Quasi One-Dimensional Photonic Crystals as Building Block for Compact Integrated Optical Refractometric Sensors

Wico Hopman, Pierre Pottier*, Didit Yudistira, Joris van Lith, Paul Lambeck, Richard De La Rue*, Alfred Driessen, Hugo J.W.M. Hoekstra, René M. de Ridder

Integrated Optical MicroSystems, MESA+ Research Institute, University of Twente, P.O Box 217, 7500 AE Enschede, The Netherlands, Tel: +31 534894440, Fax:+31 534893343, e-mail: W.C.L.Hopman@ewi.utwente.nl

*Optoelectronics Research Group, Dept of Electronics and Electrical engineering, University of Glasgow, G12 8QQ, Scotland, UK, e-mail: Pottier@elec.gla.ac.uk

A quasi one-dimensional photonic crystal has been fabricated and the applicability of this strong grating for optical sensing has been investigated by measuring the transmission spectra as a function of the cladding refractive index. The cladding index was varied a small range. By monitoring the transmitted output power the transmission stop-band was found to shift by 1 nm wavelength for either a cladding refractive index change of 0.05 or a temperature change of 120 K.

Introduction

Quasi One-Dimensional Photonic Crystals (also referred to as deeply etched gratings) have been investigated as simplified models for PhC slabs (quasi 2D-PhC's), e.g. [1]-[2], and as reflectors in semiconductor lasers. The structures have an extended transmission stop band having sometimes very steep edges, for a given propagation direction. Also, the entire transmission spectrum shifts along the wavelength axis as a function of the index modulation. Changing only the cladding index can already have a strong effect since the Bloch modes of the periodic structure can have a large overlap with the cladding material. The steep band edge allows for a very sensitive detection of small shifts of the transmission (or reflection) spectrum of the PhC. These properties make quasi 1D-PhC's interesting candidates for application in integrated optical sensors. Contrary to the well studied fibre-based Bragg sensors this sensor allows for an extremely compact integrated refractometer. We show that the thermo-optic effect of Si_3N_4 and SiO_2 can be used for tuning the stop-band over a small range, which is however easily detectable by observing the optical transmission near a band edge. This effect may be used for tuning the structure into its optimum operating point (with respect to the source wavelength) or for optical switching. Although we used bulk heating of the entire structure for measuring the thermo-optic actuation, like [3], it has recently been demonstrated that in spite of their strongly non-planar surface, photonic crystal structures can be thermally tuned using small local heaters [4], [5].

Device

A schematical cross-section of the device is shown in Figure 1. A 212 nm thick Si_3N_4 guiding layer was deposited on top of a 9 micrometer thick SiO_2 buffer layer. A ridge waveguide, needed to confine the light in both the horizontal and vertical direction, was made using standard lithography, etch and deposition processes. The width of the waveguide was 2 μm and the ridge step was 2 nm. The grating was patterned across the ridge waveguide, using direct electron beam writing followed by standard dry etching steps. The grating constant Λ was chosen to be 190 nm in order to locate the stop band in the visible (red) wavelength region. The measured filling factor was approximately 50 %. The number of periods chosen was 401, resulting in an overall grating length of 76.19 µm. Since the structure had been originally designed for a different purpose, a point defect is present, consisting of a single removed (non-etched groove) grating period in the middle. This defect is not relevant for the experiments described in this paper. The final etch depth obtained after dry etching and mask removal was approximately 10 % of the nitride layer thickness. A cuvette for containing the upper cladding fluid was sealed to the top surface of the structure, as shown in Figure 1.

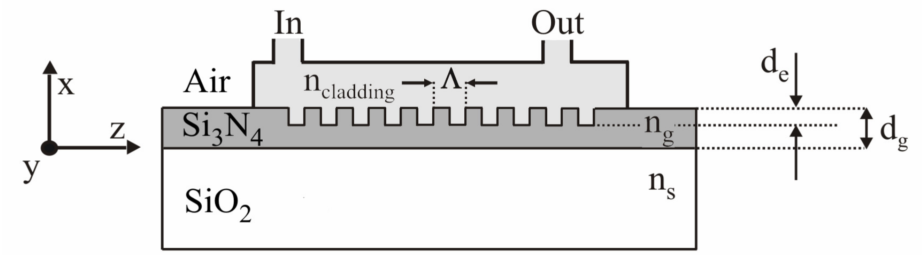

Figure 1. A cross-section of the quasi 1-dimensional photonic crystal sensor with a cuvette placed on top; Λ=190nm, d_e=22nm, d_g=190nm, n_g=2.01,n_s=1.46.

Results

The sensor was characterised by measuring the optical power transmission versus cladding index at a fixed wavelength. Two experiments were performed, one to determine the sensitivity for changes in cladding index for the small wavelength band edge (*A*) and the other for long wavelength band edge (*B*). The wavelength was set to λ_1 = 660.5 nm and λ_2 = 662.5 nm, respectively.

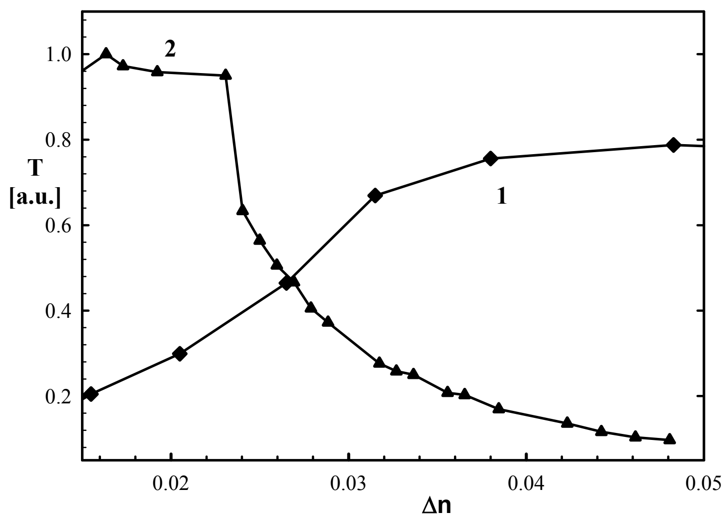

Figure 2. The normalized transmission (T) plotted versus the change in cladding index. Curve 1 and 2 are respectively measured band edge A (small wavelength edge) and band edge B (long wavelength edge). Both curves are normalised to the maximum transmitted power, for curve 1 and 2 respectively 360nW and 635nW.

The results of the measurements are presented in Figure 2. The maximum slope can be found at an index change of 0.024 for curve 2. Both band edges show a marked output power change with a change of cladding index.
We define the sensitivity of the sensor as:

$$s = \frac{1}{T}\frac{\partial T}{\partial n} \tag{1}$$

The values of parameter T and $\partial T/\partial n$ can be determined from Figure 2. With the current peripheral equipment accuracy, we can obtain a resolution (η) of 1% in the transmitted output power detection. From the data we can estimate a maximum value for s of ~25. A minimum detectable change (Δn) of the cladding index can be found using the following expression:

$$\Delta n = \frac{\eta}{s} \tag{2}$$

For this index-sensor we find a Δn of ~ 4×10^{-4}

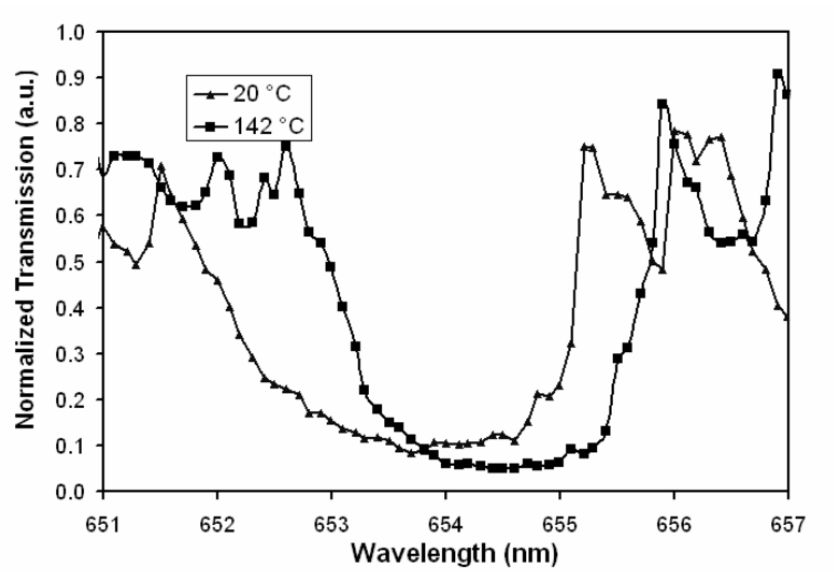

Figure 3. The normalized transmission spectra for two different temperatures

The thermal tunability of the photonic crystal is demonstrated by the normalized transmission spectra for two different temperatures shown in Figure 3. Approximately 1 nm shift of the center stop-band wavelength is observed for a 122 K temperature change, corresponding to a thermal tuning coefficient $\partial\lambda/\partial T \cong 8$ pm/K. A calculation with a 2-dimensional bidirectional eigenmode propagation method using the known thermo-optic coefficients of Si_3N_4 and SiO_2 (both approximately 1×10^{-5}), and the geometric parameters of the structure, results in a value of $\partial\lambda/\partial T \cong 4$ pm/K. The discrepancy may be attributed to the effect of thermal expansion of the bulk silicon substrate.

Conclusion

We have demonstrated the suitability of a short (76 μm) strong waveguide grating (quasi 1D-PhC) as a sensitive index sensor. As expected the transmission spectrum shows a shift of the stop band to lower frequencies when the refractive index of the cladding is increased. Measurements at two fixed wavelengths for probing both band edges showed that the steepness of these edges can be exploited for obtaining a sensitive sensor. It was found that the long wavelength band edge provided the largest sensitivity.

Without modifications this non-optimized device can be used as an extremely compact and highly sensitive sensor. With a straightforward optical power detection setup, a variation of ~ 4×10^{-4} in the cladding index has been detected. The thermal tuneability of the sensor was shown to be about 8 pm/K.

References

[1] J. Ctyroky, S. Helfert, R. Pregla, et al: Bragg waveguide grating as a 1D photonic band gap structure: Cost 268 modelling task, *in Optical and Quantum Electronics 34, p455-470,2002*.

[2] W. Bogaerts, P. Bienstman, D. Taillaert, et al: Out-of-plane scattering in 1-D photonic crystal slabs, *in Optical and Quantum Electronics 34, p195-203, 2002.*

[3] B. Wild, *et al.*, “Temperature tuning of the optical properties of planar photonic crystal microcavities,” *Appl. Phys. Lett.*, vol. 84, pp. 846-848, 2004.

[4] H. M. H. Chong and R. M. De La Rue, "Tuning of photonic crystal waveguide microcavity by thermooptic effect,” *IEEE Photon. Technol. Lett.,* vol. 16, pp. 1528-1530, 2004.

[5] E. A. Camargo, H. M. H. Chong, and R. M. De La Rue, "2D Photonic crystal thermo-optic switch based on AlGaAs/GaAs epitaxial structure," *Opt. Express*, vol. 12, pp. 588-592, 2004.