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Lithographic nanofabrication of optical cavities

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ABSTRACT

Lithographic control over nanostructures has recently evolved to an accuracy that permits the sub-wavelength manipulation of light within high refractive index semiconductors. We have used this lithographic control to fabricate two-dimensional photonic crystal cavities and micro-ring resonators. Here we will show the fabrication techniques utilized for the construction of High-Q nanocavities and, in particular, focus on the influence of present-day lithographic and etching procedures on the performance of the cavities. Applications of these optical cavities range from communications to chemical sensing and we will describe the effects of geometry on the different applications. We show the use of optical cavities for the miniaturization of optical spectroscopy systems with ultra-high spatial and spectral resolution.

Keywords: nanofabrication, optical cavity, chemical sensor, lithography

1. INTRODUCTION

The construction of compact spectroscopic tools for the optical analysis of ultra-small (~10^{-17} liter) sample volumes remains an important goal in the development of integrated microfluidics systems. Miniaturization of appropriate light sources and detectors can enable very compact and versatile "laboratory on a chip" devices, in which many analytical functions can be monolithically combined. One of the device integration platforms which is ideally suited to enable such integration of ultra-small and efficient optical components is the membrane based planar photonic crystal, defined in high refractive index contrast materials by standard lithography and semiconductor fabrication processes. High quality optical cavities with mode volumes far below a cubic wavelength have already been demonstrated, and can be used to obtain large optical field intensities and ultra-small laser sources. Here photonic crystal lasers and microfluidic delivery systems were combined with the idea of miniaturizing spectroscopic analysis tools.

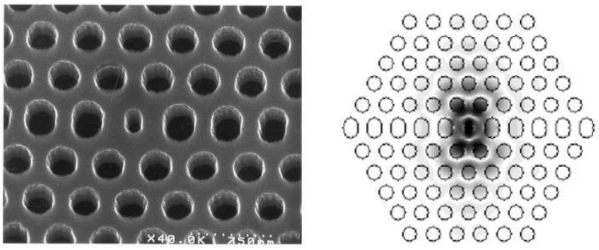

Figure 1. Scanning electron micrograph and calculated field distribution of a photonic nanocavity laser sensor.

Until recently, the applications of planar photonic crystals were restricted to large-scale integration of optical wavelength division multiplexing (WDM) components for telecommunications. Compact lasers, detectors, modulators, waveguides and prisms have been fabricated and demonstrated in thin slabs of silicon, GaAs or InGaAsP [1]. These devices can be used to generate, concentrate and route light efficiently within nanophotonic chips. Discrete planar photonic crystal nanocavities with high quality factors and small mode volumes have also been applied to cavity QED experiments [2]. These take advantage of the strong overlap between a spectrally narrow light emitter placed into the intense electromagnetic fields of a high finesse optical nanocavity. Here, we present another application of planar photonic crystal cavities in the development of chemical sensors, with high spectral resolution and excellent sensitivity to changes in the absorption or refractive index of their

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surrounding. By combining an unconventional cavity geometry (Figure 1) with optical gain at 1550nm, ultra-small sensor elements that emit a very narrow spectrum have been defined. Since these are lithographically defined, such sources can easily be integrated into large arrays to perform biological and chemical analysis on extremely small reagent volumes with outstanding sensitivity.

2. SENSOR DESIGN

2.1 Laser Design

The cavity geometry chosen for these chemical sensors is based on a single defect triangular lattice planar photonic crystal [2-11]. In addition to the introduction of a smaller hole to define the optical cavity, a fractional edge dislocation is also introduced by extending the length of one of the rows of holes to break the symmetry of the optical cavity. In our previous publications we have experimentally described the advantages of such a structure, and shown that it supports modes with both high Q [9] and small V_{mode} [12]. When defined within InGaAsP membranes, low-threshold room temperature lasers have also been defined [8]. The cavity design is shown in Figure 1 and it can be seen that the energy of the mode is mostly confined to the central defect hole. In order to increase the interaction between light and the material within that hole, a larger defect hole diameter is preferred. However, increasing this hole reduces the gain provided by the light emitting quantum wells within the laser cavity and thereby increases the threshold of our laser. Therefore, a trade off between the optical overlap with the analyte cavity and the optical gain is needed, and we have addressed this problem using numerical modeling.

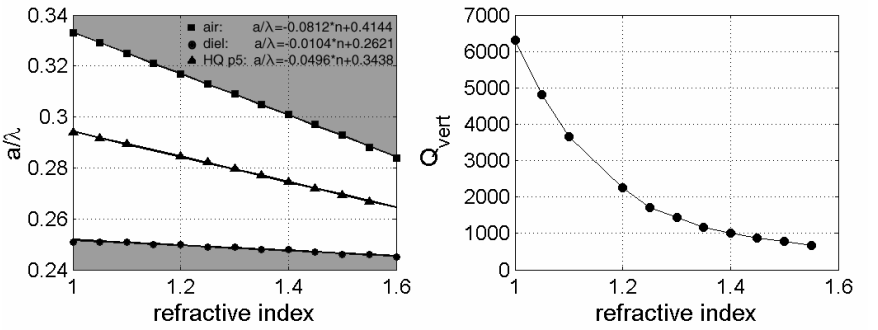

Figure 2. Dependence of the (a) eigen-frequency and (b) Q factor of HQ mode (p/a=25\%) on the refractive index of analyte.

This laser cavity has been designed using 3-D finite-difference time-domain modeling. The thickness of the slab with refractive index of 3.4 was d=0.75a, where a is the lattice parameter of the photonic crystal. The size of the holes which define the planar photonic crystal mirror surrounding the cavity was r=0.3a. A single defect donor cavity in a triangular lattice photonic crystal without the fractional edge dislocation is known to support two doubly-degenerate, linearly polarized, dipole modes [13] with rather modest quality factors of several hundred. However, as the photonic crystal lattice is stretched by introducing a fractional dislocation, these modes start to interact, the degeneracy between them is lifted, and the quality factor of one of these modes is increased to over 6000. This optical Q can be separated into a vertical component (Q_{vert}), which accounts for all out-of-plane losses from the cavity, and a lateral component (Q_{lat}), which accounts for in-plane losses. The highest Q that can be achieved within a planar photonic crystal cavity is usually limited by Q_{vert}, since Q_{lat} can be arbitrarily increased by lithographically adding more photonic crystal layers around the photonic crystal defect [13]. It is of interest to determine the change in this Q as the cavity is back-filled with reagents. From Figure 2b, it is shown that the highest Q (of above 6000) that could be achieved in the modeled cavity design occurs at an ambient refractive index n=1, and this value deteriorates as the refractive index of the ambient surrounding the photonic crystal cavity is

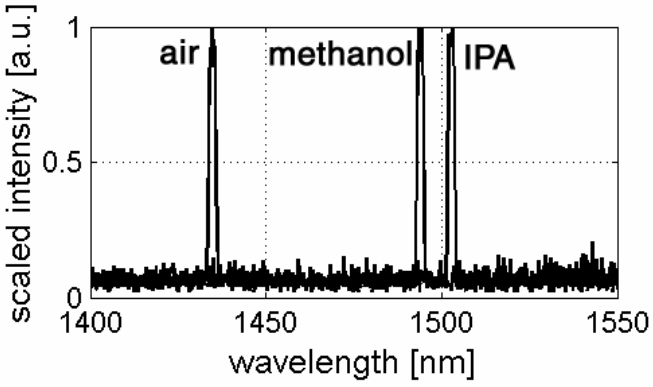

Figure 3. Measured laser spectra of photonic nanolaser sensor when filled with air, methanol and IPA

increased. This decrease in Q is a result of the weaker vertical confinement of light by total internal reflection, and we have compensated for the deterioration of the Q by increasing the thickness of the photonic crystal slab to optimize lasers functioning in n~1.5 ambient solutions. Another important figure of merit for evaluating the performance of the laser spectrometer is the gain provided by the active material to the lasing mode. As the defect hole diameter is decreased and the amount of dislocation is increased, we can expect a better overlap between the optical cavity mode and the quantum wells, and a decrease in the laser threshold. However, it is important in spectroscopy applications that the defect hole is large in order to obtain the desired interaction between optical cavity field and the reagent. Therefore, we have chosen r_{def}=0.15a and p=0.25a as a good compromise for the initial laser sensor design.

In Figure 2 the dependence of the eigen-frequency of the lasing mode is also shown, and it can be seen that this frequency of the resonant mode, as well as the band edges of the PBG, depend linearly on the refractive index of the analyte. From linear fits of the dependence of the resonant frequency on the refractive index of the analyte ($n_{analyte}$), the sensitivity of the cavity can be estimated, and this predicted that the wavelength shift of the resonance should be approximately $\Delta\lambda \approx 266 \cdot \Delta n$. If we assume that the cavity is embedded in a typical polymer ($n \approx 1.4$) and below the lasing threshold, a change in refractive index that is still observable from the cavity Q values would be $\Delta n \sim 0.002$. That would provide wavelength shift of $\Delta\lambda \approx 0.54$nm. On the other hand, once we introduce optical gain into the cavity, as in the case of the laser spectrometer described below, the linewidth of emission is significantly narrowed, and therefore much higher sensitivities of $\Delta n << 0.001$ can be measured even in cavities with modest Q factors.

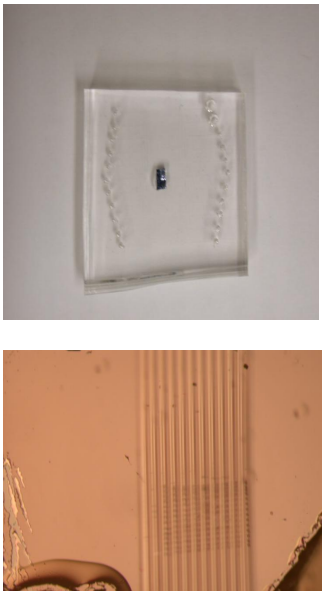

Figure 4. Laser chip embedded in elastomeric flow system. In the top figure, the elastomer is 2 cm square, and the channels are 100 μm apart in the bottom detail.

To demonstrate this, photonic crystal nanolasers were fabricated from InGaAsP quantum well material. Optical gain was provided by four 9nm thick, compressively strained quantum wells, placed in the center of a 330nm thick InGaAsP slab. The emission from the quantum wells was in the range of $1300\text{nm} < \lambda < 1600\text{nm}$, and these were constructed within a free standing membrane, patterned with a photonic crystal lattice as shown in Figure 1, and embedded into elastomeric flow channels (Figure 4). The precise emission wavelength could be controlled either by scaling the lattice parameter, or by changing the size of the defect hole introduced into the lattice to form the cavity. The structures were tested using micro-photoluminescence approach, and were optically pumped at room temperature with 30ns pulses of 3μs periodicity (λ_{pump}=830nm). Further details of fabrication procedure and experimental method can be found in Reference 8. Here we have converted these opto-fluidic devices into sensors that can analyze ultra-small volumes of material, and integrated these with microfluidic sample delivery systems.

3. RESULTS

3.1 Chemical sensing

We have already demonstrated that low-threshold laser cavities can be applied for accurate refractive index measurement. The porous cavity design presented here permits the introduction of analyte directly into the high optical field of the laser cavity, and when the overlap between that introduced analyte and the optical field generated in the laser cavity is optimized, the sensitivity of a fabricated nanocavity sensor can be maximized. Moreover, the ultrasmall mode volume of these lasers permits the sensitivity to optical changes within femtoliter volumes. Photonic crystal nano-cavities can support high optical fields with very small mode volumes (V_{mode}), and such structures are expected to be ideal for the analysis of reagent volumes below 10^{-17} liters. This enabled the sensing and analysis of individual organic molecules or self-assembled quantum dots, and offered a unique opportunity to achieve strong interaction between light and molecules on a nano-scale level. The introduction of absorbing or fluorescing molecules into such cavities has a large influence on the optical signature, and in turn the high fields obtained can be used to excite nonlinear effects and can be used for spectroscopy on the cavity contents. We have shown that, when properly designed, room temperature

lasers can operate within both aqueous and organic solutions, and changes in refractive index of the material within the laser cavity can be optically detected with excellent accuracy (Figure 5).

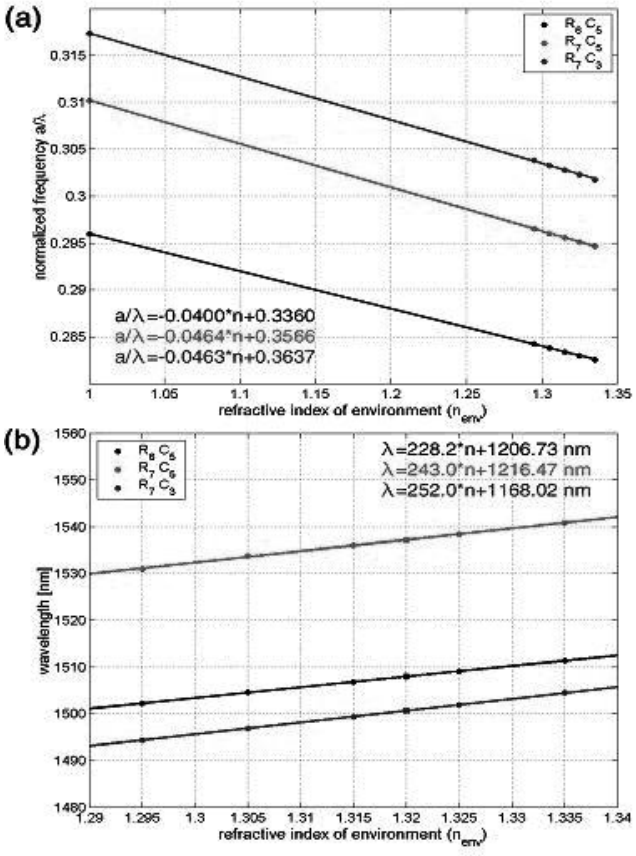

Figure 5. Laser sensor calibration curve relating the ambient refractive index to the emission wavelength for three lasers

The simplest method of optically sensing ambient material uses the laser spectrum to determine the cavity length and thus the refractive index of a reagent within the cavity. This method uses the wavelength shifts in the laser spectrum when the laser is immersed into a solution or exposed to a material to measure its refractive index. In this method, the sensitivity of the sensor depends on the smallest change in refractive index that can be optically detected. In passive devices, this is related to the width of the cavity resonance Fabry-Perot peak which in turn is determined by cavity quality Q, and can be as small as ~0.2nm in the presented cavity design. However, a laser linewidth can be much narrower than the Fabry-Perot cavity peak, and even smaller shifts in the lasing wavelength can be detected by taking advantage of the spectral narrowing from stimulated emission above laser threshold. To test the influence of a change in ambient refractive index on the laser spectrum of a cavity, the photonic crystal lasers have been backfilled with iso-propyl alcohol (IPA) and methanol. Figure 5 shows position of the resonances from three different lasers after immersion in index-matching fluids. It can be seen that the wavelength shifts linearly with refractive index. The 67nm red-shift associated with immersion into IPA corresponds to a change in refractive index from 1.0 to 1.377, and yields roughly 1nm spectral shift for a 0.0056 change in refractive index. When IPA is replaced with methanol (n=1.328), the laser resonance experiences a blue shift of ~9nm, which is again in good agreement with predicted shift of ~13nm from our theoretical predictions (Figure 2).

We have also investigated the dependence of the cavity resonance wavelength on the lithographic laser geometry, particularly the lattice constant and the dislocation in the photonic crystal cavity. Resonances experience red shifts of ~80nm when the periodicity is changed from a=446nm (dashed lines) to a=460nm (solid lines), which confirms that it is possible to lithographically adjust the emission wavelength to ensure an overlap of the cavity resonance peak with the InGaAsP quantum well emission gain curve even when the cavities are immersed in a reagent.

3.2 Dense Integration of Laser Sensors

We have also tested structures with different defect hole radii (r_{def}) within the same photonic crystal slab in order to explore the integration of multi-wavelength photonic crystal lasers with lithographically predetermined spectra. These devices are particularly interesting as compact multi-wavelength light sources, but are also useful if many reactions have to be monitored at the same time. Individual reactions can be observed in laser cavities which have predetermined spectral signatures, and optically read by observing changes in the collective spectrum of a multi-wavelength laser array. In Figure 6, we show both the structure and accompanying spectra of three optical cavities fabricated within a common photonic crystal slab with lattice constant a=446nm and r=134nm. The sizes of the defect holes which define the optical cavities were varied from r_{small}=74nm, r_{mid}=85nm and r_{big}=97nm, and a detailed view of one of the cavities is shown in

the inset. The distance between the three cavities is 10 lattice periods or ~4.5 μm. To measure these lasers, the cavities were pumped individually, and well-confined spectra were obtained from each of these cavities. The lasing wavelength of these cavities could be tuned from 1420nm (for r_{big}) to 1550nm (for r_{small}).

By using adjacent resonator cavities, the integration of light sources with detectors is also possible, since InGaAsP quantum well material can be used both for the generation of light, as well as for the detection of light. Filtered photonic crystal nanocavity detectors can be included to monitor the output of adjacent laser diodes, as long as the detector resonance wavelength coincides with the lasing wavelength. By monitoring the intensity of the detector signal, it is possible to observe small changes in the laser emission wavelength. We have demonstrated both the integration of multiple laser cavities which can be back-filled with analyte and used as refractive index probes, as well as their interrogation with wavelength-matched photonic crystal nanocavity detectors which can be fabricated in very compact tandem sensor systems.

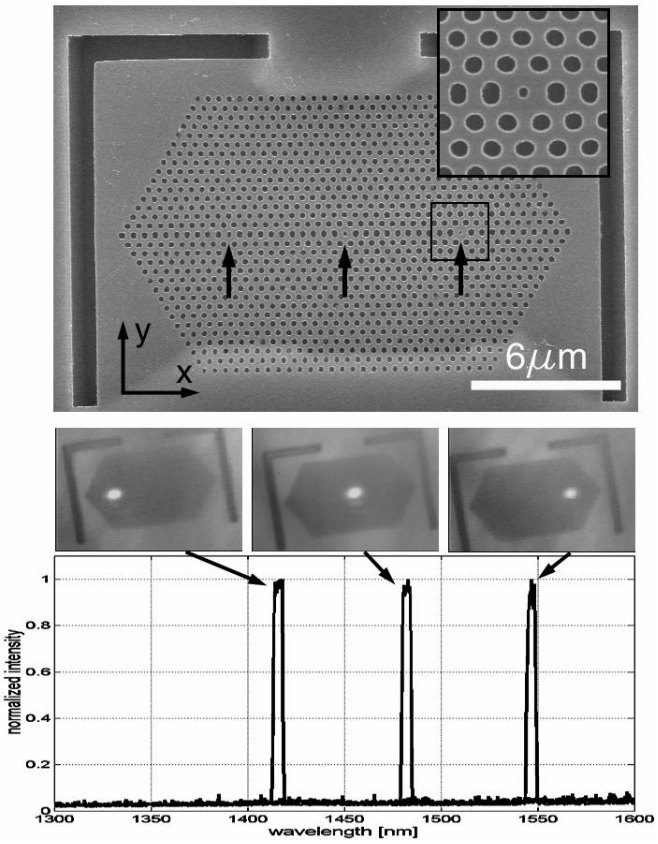

Figure 6(a) Fabricated structure consists of three cavities integrated within the same photonic crystal mirror. Defect holes are indicated by arrows, and their size increases from right to left. (b) Resonances detected in each cavity. Mode experience blue-shift as the size of defect hole increases. Positions of pump-beam are shown.

3.3 Laser Spectroscopy

The narrow emission lines from laser cavities with small mode volumes (~10^{-16}-10^{-17} liters) provided us with excellent opportunities for chip-based integration of optical spectroscopy systems. We have so far demonstrated operation of such lasers in various solvents and have shown that shifts in refractive index of the ambient material surrounding the laser cavities can be measured by monitoring the laser spectrum. Small changes in refractive index or absorption can be detected within femtoliter volumes of reagent, and such devices can be integrated into large arrays to permit the simultaneous analysis of many reagents. However, the problems of reading out the signals for compact monitoring and sensing systems are still formidable. However, if on-chip read-out of the signals is possible, and if such lasers can be demonstrated in spectral ranges where direct excitation of molecular absorption and dye fluorescence are possible, the photonic crystal laser described here will provide an unsurpassed spectroscopic capability in both size and resolution.

We have developed methods for on-chip integrated readout and analysis, as well as develop laser spectrometers with materials systems that will allow shorter wavelength operation. Since InGaAsP can serve both as a laser gain material as well as a material for light detection, it is possible to develop compact and integrated spectroscopy systems for detection of chemical and biological molecules. Such systems are similar in principle to optical communications opto-electronic integrated circuits (OEICs), but do not suffer from the severe requirements of high speed and low insertion loss needed by telecommunications systems. Since these lasers are used for biochemical sensing by backfilling the defect hole in the photonic crystal cavity with reagent, absorption and Raman spectroscopy can also be conducted for the analysis of chemicals within the nanolaser cavity. Moreover, since the optical field intensity is optimized to be highest in the center of the microfabricated hole containing the reagent, the optical field generated in the laser cavity can be used to optically trap materials (quantum dots, metallic particles, and even large molecules) of higher refractive index than the solvent surrounding the cavity.

3.4 Laser tuning, self-modulation and optical switching

Since we have now demonstrated that these lasers can be operated after filling with a variety of materials, it is possible to consider inserting photorefractive materials into the cavity. This presents us with the opportunity of switching, tuning and modulation. We have inserted optically active polymers, which have fairly low refractive indices and can be introduced into the cavities by spinning, dipping and subsequent electrostatic poling if required, into these nanocavities. Of particular interest is the self-modulation or Q-switching of the nanolasers with photorefractive material. In such a device, the high field intensities and the efficient modal overlap between electromagnetic field and nonlinear polymer assist us in defining small active devices in which the lasing mode and cavity Q are tuned to modulate above and below lasing threshold. Since the cavity only supports one or two modes, self-modulation with good contrast can be measured, since energy is not simply swapped from one mode to another.

4 CONCLUSIONS

The use of laser spectroscopy in chemical analysis has a long history. Typically, such analysis consists of an external laser as a light source, a cuvette or other sample holder, a spectrometer and an external detector. The miniaturization of such a system typically results in a significant loss of spectral resolution, as the pathlength of the spectrometer determines that value. Here, we show that it is possible to miniaturize such measurement systems by building a laser cavity into which the sample can be introduced. Indeed, we expect that both high spatial and spectral resolution result when the sample is directly introduced into a high field region of the optical cavity, provided that the optical cavity volume is very small and mode hopping can be avoided. By using photonic crystals, we believe that it becomes possible to define ultra-small spectroscopic systems in which femto-liter volumes can be analyzed.

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