Fiber-tip electric field sensors based on semiconductor photonic crystals

L.Picelli,[1] P.J. van Veldhoven,[1] E. Verhagen[1,2] and A.Fiore[1]

[1] Department of Applied Physics and Eindhoven Hendrik Casimir Institute, Eindhoven University of Technology, PO Box 513, 5600 MB, Eindhoven, The Netherlands
[2] Center for Nanophotonics, AMOLF, Science Park 104, 1098 XG Amsterdam, The Netherlands

Sensors based on the measurement of electric field or voltage are commonly used in a wide variety of applications. Use of these devices in harsh environments and remote locations is limited by the need for electrical cables. In this work we show the possibility of transducing electric field to an optical signal in a fiber with a semiconductor-based fiber-tip device. A thin InP membrane is embedded with a photonic crystal, with resonance wavelength in the near-infrared, and transferred to the cleaved facet of an optical fiber. The fiber-tip device is immersed in a frequency-modulated electric field. Through the Pockels effect, this leads to a change in the resonant wavelength, which can be sensed via the fiber using a probe laser tuned at the side of the resonance. We describe the theoretical modeling of the electro-optic effect in a photonic crystal. We validate the model by comparison of finite-element simulations with experiments. We suggest the application of the electric field sensor to the optical interrogation of electrical circuits.

Introduction

The importance of sensors in modern technology has rapidly increased over the course of the last decades. They are used in a large variety of devices and applications [1]. Most of the developed sensors are based on electrical circuits. Their metallic contacts and the electrical wiring, required to read them out, leads to signal loss over long distances and to electromagnetic interference and makes them incompatible with high temperatures and extreme environments. Optical fiber sensors (e.g. fiber Bragg gratings, FBGs) do not suffer from these drawbacks and are applied in different fields[2]. Fiber-tip sensors have also been widely explored as they have the additional advantage of very small footprint, direct contact with the surrounding medium, and large freedom in sensor design [3,4]. We have previously demonstrated the possibility of fabricating the sensing element with a wafer-scale semiconductor process and then easily transfer it to the optical fiber facet [5]. These fiber sensors are limited by the relatively small response (wavelength shift) to external stimuli and high cost of the interrogation system needed to measure it. Electrical sensors, instead, typically display a large relative change of an electrical parameter (e.g. resistance) to an external stimulus. It would thus be convenient to develop a platform which combines electrical sensing and optical read-out via a fiber. This can be done with a fiber-tip structure which transduces voltage to a change in the reflectance, easily detectable with a fixed-wavelength interrogation set-up. This could be achieved by exploiting the electro-optic effect, already used to realize fiber-tip electric field sensors with a $LiNbO_3$ photonic crystal slab [6]. In this work we focus on determining the electric field response of a fiber-tip device based on an InP photonic crystal slab using the electro-optic effect. This is a first step towards the development of the proposed platform. In fact, this semiconductor (differently from $LiNbO_3$) can be easily doped to realize p-n and p-i-n junctions, which can act as current sources upon illumination with visible light. The combination of current generation and voltage read-out could be used as a basis for an optically-interrogated fiber-tip electrical sensor.

Electro-optic effect in a photonic crystal

The proposed sensor is based on the Pockels effect, a nonlinear (second-order) optical phenomenon in which a static, or low-frequency, electric field (E) causes the change of the refractive index (n) of the material [7]. The effect is determined by the linear electro-optic tensor of the material r_{hk} where k indicates the direction of the field (1, 2, 3 or X, Y, Z) and h indicates the directions in which the refractive index is modified (1-6, where 4, 5, 6 represent XY, XZ and YZ directions). The crystalline structure of the material strongly influences which elements of the tensor are non-null. Only non-centrosymmetric materials such as $LiNbO_3$ and InP exhibit the effect. For InP only terms $\boldsymbol{r_{41}} = \boldsymbol{r_{52}} = \boldsymbol{r_{63}}$ are non-null. The application of a field along one of the main crystal axis (e.g. Z) causes a rotation of the two perpendicular optical axes by 45° with respect to the crystallographic axes, and the change of refractive index along these new directions (x and y) according to $n_{x,y} = n_0 \pm \frac{1}{2} n_0^3 r_{41} E_Z$. To study the interaction of the electro-optic effect with the photonic crystal (PhC) we adopt a perturbative approach [8] to determine the change in resonance wavelength caused by the field. In the rotated reference frame (x, y,Z) the permittivity tensor of the material is diagonal, and $\epsilon_{x,y} = n_{x,y}^2$ (where $\epsilon_{x,y}, n_{x,y}$ are real since in the wavelength region of our interest the material can be considered non-absorptive). We write the wavelength perturbation as

$$\delta\lambda = -\frac{\lambda_0}{2}\frac{\int \left(|\mathcal{E}_x(\boldsymbol{r})|^2 - \left|\mathcal{E}_y(\boldsymbol{r})\right|^2\right) n_0^4 r_{41} E_Z(\boldsymbol{r}) dr}{\int \epsilon(\boldsymbol{r})|\mathcal{E}(\boldsymbol{r})|^2 d\boldsymbol{r}}, \tag{1}$$

where λ_0 is the unperturbed wavelength, $\mathcal{E}_{x,y}$ are the in-plane components of the electric field of the PhC mode in the rotated reference frame and we neglected a small second-order term. From Eq.1 it is evident that the perturbation depends on the difference between the magnitudes of the mode electric field components in the rotated frame. To efficiently exploit the electro-optic effect in a photonic crystal sensor, it is necessary to define a mode with a strong polarisation asymmetry. For this reason, we used a photonic crystal slab (thickness of 250 nm) characterized by a rectangular unit cell. This geometry presents a mode which is strongly polarized (Fig. 1a), making it sensitive to the applied field. In addition, the mode is isolated from other spectral features and can effectively couple to the optical fiber [5]. The rectangular unit cell is obtained by shifting every other hole of a square lattice (lattice constant a=350 nm, hole radius r=126 nm) by a small quantity (s=17.5 nm) in each row. To determine the electro-optic response of the proposed device, a photonic crystal with the described design was fabricated on a InP membrane and transferred to the tip of an optical fiber tip (Fig 1b,c), using the method described in Ref. 5. Light from a tunable infrared (IR) laser is directed to the device through a circulator and a polarization controller. The circulator directs the reflected light to an InGaAs amplified detector. The voltage output of the detector is measured with a digital multimeter and an electrical spectrum analyzer (ESA). To apply the electric field, the fiber-tip device is positioned halfway the 5 mm air gap (Δz) between two metal plates (lateral dimensions 10 cm x 10 cm), perpendicularly to them. A sinusoidal AC voltage is applied to the plates using a resonant high-voltage source which can apply $\sim 230\ V_{p-p}$ at a frequency ~53-55 kHz. The applied external field is calculated as $E = V_{p-p}/\Delta z \approx 46$ kV/m. The measurement principle is represented in Figure 2a.

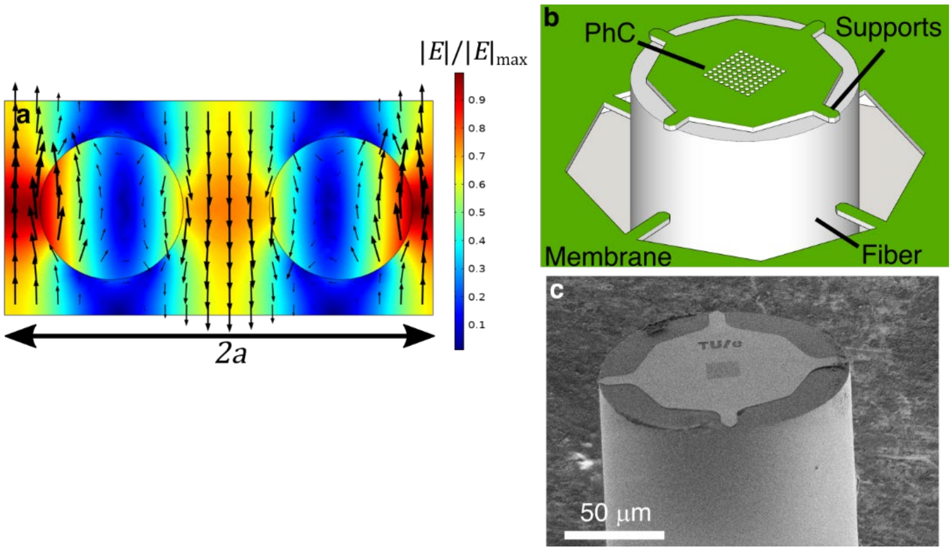

Figure 1: (a) Mode field profile for the studied rectangular cell photonic crystal. Arrows indicate field lines, color scale indicates normalized amplitude. (b) Sketch illustrating the transfer process and sensor geometry. (c) SEM image of the assembled fiber-tip sensor.

The oscillating field shifts the resonance wavelength by $\Delta\lambda$ causing a change in the reflected power (change in the detector output voltage ΔV) at the fixed probe laser wavelength λ_L (~1.54 μm). The modulated signal can be detected and resolved with the ESA and converted into the wavelength shift spectral density ($S_{\lambda\lambda}$) knowing the slope of the resonance (110 ± 7 mV/nm for 0.45 mW of incident optical power). Figure 2b shows the response of a fiber-tip device with the photonic crystal designed to maximize the electro-optic response (black solid line) and one with the crystal rotated by 45° respect to the optical axis (red dashed line). The correctly oriented crystal shows a strong response to the applied electric field. From the integration of the peak in the ESA spectrum we calculate the peak-peak wavelength perturbation to be $\delta\lambda_{exp} = (3.8 \pm 0.4) \cdot 10^{-5}$ nm, corresponding to an electric field sensitivity of $(8.3 \pm 0.9) \cdot 10^{-10}$ nm/(V/m) (referred to the field in air between the electrodes). The 45° rotated crystal still shows small response, which we attribute to the imprecision in the orientation of the crystal during the fabrication process. Due to the presence of the PhC, E_z in Eq. 1 is not uniform in the slab and the theoretical value of the wavelength shift must be calculated using finite elements method simulations. This is done by including the effect of the field in an eigenfrequency simulation of an infinite PhC to determine the perturbed mode wavelength. The effect of the fiber in the spatial distribution of the electric field within the plates is taken into account in the estimation of the static electric field in the PhC membrane. We determine a wavelength change of $\delta\lambda_{sim} = 9.7 \cdot 10^{-5}$ nm, which is in the same range, but a factor 2.5 higher that the experimental value. We attribute the discrepancy to the uncertainty in the estimation of electric field at the fiber position, sub-optimal orientation of the crystal and imprecise knowledge of the material refractive index. From the noise observed in Fig.2b ($\sqrt{S_{\lambda\lambda}^{N}} \sim 8 \cdot 10^{-7} \mathrm{nm}/\sqrt{\mathrm{Hz}}$) and the sensitivity, we estimate the external electric field measurement imprecision to be $\sim 1\ \mathrm{kV}/\left(\mathrm{m}\sqrt{\mathrm{Hz}}\right)$. This value is higher than the sensor reported in Ref.6 due to the 30 times smaller electro-optic coefficient of InP ($r_{41} = -1.63$ pm/V [9]) . Despite this drawback, the fact that p-i-n junctions are easily realized in InP, and the relatively large internal fields are generated by small voltages in the junction, makes this interrogation scheme viable for the measurement of voltages across a fiber-tip electrical device.

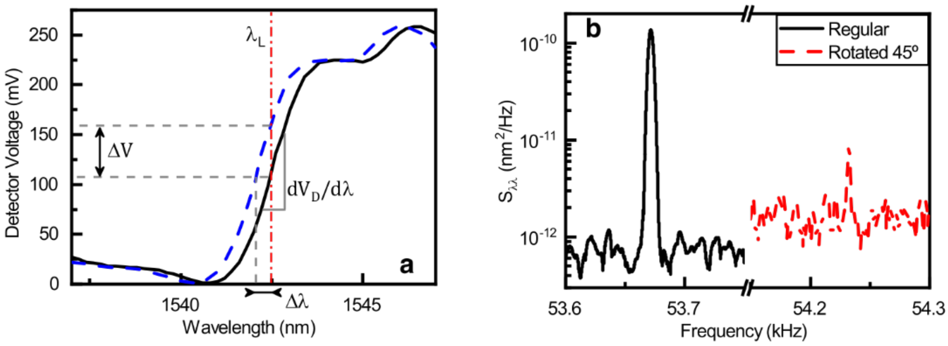

Figure 2 : (a) Optical spectrum of the photonic crystal (black curve). The blue dashed curve is artificially shifted to illustrate the fixed wavelength detection scheme. The interrogation laser is set at wavelength λ_L(red dot-dashed line). The incident optical power is 0.45 mW. (b) Frequency response of fiber-tip devices immersed in the AC electric field. The crystal aligned to the rotated optical axes (black solid line) is compared to a crystal rotated 45° around its center (red dashed line). The incident optical power on the device is 0.45 mW for both devices, the measurement bandwidth is 5 Hz (regular) and 3 Hz (rotated).

Conclusions

We showed the possibility to optically sense an electric field with a semiconductor InP photonic crystal membrane using a fixed-wavelength optical interrogation system. We obtain field imprecision of 1 $\mathrm{kV}/(\mathrm{m}\sqrt{\mathrm{Hz}})$. We propose the combination of this detection scheme, based on the Pockels effect, with a p-i-n junction embedded on a membrane of the same thickness where small voltages in mV range produce internal fields in the order of 10 kV/m. This approach would therefore allow the optical detection of the photovoltage generated across the junction by absorption of visible light. When combined with resistors or other electrical components integrated on the fiber tip, it opens the way to the optical read-out of electrical sensors.

Acknowledgements

We thank T.Huiskamp and R.Serra (TU/e) for the help in the realization of the electric field measurement set-up. This work was funded by the NWO Zwaartekracht Research Center for Integrated Nanophotonics.

References

[1] M. Alam, M. M. Tehranipoor, and U. Guin, “TSensors Vision, Infrastructure and Security Challenges in Trillion Sensor Era,” *J. Hardw. Syst. Secur.*, vol. 1, no. 4, pp. 311–327, Dec. 2017.

[2] M. A. Riza, Y. I. Go, S. W. Harun, and R. R. J. Maier, “FBG Sensors for Environmental and Biochemical Applications - A Review,” *IEEE Sens. J.*, vol. 20, no. 14, pp. 7614–7627, 2020.

[3] G. Kostovski, P. R. Stoddart, and A. Mitchell, “The optical fiber tip: An inherently light-coupled microscopic platform for micro- and nanotechnologies,” *Adv. Mater.*, vol. 26, no. 23, pp. 3798–3820, 2014.

[4] P. Vaiano *et al.*, “Lab on Fiber Technology for biological sensing applications,” *Laser Photonics Rev.*, vol. 10, no. 6, pp. 922–961, 2016.

[5] L. Picelli *et al.*, “Scalable wafer-to-fiber transfer method for lab-on-fiber sensing,” *Appl. Phys. Lett.*, vol. 117, no. 15, 2020.

[6] V. Calero *et al.*, “An ultra wideband-high spatial resolution-compact electric field sensor based on Lab-on-Fiber technology,” *Sci. Rep.*, vol. 9, no. 1, p. 8058, 2019.

[7] J. Coutaz and L. Duvillaret, “Electro-optic sensors for electric field measurements. II. Choice of the crystals and complete optimization of their orientation ´,” vol. 19, no. 11, pp. 2704–2715, 2002.

[8] J. Bravo-Abad, S. Fan, S. G. Johnson, J. D. Joannopoulos, and M. Soljačić, “Modeling nonlinear optical phenomena in nanophotonics,” *J. Light. Technol.*, vol. 25, no. 9, pp. 2539–2546, 2007.

[9] N. Suzuki and K. Tada, “Electrooptic Properties and Raman Scattering in InP,” *Jpn. J. Appl. Phys.*, vol. 23, no. 3, pp. 291–295, 1984.