Ultra-Sensitive biochemical Sensor based on Circular Bragg Micro-Cavities

Jacob Scheuer, William M. J. Green, Guy DeRose and Amnon Yariv
Departments of Electrical Engineering and Applied Physics, California Institute of Technology, MC 128-95, 1200 E. California Blvd., Pasadena, CA 91125, USA koby@caltech.edu

Abstract: We demonstrate an ultra-sensitive sensor realized in high quality circular semiconductor micro-cavities employing radial Bragg reflectors. Resolution enhancement by a factor of ten, compared to conventional ring resonators, is demonstrated experimentally.

OCIS codes: 230.5750 Resonators; 280.3420 Laser sensors

1. Introduction

The realization of highly miniaturized spectroscopic components capable of detecting selective binding of ultra-small quantities of chemical or biological agents is a significant step towards the development of compact and versatile "lab-on-chip" devices. One of the most attractive approaches for the realization of compact integrated optical sensors is detecting the shifts of the resonance frequency of a micro-resonator caused by changes in the refractive index of the device surroundings [1-4]. To achieve high sensitivity, large interaction volume between the modal field profile and the analyte is desired. In conventional resonators, employing total internal reflection (TIR) as the radial confinement mechanism, only the small evanescent tail of the field interacts with the surroundings, which consequently limits the sensitivity. Microcavities employing distributed Bragg reflection as the transverse confinement mechanism such as photonic crystal (PC) defect cavities [4-6] and annular Bragg resonators (ABRs) [7-10] exhibit unique mode profile which can offer enhanced sensitivity because of the larger interaction volume (see Fig. 1).

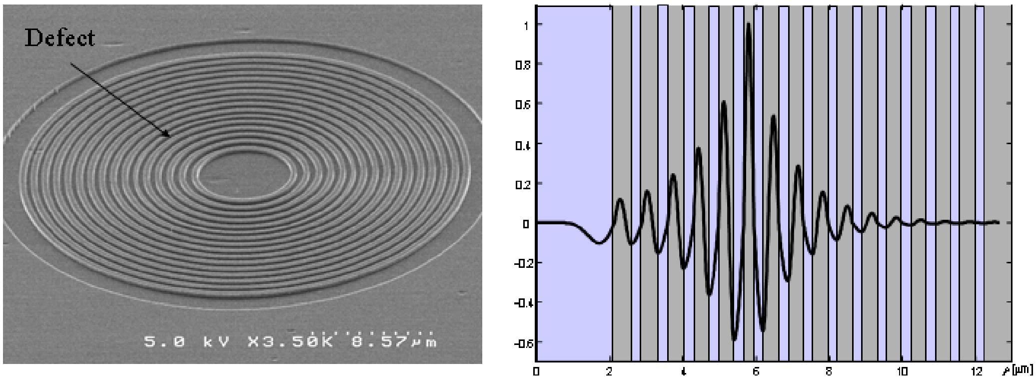
Here, we demonstrate an ABR laser for biochemical sensing applications with high spectral resolution and excellent sensitivity to changes in the absorption or refractive index of its surrounding. We compare the sensitivity of the ABR sensor to that of a conventional, TIR based, resonator of similar material and dimensions and find that the measurement resolution of the ABR sensor is ten times larger than that of the conventional device.

2. Design concept and theory

Figure 1a shows an SEM micrograph of an ABR sensor realized within a thin membrane of InGaAsP active material. The device consists of a circumferentially guiding defect surrounded by radial Bragg stacks from both sides. The electromagnetic propagates along the circumference of the defect while radially confined in the defect by the radial Bragg mirrors.

The reflectors of the ABR shown in Fig. 1a consist of 5 and 10 Bragg layers respectively and the device is designed for angular propagation coefficients of m=9. Due to the circular geometry, the optimal layer widths required to confine the light in the radial defect are not constant [7, 8] but rather monotonically decreasing with the radial distance, asymptotically approaching a constant width for large radii. Like conventional DBRs, radial Bragg reflector also consists of "quarter-wavelength-like" layers but in the sense of the quasi-periodicity of the Bessel function of the corresponding order (9 for the device shown in Fig. 1a) where we define "quarter-wavelength" as the separation between successive zero and extremum of the Bessel functions. The defect should be "half-wavelength" wide in the same notations .For practical reasons, the Bragg reflectors are of mixed order, i.e., the low-index layers are quarter-wavelength wide while the high-index layers are three quarter-wavelength wide. Such an approach facilitates the fabrication of the device and induces efficient emission in the vertical direction, enabling simple collection of the emitted light from the device.

Figure 1b depicts the radial mode profile and index structure of the fabricated ABR. The field peaks in the defect and decays while oscillating in the reflector regions. Fig 1b also illustrates the advantages of the ABR structure for sensing applications. Even though the main lobe of the mode profile does not interact with the device surroundings, significant parts of the field within the trenches between the semiconductor rings are exposed to the surroundings (light gray if Fig. 1b), thus yielding large interaction volume (compared to a conventional resonator). Therefore, an ABR based sensor is expected to exhibit enhanced sensitivity compared to a conventional resonator of similar dimensions.



a b

Fig. 1. (a) SEM image of the ABR sensor and (b) the radial mode profile and index structure of the device: dark gray – high index; light gray – low index.

3. Fabrication and measurement

ABRs of several geometries were fabricated within a 250nm thick membrane of InGaAsP with six 75Å quantum wells (QW) positioned at the center. After the ABR patterns were etched into the active material, the original InP substrate was removed and the membrane was transferred to a sapphire plate using an ultraviolet curable optical adhesive to improve the vertical confinement of the electromagnetic field in the device [9, 10]. The effective index of the membrane was found to be approximately 2.8 for the H_z polarization and 2.09 for the E_z polarization. Since the H_z polarization is more confined than the E_z polarization and the optical gain of the compressively strained QW structure used favors the H_z polarization [11], we optimized the radial structure to this polarization.

The emitted spectrum of the lasers was examined at room temperature under pulsed optical pumping. An 890nm pump beam from a Ti:Sapphire mode locked laser was focused through the transparent sapphire substrate on the backside of the sample with a 50X objective lens. A 20X objective lens was used to collect the vertical emission from the front side of the sample and to couple the light into a multi-mode fiber to obtain the emitted spectrum.

To test the influence of a change in the ambient refractive index on the laser spectrum, the ABR was sequentially immersed in a specially designed beaker containing index-matching fluids with increasing index of refraction. For each fluid, the emitted spectrum is measured under similar pump intensity (P_{pump} ~ 2.5mW) and spot size. Between measurements the ABR is rinsed thoroughly in acetone and isopropyl alcohol (IPA) in order to remove any residual traces of the previously used index-matching fluid. Figure 2a shows the emitted spectrum from a single ABR laser immersed in various fluids. It can be seen that wavelength shifts by more than 10 nm when the ambient refractive index of the cavity is changed by 0.08, demonstrating sensitivity of $d\lambda/dn$ ~ 130nm (see Fig. 3).

The FWHM of the lasing peak emitted from the device was ~1nm. For such linewidth, shifts in the resonance wavelength of 0.1nm can be easily resolved, thus allowing the detection of ambient index changes of Δn~5×10^{-4}, which to our knowledge is the one of the best resolutions ever demonstrated using integrated optical nano-sensors [4].

To demonstrate the advantages of ABR-sensors in terms of sensitivity and resolution, we compare the performance of our device to that of a conventional ring resonator with 5μm radius consisting of the same material. Figure 2b shows the shifts in the resonance wavelength of the conventional resonator for the same ambient indices of refraction used to characterize the ABR sensor. The sensitivity of the conventional resonator is approximately $d\lambda/dn$ ~ 33nm (see Fig. 3) and the resonances FWHM are ~1.4nm wide. As a result, the advantage of the ABR as a sensor is two-fold: 1) The sensitivity of the ABR is 4 times larger than that of the conventional device because of the larger interaction volume and 2) the conventional resonator has wider linewidth because of its lower Q, which reduces the ability to resolve the resonance wavelength. For 1.4nm FWHM, the ability to resolve the resonance wavelength is limited to ~0.14nm, which when combined with the lower sensitivity of the conventional device, yield a minimum detectable index change of Δn~4×10^{-3} – approximately an order of magnitude less than that of an the ABR sensor.

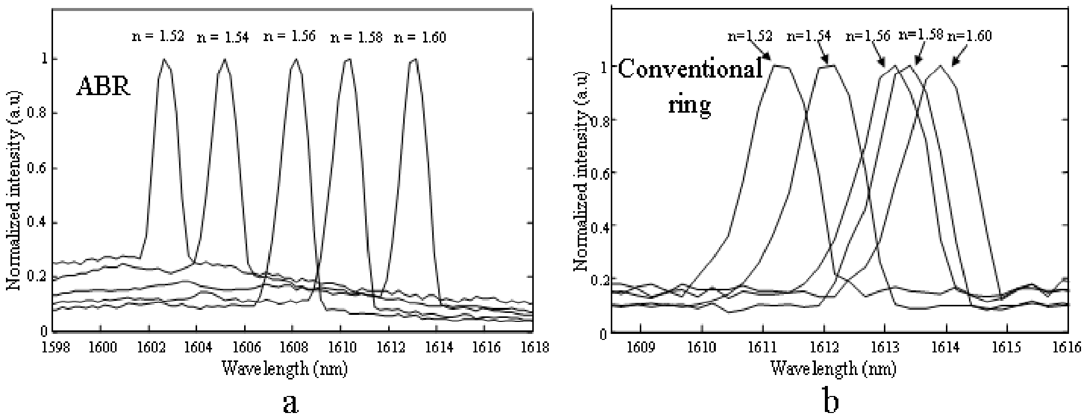


Fig. 2. Lasing spectra from the (a) ABR and (b) conventional ring resonator for five different ambient refractive indices ranging from n=1.52 to n=1.6 in 0.02 increments.

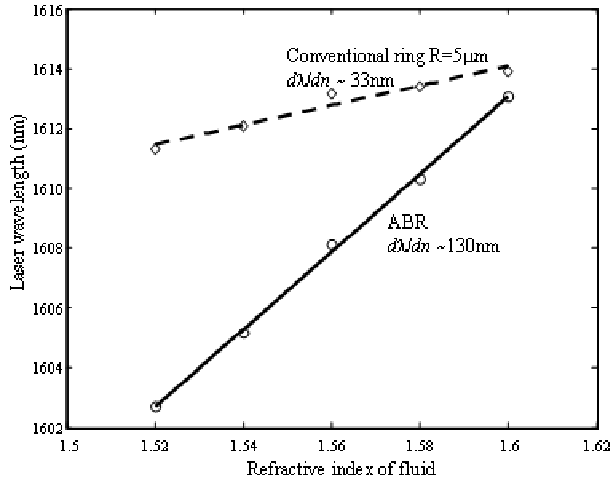


Fig. 3. Comparison between the shifts in the emitted wavelength of an ABR and a conventional resonator for changes in the ambient refractive index.

4. Conclusions

High Q circular Bragg micro-cavity lasers offer significant improvement of the ability to detect small changes in the ambient refractive index. We demonstrated lasing at room temperature from such lasers and showed that small changes in the ambient refractive index can be detected by observing the corresponding shifts in the lasing wavelength. Compared to conventional resonators, sensitivity enhancement of an order of magnitude was demonstrated experimentally. The resolution of the ABR sensor can be further improved by using an air-defect design. Because of their highly compact dimensions and enhanced resolution, ABR lasers have great potential for becoming key components for the realization of compact, integrated biochemical sensor arrays.

References

[1] R. W. Boyd et al, “Nanofabrication of optical structures and devices for photonics and biophotonics“, J. Mod. Opt. 50, 2543 (2003).

[2] C. Y. Chao and L. J. Guo, “Biochemical sensors based on polymer microrings with sharp asymmetrical resonance,” Appl. Phys. Lett., vol. 83, 1527 (2003).

[3] M. Loncar, A Scherer and Y. Qiu, “Photonic crystal laser sources for chemical detection”, Appl. Phys. Lett. 82, 4648 (2003).

[4] E. Chow, A. Grot, L. W. Mirkarimi, M. Sigalas, and G. Girolami, “Ultracompact biochemical sensor built with two-dimensional photonic crystal microcavity”, Opt. Lett. 29, 1093 (2004).

[5] O. Painter et al., “Two-Dimensional Photonic Bandgap Defect mode laser”, Science 284, 1819 (1999).

[6] J. Vučković, M. Lončar, H. Mabuchi and A. Scherer, “Design of photonic crystal microcavities for cavity QED,” Phys. Rev. E. 65, 016608 (2001).

[7] J. Scheuer and A. Yariv, “Annular Bragg Defect mode Resonators”, J. Opt. Soc. Am. B. 20, 2285 (2003).

[8] J. Scheuer and A. Yariv, "Coupled-Waves Approach to the Design and Analysis of Bragg and Photonic Crystal Annular Resonators", IEEE J. Quantum Electron. 39, 1555 (2003).

[9] J. Scheuer, W. M. J. Green, G. DeRose and A. Yariv, “Low Threshold Two-Dimensional Annular Bragg Lasers”, Opt. Lett. 29, p. 2641, 2004.

[10] W. M. J. Green, J. Scheuer, G. DeRose and A. Yariv, “Vertically emitting annular Bragg lasers using polymer epitaxial transfer”, Appl. Phys. Lett. 85, p. 3669, 2004.

[11] L. A. Coldren and S. W. Corzine, Diode Lasers and Photonic Integrated Circuits. New York: Wiley, 1995.