

Frequency locked micro disk resonator for real time and precise monitoring of refractive index

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We experimentally demonstrate a frequency modulation locked servo loop, locked to a resonance line of an on-chip microdisk resonator in a silicon nitride platform. By using this approach, we demonstrate real-time monitoring of refractive index variations with a precision approaching 10^{-7} RIU, using a moderate Q factor of 10^4 . The approach can be applied for intensity independent, dynamic and precise index of refraction monitoring for biosensing applications. © 2012 Optical Society of America

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Frequency modulation (FM) spectroscopy and the similar Pound–Drever–Hall techniques are widely used to lock the optical frequency to a desired resonance frequency and to measure the dispersive properties of resonant phenomena [1,2]. In these methods, an error signal is fed back to the laser, and consequently aligns the laser to the desired resonance. Using the frequency-locking scheme, one can be immune to frequency variations in time by matching the resonance frequency to that of the source [3–5]. Moreover, one can simultaneously monitor these frequency changes and detect precise frequency changes. For example, in an atomic clock a frequency uncertainty ($\Delta f/f$) of 10^{-11} at time constant of 1 sec is achieved [6], being often five orders of magnitude smaller than the inverse Q factor of the atomic line.

The quest for miniaturization offers a variety of potential benefits for using such a scheme in on-chip photonic devices. Specifically, its precise and dynamic nature is suitable for on-chip sensing applications often achieved by tracking the resonance shift of photonic resonators due to presence of analytes [7]. Here, we demonstrate highly precise, real-time on-chip sensing of refractive index variations in a moderate Q factor silicon nitride microdisk resonator (SNMR) using a frequency locked loop.

The experimental FM spectroscopy frequency locked loop setup is illustrated in Fig. 1.

A frequency modulated (the frequency is set in the range 300 Hz and the modulation depth set in the order of the width of the resonance) 980 nm source (Newfocus 6300) is coupled to a SNMR. The 30 μ m radius SNMR is similar in concept to microring resonators reported and was realized by chemical vapor deposition of a 200 nm SiN layer followed by electron-beam lithography and reactive ion etching [8]. The near IR wavelength (980 nm) is ideal for biosensing applications as it provides a decent compromise between the absorption of water (which is increased toward the infrared) and the absorption of proteins (which is increased at shorter wavelength toward the visible) [9]. The Q factor of the SNMR at this wavelength was found to be in the range of 10,000.

The light is coupled to and out of the SNMR using an adjacent bus waveguide, and is monitored by a silicon photo detector (Thorlabs DET100A). The detected signal

is demodulated by a lock-in amplifier (LIA, Stanford Research SR510) at the modulation frequency. The quadrature output of the LIA is integrated using an integrator and fed back to the laser as a frequency offset using the piezo control of the source. This approach can be thought of as a means to differentiate the SNMR's resonance. The differentiated signal is used as an error signal, with a zero crossing at resonance. This error signal is fed back to the laser. The integrator has the role of a memory: it enables the system to dynamically lock the frequency and, in parallel, to track the frequency detuning of the resonator.

Under the conditions demonstrated in this work the measured time constant of the servo loop was 2.8 seconds. However, if needed, the time constant can be reduced by orders of magnitude (e.g., by increasing the gain of the LIA and/or by changing the time constant of the integrator).

To demonstrate the proposed scheme, we perturbed the SNMR's resonance frequency via the thermo-optic effect by changing its temperature using a thermoelectric cooler (TEC, Thorlabs TEC3-2.5), which is positioned below the chip. A thermistor (Thorlabs HT10K, 15 seconds time constant), mounted on the chip (a few mm away from the SNMR), is used to monitor the temperature. Both the thermistor and TEC are controlled by a temperature controller (Newport 325), used to modify the temperature of the chip in an open loop configuration.

Next, the frequency servo loop is closed, and the output of the integrator is monitored. During this time, the second harmonic of modulation frequency of the output of the SNMR was dominant, while the first harmonic was absent, indicating that the system was locked to the resonance. It should be noted that, in addition to changing

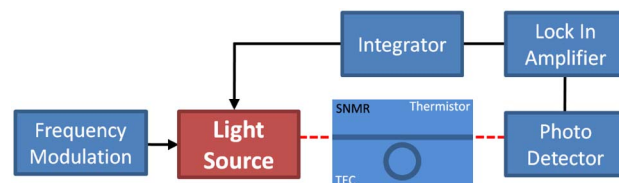


Fig. 1. (Color online) Schematic representation of the experimental setup.

the resonance frequency, the thermal effect may also change the SNMR's coupling condition and thus the extinction ratio of the device. However, being intensity independent, our scheme is insensitive to this effect (as long as a sufficient signal-to-noise ratio is maintained).

Next, the output voltage of the integrator was converted to wavelength units by scanning the laser (in 10 pm steps) over two resonances corresponding to two different temperatures. The conversion factor was found to be 0.038 ± 0.01 nm/V. In Fig. 2(a), we show an example of these two resonance curves. The difference between the two resonance curves corresponds to a temperature difference of $\sim 1^\circ\text{C}$. The calibration error could be reduced, using, for instance, a Fabry–Perot cavity as a frequency ruler. As in other sensing approaches, this calibration mainly affects the systems accuracy, as opposed to its precision around the working point. In Fig. 2(b), we illustrate the detuning in resonance wavelength as a function of the change in temperature. As can be clearly seen, a linear dependence is found as anticipated to the first order by the relation $\Delta n/\Delta\lambda = n/\lambda$ and the linear thermo-optic relation between temperature and refractive index change. From Fig 2(b) we can estimate the thermo-optic coefficient of the nitride and the oxide layers to be on the order of 10^{-5} $1/^\circ\text{C}$, which is in agreement with values known from the literature.

Next, we demonstrate the dynamic and precise nature of our scheme (i.e., the ability to track in real time small changes in the refractive index). To do so, we apply a varying temperature profile by applying a sequence of current steps to the TEC. The measured temperature profile is plotted in Fig 3(a). One can see the temperature at equilibrium at temperatures T_1 , T_2 , and T_3 , and the equilibration of the temperature between these points. The temperature uncertainty is measured to be ~ 50 mK and reflects the thermal controller monitor's noise limit.

In Figure 3(b), we plot the integrator's output (calibrated to units of wavelength detuning) as a function of time. As can be clearly seen, the error signal follows the temperature profile, with a relatively high signal-to-noise ratio. Careful examination and averaging of the initial and final temperatures, denoted by T_1 and T_3 , respectively, reveal a temperature difference corresponding to 70 mK. This difference is in agreement with the measured red shift of 1.1 pm, revealed from the integrator's signal [Fig. 3(b)]. The signal difference between T_1 and T_3 (30 mV) is sufficient for detection by our integrator. We estimate the standard deviation of the integrator's output while locked and at a fixed TEC current to be 3 mV,

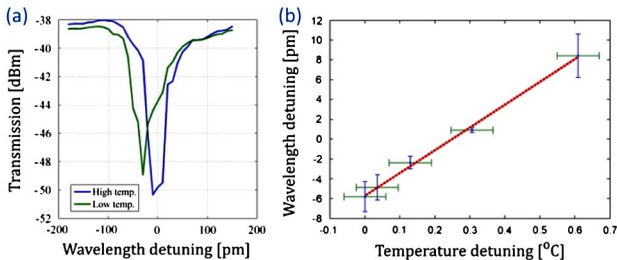


Fig. 2. (Color online) (a) Two resonance curves corresponding to a temperature difference of $\sim 1^\circ\text{C}$. (b) Wavelength detuning as a function of temperature detuning.

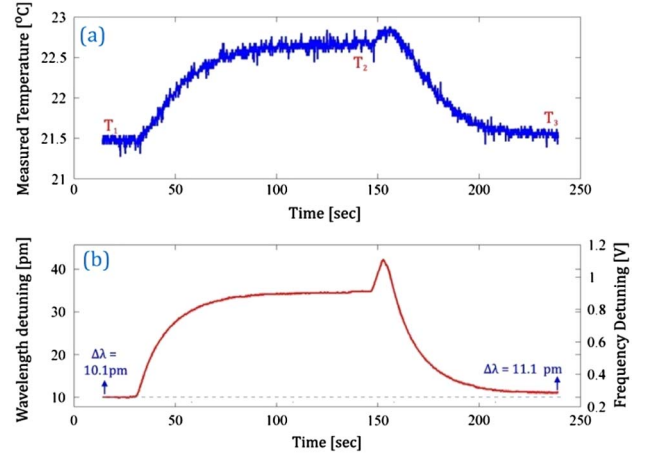


Fig. 3. (Color online) (a) Thermistor measurement as a function of time. (b) Integrator signal as function of time, while servo loop is closed.

corresponding to 0.1 pm. This typical value has been measured in five independent measurements. This noise limit is most likely due to the thermal variations of our system, which is not isolated from the environment and thus subject to heat convection and conduction. In many bio-sensing scenarios, the dynamic range of the system is important. In our case it is limited to the piezo scanning range being approximately 50 GHz and supporting variations of refractive index in a range between 10^{-4} and 10^{-7} . The dynamic range can be orders of magnitude larger (using, for instance, the full tuning range of the tunable laser for abrupt changes and the piezo for smaller, precise changes).

The measured frequency detuning corresponds to a refractive index shift of $\sim 10^{-6}$, and the detection limit, according to the standard deviation of the integrator, corresponds to $\sim 10^{-7}$. Note that this number is three orders of magnitude smaller compared with the resonance-normalized linewidth. Even if we assume a typical scenario of sensing based on evanescent waves (where one tracks the change in the refractive index of the cladding of the resonator), with 10% of the mode interacting with the cladding, a refractive index shift of $\sim 10^{-6}$ is expected as a detection limit. This figure of merit is comparable to the sensing capabilities achieved using state-of-the-art resonator sensing systems [10], although better values were reported for resonators with ultrahigh Q factors [11].

In general, the frequency uncertainty in such a scheme can be characterized by the Allan deviation, which is a measure of frequency uncertainty in oscillators and resonators. Because it is a two-sample statistic, it can eliminate drifts, such as thermal ones, in the system. It has been shown [6] that the Allan deviation of FM spectroscopy locked resonance is proportional to $Q^{-1}(\text{SNR})^{-1}(t)^{-1/2}$ where Q is the Q factor, SNR is the signal-to-noise ratio, and t is the time constant. Thus, to improve the detection limit, one can enhance the Q factor of the resonator and the SNR (e.g., by improving the extinction ratio and coupling conditions from the bus waveguide to the resonator and from the external light source to the chip as well as by reducing the noise). Furthermore, the

modulation frequency and modulation depth should be chosen to maximize the slope of the error signal.

Additional limiting factors need to be considered. First, non-linear and thermal effects may induce resonance frequency shift, as well as lineshape distortions. In this work, we have used moderate levels of power, in the μW regime. The main contribution to the frequency shift in silicon nitride systems is the thermal effect. The frequency shift was measured in a structure similar in dimensions to ours to be 1.58 pm/mW [12]. Based on this value, and taking into account that even after resonant enhancement of the field within the resonator (energy enhancement is proportional to the Finesse, 10 in our case), the wavelength is expected to change no more than a few tens of fm, which is still smaller than our detection limit. As to the Kerr effect, using the SiN Kerr coefficient of $2.4 \times 10^{-10} \text{ W/cm}^2$, [12] we obtain a negligible index of refraction shift.

Additionally, thermal fluctuations of the SNMR and/or the frequency instability of the source might dominate the detection limit. In the time constant of seconds (demonstrated in this work), the latter has a negligible impact. However, in the case of longer measurements ($\sim$ hours), as often required by biosensing applications, the use of a reference signal is recommended. In this scheme, one can lock a modulated laser to two SNMRs with adjacent resonant peaks, subject to the same thermal environment, and monitor the frequency difference between them. This approach cancels the effect of laser drifts, and the temperature instability of the SNMR.

In summary, we have experimentally demonstrated a simple, intensity-independent, dynamic, and highly sensitive scheme to frequency lock a laser to an SNMR's frequency, using a moderate Q factor in a chip-scale environment optimized for biosensing. Due to the dynamic nature of the scheme, we suggest to exploit the method for dynamic and high precision transient sensing applications. Using this approach, we were able to track changes in the refractive index with a precision of 10^{-7} refractive index units. This detection limit is about three orders of

magnitude better compared with the linewidth of the microdisk resonator. The precision can be further improved by enhancing the Q factor and the SNR, as well as by optimizing the modulation frequency and the modulation depth. Finally, the proposed platform could be scaled up by either splitting the signal into multiple SNMRs and locking on each of them or by using a VCSEL array integrated with a chip consisting of multiple SNMRs.

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References

1. G. C. Bjorklund, M. D. Levenson, W. Lenth, and C. Ortiz, *Appl. Phys. B* **32**, 145 (1983).
2. R. W. P. Drever, J. L. Hall, F. V. Kowalski, J. Hough, G. M. Ford, A. J. Munley, and H. Ward, *Appl. Phys. B* **31**, 97 (1983).
3. T. Carmon, T. J. Kippenberg, L. Yang, H. Rokhsari, S. Spillane, and K. J. Vahala, *Opt. Express* **13**, 3558 (2005).
4. P. Del'Haye, O. Arcizet, A. Schliesser, R. Holzwarth, and T. J. Kippenberg, *Phys. Rev. Lett.* **101**, 053903 (2008).
5. D. O'Shea, A. Rettenmaier, and A. Rauschenbeutel, *Appl. Phys. B* **99**, 623 (2010).
6. J. Vanier and C. Mandache, *Appl. Phys. B* **87**, 565 (2007).
7. A. Yalcin, K. C. Popat, J. C. Aldridge, T. A. Desai, J. Hryniewicz, N. Chbouki, B. E. Little, O. King, V. Van, S. Chu, D. Gill, M. Anthes-Washburn, M. S. Unlu, and B. B. Goldberg, *IEEE J. Sel. Top. Quantum Electron.* **12**, 148 (2006).
8. I. Goykhman, B. Desiatov, and U. Levy, *Appl. Phys. Lett.* **97**, 081108 (2010).
9. K. C. Neuman and S. M. Block, *Rev. Sci. Instrum.* **75**, 2787 (2004).
10. N. Jokerst, M. Royal, S. Palit, L. Luan, S. Dhar, and T. Tyler, *J. Biophotonics* **2**, 212 (2009).
11. H.-S. Choi, S. Ismail, and M. A. Armani, *Opt. Lett.* **36**, 2152 (2011).
12. K. Ikeda, R. E. Saperstein, N. Alic, and Y. Fainman, *Opt. Express* **16**, 12987 (2008).