

Enhanced transduction of polymer photonic crystal band-edge lasers via additional layer deposition

Cameron L.C. Smith, Mads B. Christiansen, Thomas Buß, Anders Kristensen

Department of Micro- and Nanotechnology, DTU Nanotech, Technical University of Denmark, DK-2800 Kongens Lyngby, Denmark
Corresponding author: anders.kristensen@nanotech.dtu.dk; Phone: +45- 4525 6331, Fax: +45- 4588 7762

Claus H. Nielsen, Niels B. Larsen

Department of Micro- and Nanotechnology, DTU Nanotech, Technical University of Denmark, DK-4000 Roskilde, Denmark

Abstract: We present the concept of enhanced transduction for polymer photonic crystal lasers by deposition of an additional polymer layer with selective gas response. We report a significant increase in sensitivity to changes in gas concentration.

© 2010 Optical Society of America

OCIS codes: (230.5298) Photonic crystals; (310.6860) Thin films, optical properties

1. Introduction

Photonic crystals (PhCs) offer unprecedented nano-scale control of light, having been shown to steer, slow and/or prevent electromagnetic propagation. As such, PhCs have been widely investigated for sensing applications in a number of different architectures [1, 2], with one configuration in particular – the PhC cavity – generating considerable research interest in recent years [3-5]. PhC intra-cavity sensing designs generally rely on detecting the changes in effective refractive index (ERI) of a liquid analyte [6]; however, detecting changes in a *gas* is difficult with refractive index-based schemes as the variations in gas indices are very small when compared to liquids. In this work we report a polymer-based PhC intra-cavity sensing approach that utilizes an additional absorptive polymer layer that selectively expands when exposed to specific contents in a gas. We present a numerical and experimental study that demonstrates large changes in ERI with changes in gas composition due to the additional absorptive polymer layer. The findings conclude that an adequately enhanced transduction of PhC intra-cavity sensor devices is readily plausible, laying the groundwork to significantly optimize and broaden their functionality as detectors.

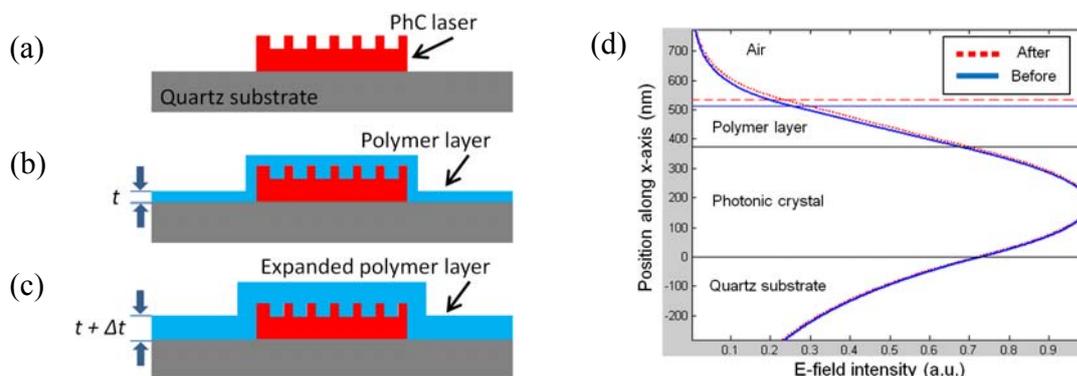


Figure 1. (a) Schematic of PhC band-edge laser with (b) additionally deposited polymer layer and (c) expansion of that layer due to exposure to a specific gas. (d) The four-layer system with thicknesses of the PhC, $T_{PhC} = 375$ nm, and pre-expanded polymer layer, $T_{Pol} = 138$ nm. Superimposed are E-field profiles of the 0th modes for the cases before (solid) and after (dotted) the polymer layer expansion.

2. Concept

Figure 1 (a)-(c) illustrates the operating principle of the device. An additional polymer layer, deposited by polymerization in a pulsed AC plasma [7], covers the device surface after the initial fabrication. The polymer layer maintains a similar refractive index throughout its volume as it expands with exposure to a specific vapor, resulting in a dramatic shift of the device's ERI. The additional layer can be tailored to selectively respond to specific gases - e.g. poly(styrene) (PS) has a high response to unpolar compounds such as heptane and low response to polar compounds such as water; poly(vinyl pyrrolidone) (PVP) the opposite. The devices include PhC band-edge lasers

with rectangular lattice [8] formed in a polymer-based platform made with nanoimprint technology [9]. Polymer PhC lasers have previously been shown to respond to changes in refractive index of an optofluidic cladding as an intra-cavity sensor [10].

3. Results

Our numerical study considers the geometry shown in Fig. 1 (d), solving for mode profiles of the four-layer system. The PhC layer is treated as a uniform slab with an ERI $n_{PhC} = 1.562$ and thickness $T_{PhC} = 375$ nm. The refractive indices for air and the substrate are $n_{air} = 1.000$ and $n_{subs} = 1.462$ respectively, while their thicknesses extend to infinity. The polymer layer refractive index is approximated to remain close to its original value ($n_{PS} = 1.590$; $n_{PVP} = 1.530$) as the added volume is composed of absorbed vapor in its condensed state (e.g. ethanol: $n = 1.362$). We study the effect of expanding the additional polymer layer by 15% of its initial volume. The polymer layer thickness before its expansion is $T_{Pol} = 138$ nm.

Figure 2 (a) shows initial experimental measurements on PhC laser devices with a 42 nm thick additional polymer layer deposited. The wavelength shift observed is $\Delta\lambda = 0.22$ nm ($\Delta n_{eff} = 3.7 \times 10^{-4}$); estimating an upper limit of refractive index change in the gas, $\Delta n_{fluid} = 6 \times 10^{-4}$, this results in a sensitivity, $\Delta\lambda/\Delta n_{fluid}$, exceeding 350 nm/RIU. This value compares favorably with other liquid-based PhC intra-cavity sensors [3-5].

Figure 2 (b) displays a numerical optimisation of the deposition thickness of the additional polymer layer, plotting the change in ERI of the system versus varying the pre-exposed polymer layer thickness. The optimal thickness of the deposited layer to achieve maximum change in ERI, Δn_{eff} , is 138 nm, corresponding to a wavelength shift of $\Delta\lambda = 0.48$ nm. The refractive index of the polymer layer in the calculation is $n_{pol} = 1.5$.

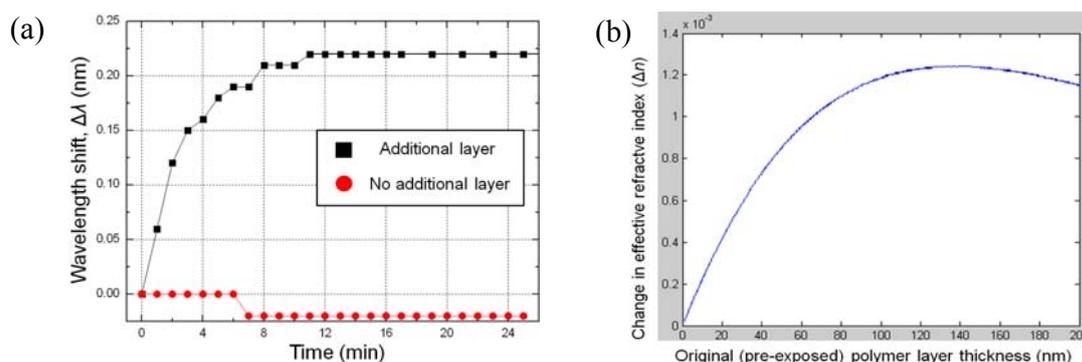


Figure 2. (a) Experimental measurement of the wavelength shift over time for ethanol vapor pressure approaching equilibrium, comparing the additional polymer layer (poly(styrene)) to the case without. (b) Change in effective refractive index versus original polymer layer thickness for a 15% expansion of the polymer layer. Optimal thickness of the deposited layer ($n_{pol} = 1.5$) is 138 nm, corresponding to $\Delta\lambda = 0.48$ nm.

In conclusion, we present a concept for enhanced transduction of polymer-based PhC band-edge lasers for intra-cavity sensing of gases by deposition of an additional select-absorptive polymer layer. The enhancement is achieved by the expansion of the additional polymer causing an increase in the device's ERI. This work is highly relevant for applications such as threat detection, environmental monitoring and bio-sensing.

- [1] D. Erickson, T. Rockwood, T. Emery, A. Scherer, and D. Psaltis, "Nanofluidic tuning of photonic crystal circuits," *Opt. Lett.* **31**, 59-61 (2006).
- [2] N. A. Mortensen, and S. S. Xiao, "Slow-light enhancement of Beer-Lambert-Bouguer absorption," *Appl. Phys. Lett.* **90**, 3 (2007).
- [3] 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**, 1093-1095 (2004).
- [4] U. Bog, C. L. C. Smith, M. W. Lee, S. Tomljenovic-Hanic, C. Grillet, C. Monat, L. O'Faolain, C. Karnutsch, T. F. Krauss, R. C. McPhedran, and B. J. Eggleton, "High-Q microfluidic cavities in silicon-based two-dimensional photonic crystal structures," *Opt. Lett.* **33**, 2206-2208 (2008).
- [5] P. S. Nunes, N. A. Mortensen, J. P. Kutter, and K. B. Mogensen, "Photonic crystal resonator integrated in a microfluidic system," *Opt. Lett.* **33**, 1623-1625 (2008).
- [6] C. Monat, P. Domachuk, and B. J. Eggleton, "Integrated optofluidics: A new river of light," *Nat. Photonics* **1**, 106-114 (2007).
- [7] Z. Ademovic, J. Wei, B. Winther-Jensen, X. L. Hou, and P. Kingshott, "Surface modification of PET films using pulsed AC plasma polymerisation aimed at preventing protein adsorption," *Plasma Process. Polym.* **2**, 53-63 (2005).
- [8] M. B. Christiansen, A. Kristensen, S. S. Xiao, and N. A. Mortensen, "Photonic integration in k-space: Enhancing the performance of photonic crystal dye lasers," *Appl. Phys. Lett.* **93**, 3 (2008).
- [9] X. Cheng, and L. J. Guo, "A combined-nanoimprint-and-photolithography patterning technique," *Microelectron. Eng.* **71**, 277-282 (2004).
- [10] M. B. Christiansen, J. M. Lopacinska, M. H. Jakobsen, N. A. Mortensen, M. Dufva, and A. Kristensen, "Polymer photonic crystal dye lasers as Optofluidic Cell Sensors," *Opt. Express* **17**, 2722-2730 (2009).