) is the cross-coupling coefficient for the directional coupler, \(r\) is the self-coupling (transmission) coefficient, \(\alpha\) is the round-trip loss factor, and \(\theta\) is the round-trip accumulated phase, given as

\[
\theta_i = \frac{2\pi}{\lambda} n_{di} L_i.
\]

In this expression, \(L_i\) is the circumference of the microring and \(\lambda\) is the wavelength of light. At the output of the device shown in Fig. 1, the integrated power spectrum is given by the expression:

\[
I_{out}(\theta_f, \theta_s) = \int P_{d_f} P_{d_i} d\lambda.
\]

Here, \(f\) and \(s\) subscripts indicate filter and sensor microrings. Output intensity is highest when both filter and sensor spectra match perfectly, resulting in maximum overlap.

Figure 2(a) shows the spectral overlap between filter and sensor microrings and the output spectrum. The round trip phase of sensor shifts when the refractive index of the analyte is changed, resulting in variation of the output intensity, in accordance with Eq. (3). In turn, the spectrum of the filter microring is thermo-optically tuned to track the position of maximum overlap, as shown in Fig. 2(b). In the figure, the width of intensity peaks is about 0.0009 RIU of the effective index. This translates to about 0.0092 RIU of aqueous analyte index for a single-mode rib-waveguide-based device described in this Letter. Such a large peak width has a negative impact on the limit of detection of the sensor. In general, the width of intensity peak can be minimized by improving the quality factor of resonances of filter and sensor microrings and also by obtaining a close match between the spectra of the same. This can be achieved by careful optimization of design and fabrication processes. However, the quality factor of the sensor ring resonances is inevitably affected by absorption of aqueous media of the analyte, thus imposing a lower limit to the width of intensity peak.

In Fig. 2(b), it is observed that, at the peak position, slope of the intensity curve is close to zero, while its second derivative (curvature) is nonzero. Consequently, the ratio of the second derivative to the first attains a maximum at this position. Furthermore, the second derivative reduces in magnitude rapidly on either side of the peak whereas the opposite is true for the first derivative. Therefore, it would be advantageous to use this ratio for tracking shifts rather than the intensity peak itself. This requires a method to extract the curvatures of the intensity curve in real time. We implement this by using the dual-harmonic lock-in detection method [8]. The spectrum of the filter ring is provided with a sinusoidal modulation, along with the ramp input used to sweep the effective index of filter microring. Due to this combined input, the effective index of the filter ring waveguide undergoes variation in accordance with the following equation:

\[
n_{di} = n_s(p) + a_{nf} \sin(2\pi f t).
\]

Here, \(n_s(p)\) is the mean effective index shift resulting from the ramp input power \(p\) applied to the filter ring, \(a_{nf}\) is the amplitude (in refractive index units) of the index modulation occurring at frequency \(f\) of lock-in reference signal, and \(t\) is time. The modulated optical output, in general, consists of several harmonics of the lock-in reference frequency. Using Taylor series expansion, one can express the modulated optical signal at the output port as

\[
I_{out}(n_{di}) = I_{out}(n_s) + I'_{out}(n_s) \cdot a_{nf} \sin(2\pi f t)
\]

\[
+ (I''_{out}(n_s)/2) \cdot a_{nf}^2 \sin^2(2\pi f t) + \ldots.
\]

From this expression, we extract the amplitudes of the fundamental and second harmonic components as given below:

\[
A(f) \propto a_{nf} I'_{out}(n_s),
\]

\[
A(2f) \propto a_{nf}^2 I''_{out}(n_s).
\]

The ratio of amplitudes of the second harmonic (2\(f\)) and the fundamental (1\(f\)) is independent of input optical power and, hence, any fluctuations caused due to input noise of the broadband source. As mentioned earlier, the ratio has a maximum at the peak intensity position. Figure 3 shows a comparison between the simulations of intensity peak, 1\(f\) component, 2\(f\) component, and their ratio. Parameters required for this simulation, such as waveguide losses, were derived from experimental measurements.

A brief description of device fabrication is provided below. Electron-beam lithography was used to define patterns on an
SOI wafer with a 220 nm device layer thickness and 2 μm thick buried oxide. Shallow etched rib waveguides and gratings (630 nm period with 0.5 fill factor, TE mode operation), with a single step etch depth of 70 nm, were used in the process. This was followed by 1.8 μm of PECVD oxide deposition, to form an oxide spacer to separate the waveguide from metal heaters. Subsequently, metal heaters were patterned using UV lithography, metal deposition, and lift-off processes. A bi-layer metal Cr–Pt with 10 μm thickness was used for heater definition. Figure 4 shows images of the fabricated device.

As mentioned earlier, we have used thermo-optic effect on the sensor microring to emulate the effect of analyte index change. Radii of both rings were set to 100 μm with short couplers of 7 μm length. The free spectral range of the filter and sensor microrings were measured to be, respectively, 1.009 and 1.010 nm. The electrical resistance of the filter and sensor microheaters were, respectively, measured to be 261 Ω and 273 Ω at room temperature.

A 2.5 mW broadband input (SLD-Thorlabs) centered at 1560 nm and with Gaussian power distribution with 45 nm half-power bandwidth was used at the input port. The sensor microheater was powered by a high precision source-measure unit (SMU) (Keithley 2401). The filter microheater was driven by another SMU (Keithley 2400), which was connected in series to a reference signal generator (SRS DS-345). The output of the device was supplied to a digital lock-in amplifier (Signal Recovery 7265), which used the output of the signal generator for reference. The chip was mounted on a thermally stabilized platform to minimize effects of ambient thermal variations. We measured the thermo-optically induced wavelength shift coefficient of the filter microheater to be about 13.9 pm/mW of electrical power. This corresponds to an effective index shift of about $3.33 \times 10^{-5}$ m/W at 1550 nm. For calculations, the thermo-optic shift coefficients of the sensor microheater were assumed to be the same as that of the filter microheater because both microrings and heaters were identical in design.

Figure 5 shows the measured plots of intensity peaks, first harmonic, second harmonic, and the ratio signals. In this case, the SMU provided power in steps of 50 mW. The modulation frequency was set to 1 kHz, at 0.2 V amplitude, which resulted in optimum values of $1f$ and $2f$ output signals.

As expected, the ratio plot provides much narrower FWHM than the intensity peak plot. We observe a slight offset between the maxima of $2f$ signal and the minima of $1f$. This offset is the result of an asymmetry in the intensity peak curve and had no adverse effect on the results of our experiments. The FWHM width of intensity peak is about 12 mW, whereas that of the ratio signal is about 0.3 mW providing a reduction by a factor of 40, for this particular case. In order to demonstrate the peak shift tracking capability, the sensor microheater was powered in steps of 50 μW while the filter microheater was scanned to track the shift in peak position. Figure 6(a) shows the shift in peak position with an increase in power applied to the sensor microheater. The upper axis (effective index shift) of this figure was estimated using the thermo-optic coefficient measured previously. As expected, the $2f/1f$ peak shift is linear with respect to applied electrical power to the sensor microheater.

Several experiments were performed to determine the limit of detection of the device. The filter microring was scanned (in steps of 10 μW) to find the peak position of the $2f/1f$ ratio plot, while the sensor microring was maintained at a constant power. This resulted in a spread of the ratio peak position, as shown in Fig. 6(b). In each case, the ratio curve was fitted with a Lorentzian curve to accurately determine the peak position. The FWHM of fitted curves was measured to vary between 9 and 16 μW. Widths of peaks in Fig. 6(b) are much lower than those in Fig. 5. This is because smaller step sizes in filter electrical power (10 μW) enable the $1f$ signal to approach close to zero value near the maximum of intensity peak, resulting in a

**Fig. 3.** Simulated results comparing the intensity peak curve, magnitudes of $1f$ signal, $2f$ signal, and the $2f/1f$ ratio showing the reduction in FWHM.

**Fig. 4.** Optical microscope image of the tunable cascaded microrings. Inset (a): Simulated mode profile for a single-mode rib waveguide. Inset (b): SEM image of directional couplers used for microrings. Scale bar of the inset measures 500 nm.

**Fig. 5.** Measured plots of intensity curves at the output showing the reduced FWHM of $2f/1f$ peak, as a function of electrical power applied to filter microheater. Power applied to the sensor microheater is 0 mW.
steep rise of the $2f/1f$ ratio. Further, the smallest FWHM (9 μW) of $2f/1f$ ratio peak is narrower by a factor of nearly 1330, compared with that of the unprocessed intensity peak (12 mW). The mean value and standard deviation ($σ$) of the ratio peak position were calculated to be, respectively, 6.316 mW and 8.6 μW. Figure 6(b) also shows the intensity peaks measured directly at the output port of the device.

Uncertainty in peak position can result from several factors such as repeatability of the SMU powering the microheaters, amplitude variations of the reference signal generator providing input modulation, and the effect of ambient temperature variations. The impact of the last factor, that is ambient temperature variations, is minimized due to similar responses of filter and sensor microcircuits to temperature drifts [11]. Using values from the datasheets of the Keithley-2400 SMU and DS-345 signal generators, the worst case standard deviation in position of the peak $2f/1f$ ratio plot was estimated to be close to 14.4 μW, indicating that the measured uncertainty is within expected values.

Because the limit-of-detection (LOD) corresponds to the smallest measurable shift in the analyte index, it is necessary to link the effective index shift in a sensor microcircuit with change in fluid index. A single microcircuit, fabricated with the same dimensions and process steps as previously described was used for this purpose. Glycerin–water mixtures of different proportions were drop-cast over the microcircuit, and the resultant shift in the output spectrum was monitored. Results of several trials from the device showed a mean wavelength sensitivity of 40.9 nm/RIU from which the effective index shift coefficient was calculated to be about 0.0978 using the following expression [12]:

$$\frac{\Delta n_{\text{eff}}}{\Delta n_{\text{fluid}}} = \frac{n_{\text{eff}}}{n_{\text{fluid}}} \frac{\Delta \lambda}{\lambda_0} \frac{\Delta n_{\text{fluid}}}{\sigma}.$$  (8)

In this expression, $Δ\lambda$ is the shift in wavelength, $Δn_{\text{eff}}$ is the shift in effective index, $Δn_{\text{fluid}}$ is the shift in fluid index, and $n_{\text{eff}}$ is the group index of the waveguide at $\lambda_0$, the central wavelength.

Using this value, along with the effective index shift coefficient ($3.33 \times 10^{-3}$/mW) and the 3σ value of $2f/1f$ peak power position uncertainty (25.8 μW), the limit of detection was calculated to be $8.7 \times 10^{-6}$ RIU of analyte index. However, from Fig. 6(b), it is clear that the LOD is not limited by the width of peaks but by noise from measurement electronics. With the use of equipment with better noise specifications than those used in our experiments, we believe that the limit of detection can be improved even further. In accordance with analysis shown in [7], the total detection range of the device was 0.0241 RIU of the fluid analyte index.

In summary, we have described and demonstrated a method to track peak shifts precisely in the tunable cascaded double microcircuit sensor by using dual-harmonic lock-in detection. The tunable cascaded microring configuration enables low-cost operation because it uses a low power broadband source and a single photodetector for operation. By implementing the lock-in-based peak tracking method using embedded electronic equipment with high precision and reliability, the LOD of the tunable cascaded microring device configuration can be improved further, possibly to under $1 \times 10^{-6}$ RIU, at low unit costs.

Acknowledgment. The authors thank the staff of the National Nano-Fabrication Centre (NNFC) and the Micro and Nano Characterization Facility (MNCF) at the Indian Institute of Science-Bangalore for their assistance. Prashanth R. Prasad is grateful to the Ministry of Human Resource Development, Government of India for funding his scholarship.

REFERENCES