Quasi 1-Dimensional Photonic Crystals as Building Block for Compact Integrated Optical Sensors

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ABSTRACT

A quasi one-dimensional photonic crystal has been fabricated and the applicability of this kind of structure for optical sensing has been investigated by measuring the transmission spectra as a function of the cladding refractive index. The cladding index was varied using a liquid flow, of which the index was slowly varied over a small range. The shift with cladding index of the steep stop band edge provides a relatively sensitive detection mechanism in an extremely compact device.

Keywords: photonic crystal, sensor, waveguide, Bragg, grating, silicon nitride.

1. INTRODUCTION

A deeply etched grating in a slab or channel waveguide is often denoted as a quasi one-dimensional photonic crystal (1D-PhC) (one-dimensional because the periodicity is in one dimension, "quasi" because the structure has features, e.g. slab interfaces, in one or two other dimensions). These structures have been investigated as simplified models for PhC slabs (quasi 2D-PhC's), e.g. [1]-[2], and as reflectors in semiconductor lasers. Although these gratings cannot have a full photonic band gap (a stop band for all propagation directions and arbitrary polarisation), they share an important feature with higher-dimensional PhC's: 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 refractive index of the materials involved (an increase of the average index causes a shift towards longer wavelengths). A change of 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. These properties make quasi 1D-PhC's interesting candidates for application in integrated optical sensors, where a measurand usually modifies the refractive index of parts of a waveguiding structure. The steep band edge allows for a very sensitive detection of small shifts of the transmission (or reflection) spectrum of the PhC. Although grating-based sensors have been studied before, especially in optical fibres [3], to our knowledge this paper presents the first experimental demonstration as of an extremely compact refractometer (refractive index sensor), based on transmission through a short strong waveguide grating that may well be suitable for integration into sensing arrays.

One of the advantages of PhC –based sensors is their compactness (i.e. less than 100 μm for the sensor reported here versus 1 cm typically for Mach Zehnder Interferometers (MZI) based sensors [4]). In comparison with a recently proposed micro-ring resonator type sensor [5], the photonic crystal has a similar advantage with respect to the very small measurand volume needed and also a similar resolution is obtained in measurements.

2. DEVICE AND SETUP

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 grating structure, as shown in Fig. 1.

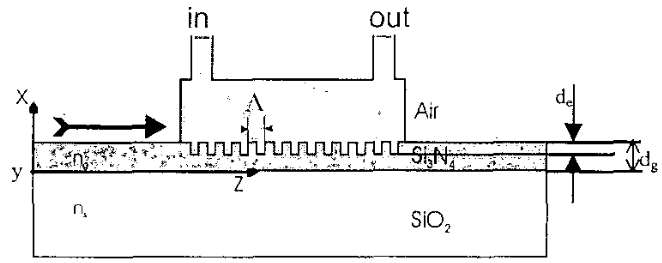

Figure 1. A cross-section of the quasi 1-dimensional photonic crystal sensor with a cuvette placed on top.

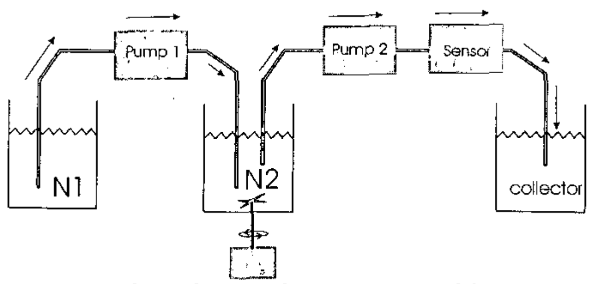

Figure 2. A schematical representation of the setup.

In order to characterise the sensor, a material with a variable and well-defined refractive index should be fed through the cuvette. A continuous change in refractive index can be realized by slowly mixing together two fluids of different refractive indices. The vessel N2 is used for mixing. At the start of the experiment, it contains pure ethanol (refractive index $n = 1.36$). The vessel is stirred in order to obtain a homogenous mixture. Vessel N1 contains a benzyl-alcohol with a higher refractive index ($n = 1.54$) than that of ethanol. After leading the fluid through the cuvette, a third vessel is needed to collect the mixture. In the experiment the two pump speeds were chosen equal. During the measurements the index of vessel 2 was monitored using an Abbe refractometer. By fitting this data with the solution of the differential equations belonging to the system illustrated in Figure 2, the index can be determined with an accuracy of approximately 5×10^{-4}.

The optical transmission of the grating is measured using a commonly used end-fire setup, consisting of a polarizer, half-wave plate, objectives (40X) and a photodiode. For all measurements TE polarization was used.

By choosing a measurement wavelength to be approximately halfway the slope of the band edge, the index of the cladding (fluid) can be determined very accurately by monitoring the transmitted power. A small change in cladding index will correspond to a large change in output power, because the stop band will shift to higher or lower wavelength, depending on the sign of the index change.

3. RESULTS

Before and after a sequence of measurements a full transmission scan was made; the results are presented in Figure 3.

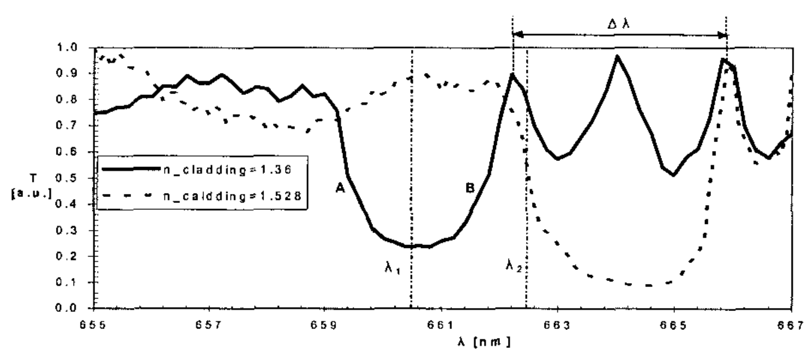

Figure 3. The normalized transmission spectra (T) for the different cladding indices. The air band and the dielectric band are respectively denoted by the letters A and B. λ_1 and λ_2 are the fixed wavelengths for probing respectively edge A and B, see Fig. 4.

One scan was made with pure ethanol (n = 1.36), the other with a mixture (n = 1.528) of ethanol and benzyl-alcohol. A wavelength shift (shift of band B) of about 4 nm was found for a cladding index change of 0.168.

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 band edge A and the other for band edge B. The wavelength was set to $\lambda_1 = 660.5$ nm and $\lambda_2 = 662.5$ nm, respectively.

The results of the measurements are presented in Figure 4. 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.

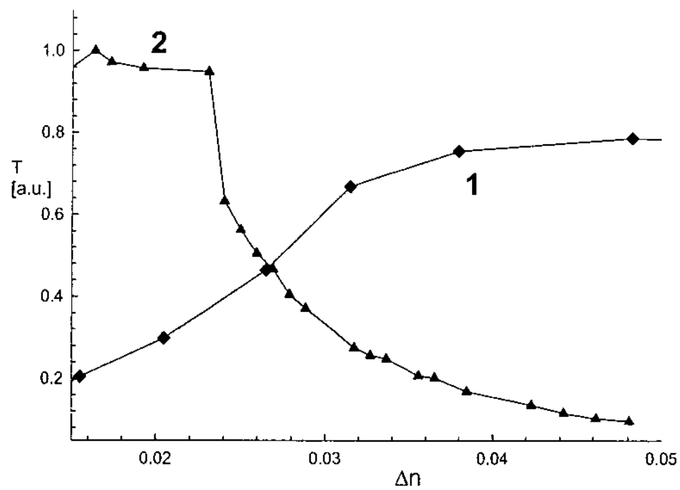

Figure 4. The normalized transmission (T) plotted versus the change in cladding index. Curve 1 (scanning edge A) is measured at λ_1 and curve 2 (edge B) is measured at λ_2 (c.f. Fig. 3). Both curves are normalised to the maximum transmitted power, for curve 1 and 2 respectively 360 nW and 635 nW.

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 T/ n can be determined from Figure 4. 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 ~$4\text{x}10^{-4}$. Approximately the same s-value can be estimated from Figure 3.

4. DISCUSSION

As expected, a wavelength shift of the photonic band edges was observed on changing the cladding index. The result from the previous section proves that this PhC device can be used as a sensitive integrated device for determining the cladding index. With some caution we can assume that the sensitivity of the sensor can be enhanced by increasing the slope $dT/d\lambda$. One possible way to do this is by increasing the number of periods. Figure 5 shows the 1D modelling results of the maximum slope (at the band edge) versus the number of periods (length of the grating). An effective index approximation together with plane wave expansion was used as modelling tool. This figure suggests that the sensitivity of this device is increasing stronger than linear with the number of periods. Increasing the etch depth and thus increasing the contrast will also strongly enhance the sensitivity ($dT/d\lambda$).

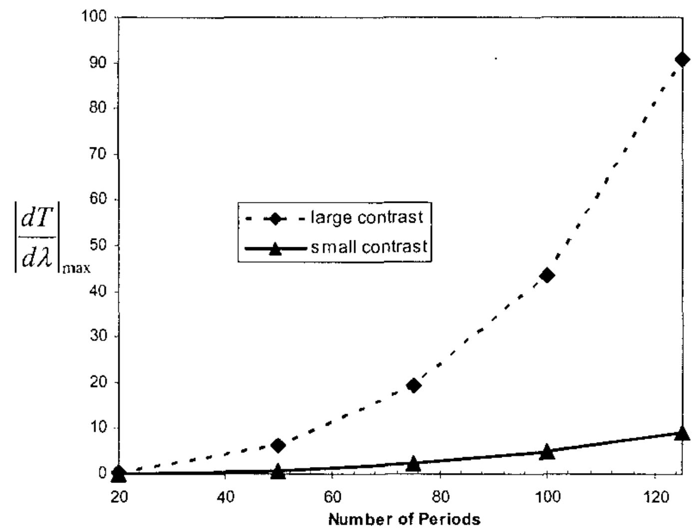

Figure 5. The maximum transmission slope: dT/dλ versus the number of periods. Increasing the contrast in this 1D model corresponds to increasing etching depth of the grating.

The characterised photonic crystal sensor device has not been optimised in any way. There are several ways for optimizing this sensor. Besides the two methods described above, increasing the etch depth and the number of periods, also improving the uniformity of the PhC will result into a steeper band edge slope. We estimate that an increase of at least one order of magnitude can be achieved in this way.

The optical insertion loss of the grating device can be strongly reduced by using an optimised fibre-chip coupling (e.g. [3]). Clever signal processing, e.g. by simultaneously using both band edges in a push-pull way (requiring two light sources at different wavelengths) will increase the sensitivity. The resolution η can be increased by a factor of 10, from 1% to 0.1%, by using a more sophisticated photo-detection setup.

The resulting increase in sensitivity of at least two orders of magnitude will make this PhC sensor and interesting building block for densely integrated optic sensor arrays.

5. CONCLUSION

We have demonstrated for the first time, to our knowledge, 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. An index difference of 0.168 produced a shift of approximately 4 nm. 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 dielectric 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. Further optimizations may decrease this value by two orders of magnitude

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