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Long period gratings and rocking filters written with a CO_2 laser in highly-birefringent boron-doped photonic crystal fibers for sensing applications

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ABSTRACT

In this work, we demonstrate the possibility of fabricating short-length long-period gratings and rocking filters in highly birefringent Photonic Crystal Fiber using a CO_2 laser. In our experiments both kinds of gratings were made in the same Boron doped highly birefringent PCF using similar exposure parameters. We also present the sensing capabilities of both fabricated gratings to temperature, strain and hydrostatic pressure by interrogation of the wavelength shifts at different resonances.

1. Introduction

Long period gratings (LPG) [1–4] are fiber optic structures with periodic axial modulation of refractive index in the core or with modulation of external fiber diameter, typically with a periodicity of 100 μm to 10 mm. This refractive index modulation couples light from the fundamental core mode to the co-propagating cladding modes or higher order modes at discrete wavelengths defined by the phase matching condition. As the excited cladding modes are typically highly attenuated, it results in the appearance of a selective resonance loss in the transmission spectrum of the fundamental mode. The shape of the optical spectrum, with several wavelength attenuation bands, is sensitive to the fiber design, LPG period and length, and to the local environment: temperature, strain, bend radius and also to the refractive index of the surrounding medium [5]. Changes in such parameters can modify the LPG period and/or the differential refractive index of the core and cladding modes. In consequence, the phase matching condition is modified, which results in a change of the attenuation bands spectrum profile. For the LPGs written in the photonic crystal fibers (PCFs), due to its particular design, different behaviors could be observed when subjected to a physical parameter. For example it was noticed that this kind of structures presents very low sensitivity to temperature [6].

An optical fiber rocking filter is a special type of a long period grating which resonantly couples the fundamental polarization modes launched in the principal axes of a birefringent fiber [7]. Typically, the coupling effect is achieved by periodic mechanical twist of the

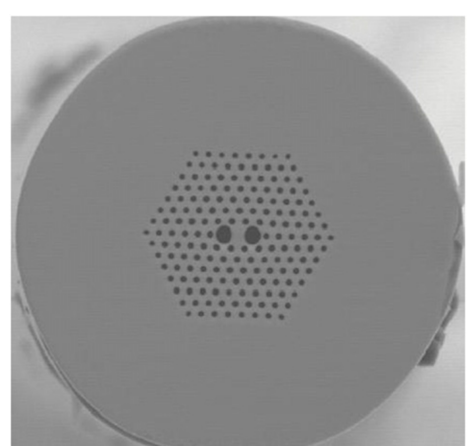

Fig. 1. SEM image of the highly birefringent PCF used for fabrication of the LPGs.

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Table 1
Geometrical parameters of the highly birefringent PCF.

Λ_F [μm]	D [μm]	d [μm]	ϕ [μm]
3.76	4.6	1.63	127

birefringent fiber. If the distance between successive twist points equals the fiber beat length, resonant coupling between orthogonally polarized modes occurs. In the sensing field, similarly to what happens with LPGs, rocking filters have proved to be effective sensing elements of different measurands [8,9].

In this work, the spectral characteristics and sensing capabilities of two different kinds of optical filters, LPGs and rocking filters are compared. Both elements were fabricated by CO_2 laser inscription method in a highly birefringent photonic crystal fiber.

2. Highly birefringent photonic crystal fiber

For fabrication of the LPGs and rocking filters, an highly birefringent (Hi-Bi) PCF produced by the Department of Optical Fibre Technology – from the University of Marie-Curie Sklodowska (UMCS) in Lublin, Poland – was used. The birefringence in this fiber is induced by two holes located symmetrically with respect to the core. The cross-section of the fiber obtained in the scanning electron microscope (SEM) is shown in Fig. 1.

From this image, the geometrical parameters are determined and gathered in Table 1, where Λ_F is pitch distance, D the diameter of the large holes, d the diameter of the cladding holes and ϕ the external diameter of the cladding.

3. Fabrication of long period gratings and rocking filters

To fabricate the gratings in the Hi-Bi PCF presented in the previous section the point-by-point CO_2 laser based inscription system shown in Fig. 2 was used.

During the gratings fabrication process, the fiber was illuminated using a broadband Xe-lamp and the grating growth was monitored using an ANDO AQ6317B optical spectrum analyzer (OSA).

In case of the LPG fabrication the polarizers 'P' and 'A' could be discarded, as well as the nanorotator. For the rocking filter formation, the nanorotator allows the Hi-Bi PCF principal axes to be pretwisted with a constant angle. After that, the fiber twist is partially realeased by heating the fiber at one point with the CO_2 laser beam. The polarizers 'P' and 'A' permit to excite at the fiber input and attenuate at the fiber output the desired polarization modes.

4. LPG characterization and sensing properties

The investigated LPG contained 25 coupling points fabricated in the Hi-Bi PCF using the CO_2 laser based system The grating with a period of 650 μm and a total length of 15.6 mm, was then optically characterized. Its transmission spectrum shown in Fig. 3 features three pronounced pairs of attenuation bands centered at 670 nm, 960 nm and 1450 nm, respectively.

When the two polarizers are rotated it is possible to check if the nature of the resonances is due to the polarizing properties of the Hi-Bi PCF. As can be seen in Fig. 4, the two observed peaks in the first pair of resonances are polarization sensitive, which proves they arise due to coupling between the fundamental polarization modes and the cladding modes located in the fiber microstructure. The same behavior was observed for the second pair of resonances located around 950 nm. On the other hand, the third pair of resonances arising around 1450 nm was not polarization sensitive. We therefore believe that the two peaks correspond to resonances of different order, each of them having negligible spit versus polarization. This effect can be attributed to very small birefringence difference between the fundamental mode and the cladding mode producing the resonant coupling.

Concerning the LPG sensing properties, the device was submitted to temperature changes and characterized. The third pair of resonances optically characterized was insensitive to temperature in terms of its wavelength dependence, but the same did not happen for the ~670 nm and ~960 nm resonances, as the data in Fig. 5 shows. Although the temperature measurement was initially idealized for the [0°, ~90°] range, the experimental test was extended to higher temperatures in order to verify if the system has a linear behavior.

We can observe a similar response for the two peaks in each resonance pair. The data indicates that the sensitivities are ~11 pm/°C for the first pair of resonances and ~21 pm/°C for the second one.

Regarding the hydrostatic pressure sensitivity, a wavelength dependence of the three pairs of resonances against pressure change was not observed. Although, for the first pair of resonances, at the 670 nm region, an amplitude variation for the optical transmission spectrum of the two attenuation depths was detected, as can be seen in Fig. 6. It is important to point out that these measurements were taken while monitoring a constant optical source power.

The presented results were obtained, in a constant temperature measurement, using a coupler after the optical source which allowed the monitoring of the Xe lamp power. Such basic optical referencing scheme permitted to obtain the normalized results presented in Fig. 6. As can be seen, the two resonances at ~670 nm (λ_{fast} and λ_{slow}) show different behaviors, with the peak loss associated with λ_{fast} showing a

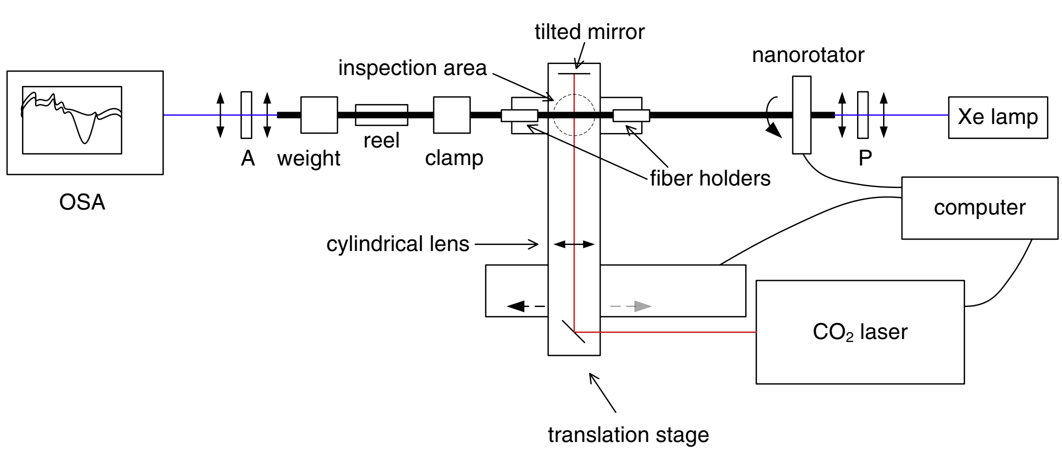

Fig. 2. Setup for LPG and rocking filter inscription using a CO2 laser.

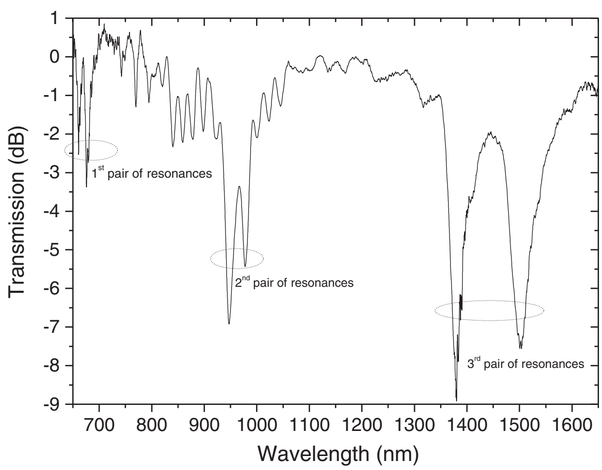

Fig. 3. LPG transmission spectrum after 25 exposition points separated by 650 μm.

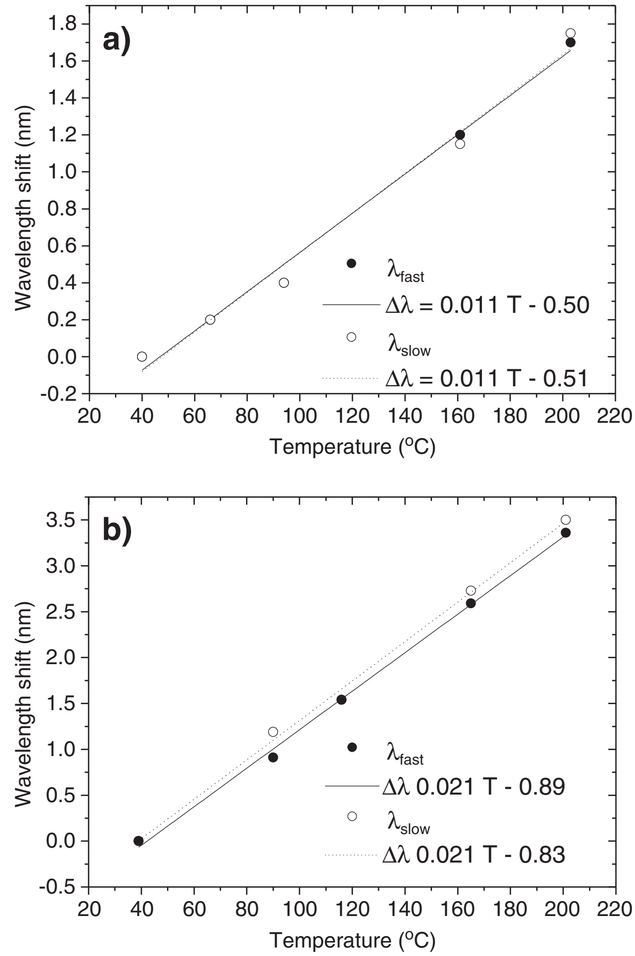

Fig. 5. Variation of the resonance wavelength versus temperature for: a) pair of resonances around 670 nm region: b) pair of resonances around 960 nm region.

linear response with hydrostatic pressure, while for the one relative to λ_{slow} the dependence is parabolic.

It was not possible to obtain results for the strain sensitivity with this LPG because it broke after the appliance of strain. Unfortunately, this is one of the impairments of the structures developed with a CO_2 laser since the exposure of the fiber to the laser beam increases tremendously its fragility.

These results indicate that LPGs fabricated with CO_2 lasers show a moderate sensitivity to temperature, between 11 pm/°C and 22 pm/°C. The spectral response of the LPG to hydrostatic pressure presented no change, but we did notice a small increase of optical peak loss against pressure for the first pair of resonances.

5. Rocking filter characterization and sensing properties

The developed rocking filter was done after 13 beam exposures, physically separated by 8 mm, being the rocking angle 30° and the twisted length ~100 μm. The transmission spectra of the guided mode, as well as, of the orthogonal mode are shown in Fig. 7, where it is evident four pronounced resonances centered at ~700 nm, ~1000 nm, ~1300 nm and ~1500 nm.

Considering the sensitivity of the resonant wavelengths to temperature, the behavior of the second, third and fourth resonances was studied. The linear expected behavior of Δλ with temperature can be confirmed by the data in Fig. 8.

From the previous figure, it should be pointed out that the rocking filter sensitivity is decreasing for longer wavelengths. As can be observed, for the fourth resonance a sensitivity value of 12 pm/°C was

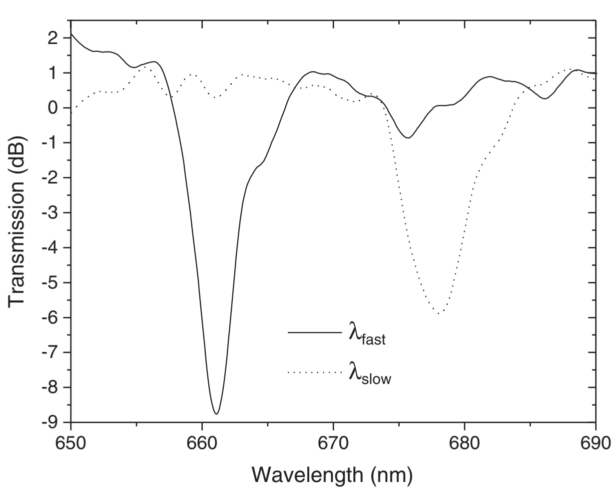

Fig. 4. Location of the LPG resonance pair corresponding to different polarization modes in the Hi Bi PCF in the wavelength region near 670 nm.

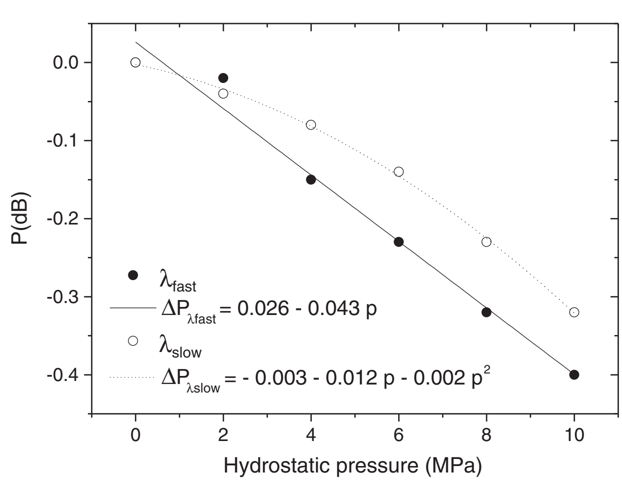

Fig. 6. Variation of the LPG resonance loss as a function of hydrostatic pressure (resonance pair in ~670 nm region).

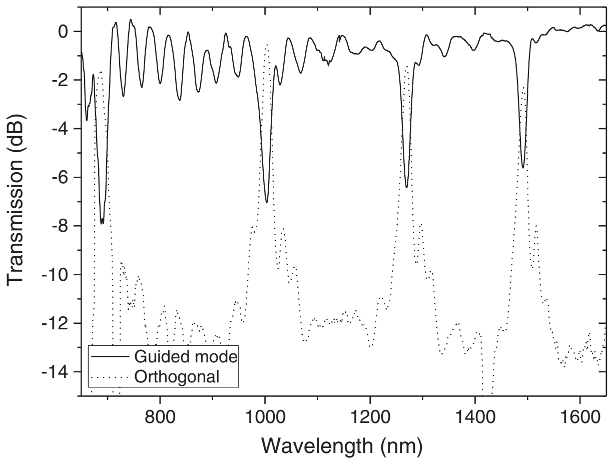

Fig. 7. Rocking filter (with a period Λ = 8 mm and 13 coupling points) transmission spectra for the two eigen polarization components of the fiber. The solid line and dotted line correspond to the polarization component parallel (guided mode) and orthogonal, respectively, to the input polarization state.

achieved, which is more than a factor of two smaller than the one associated with the second resonance (26 pm/°C).

The sensitivity of the resonance wavelengths of the fabricated rocking filter was also tested to hydrostatic pressure measurement. The obtained results are shown in Fig. 9.

The sensitivity of the rocking filter to hydrostatic pressure ranges from 5.7 nm/MPa down to 3.1 nm/MPa (for the second and the fourth resonance wavelengths, respectively). Again, the rocking filter sensitivity is decreasing for longer wavelengths. Fig. 10 shows the evolution of the fourth resonance of the rocking filter for different values of applied pressure.

As can be observed, beyond the resonance spectral shift, its shape does not change with hydrostatic pressure, a positive feature of this fiber device, when considering the implementation of a simple interrogation system [10].

Finally, it was tried to quantify the rocking filter strain sensitivity. Due to the fragility of this Hi-Bi PCF based structure, strain was measured till the appliance of 300 με. From Fig. 11 a linear dependence could be observed with a coefficient of ~0.95 pm/με.

The results obtained indicate that it is feasible to fabricate rocking filters in highly birefringent PCFs using a CO_2 laser showing several resonances. Measurements of the sensing characteristics of these devices indicate that their sensitivity to temperature is moderate (between 12 and 26 pm/°C), while the sensitivity to hydrostatic pressure is higher (between 3.1 and 5.7 nm/MPa). The obtained value for sensitivity to strain is low (0.946 pm/με), being noticed the fiber became very breakable after the CO_2 laser beam exposition. As consequence of such results, the ratio of the pressure sensitivity to the temperature sensitivity is high and in the range of 220–260 °C/MPa. These results make the rocking filter an adequate solution for hydrostatic pressure measurement with relatively small cross-sensitivity to temperature.

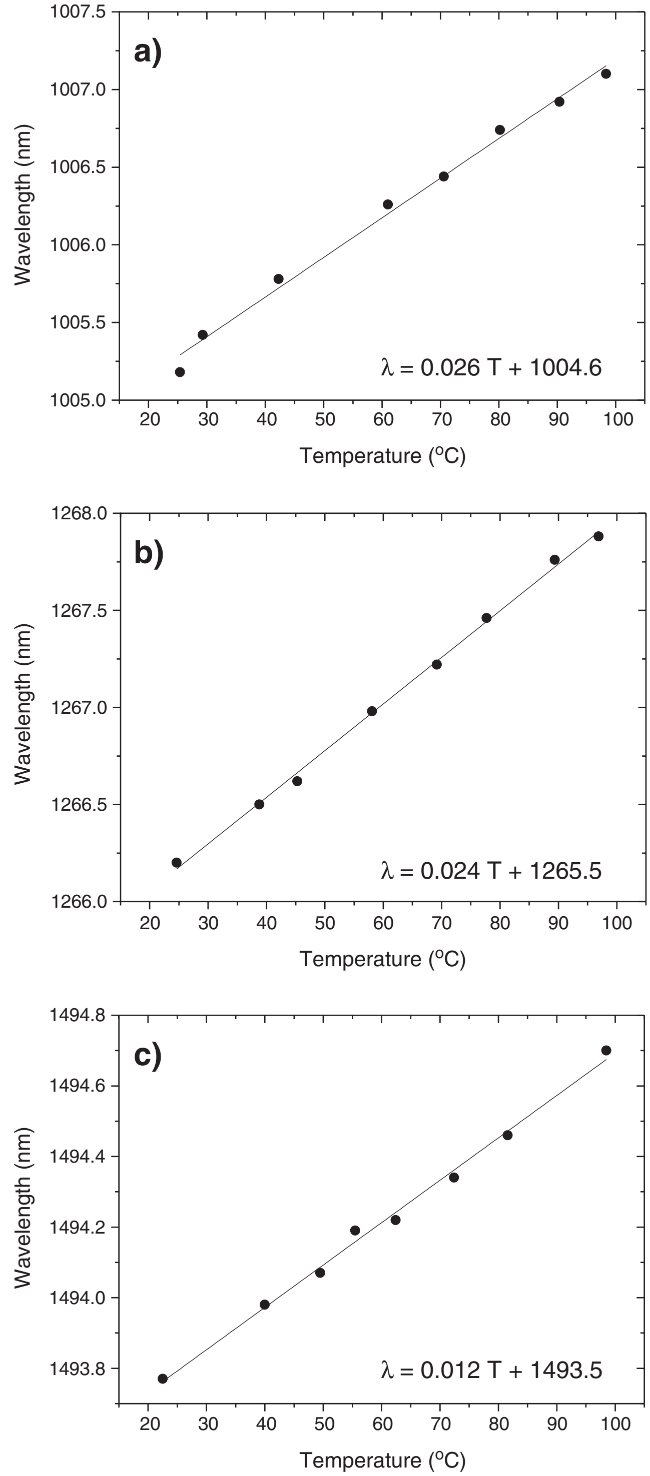

Fig. 8. Rocking filter resonant wavelength as function of temperature for: a) second resonance at ~1004 nm; b) third resonance at ~1265 nm; and c) fourth resonance at ~1493 nm.

6. Conclusions

In this paper, the possibility of LPGs and rocking filter fabrication with several resonances in a Hi-Bi PCF using a CO_2 laser inscription technique was presented. The observed variations of resonant wavelengths depend on the type of filter (LPG or rocking) and on the type of measurand that interacts with the fiber device. The sensitivity of the LPG to temperature is low and varies between 11 and 22 pm/°C, being similar to that of the rocking filter (12–26 pm/°C). These values are higher than those obtained with LPGs fabricated in endlessly single mode PCFs (that range from 2.0 to 6.0 pm/°C [6,11–13]). Our measurements also show that the wavelength sensitivity of the LPG is pressure independent, while it is high for the rocking filter (3.1–5.7 nm/MPa). This last result is far greater than the sensitivity of the LPG in endlessly single mode PCF (0.1 nm/MPa [14]), as well as the sensitivity of the rocking filter in conventional elliptical core fibers (0.5 nm/MPa [15]). The fragility of CO_2 fabricated structures did not allow to measure the sensitivity of the LPG to strain, but for the rocking filter, the measured sensitivity

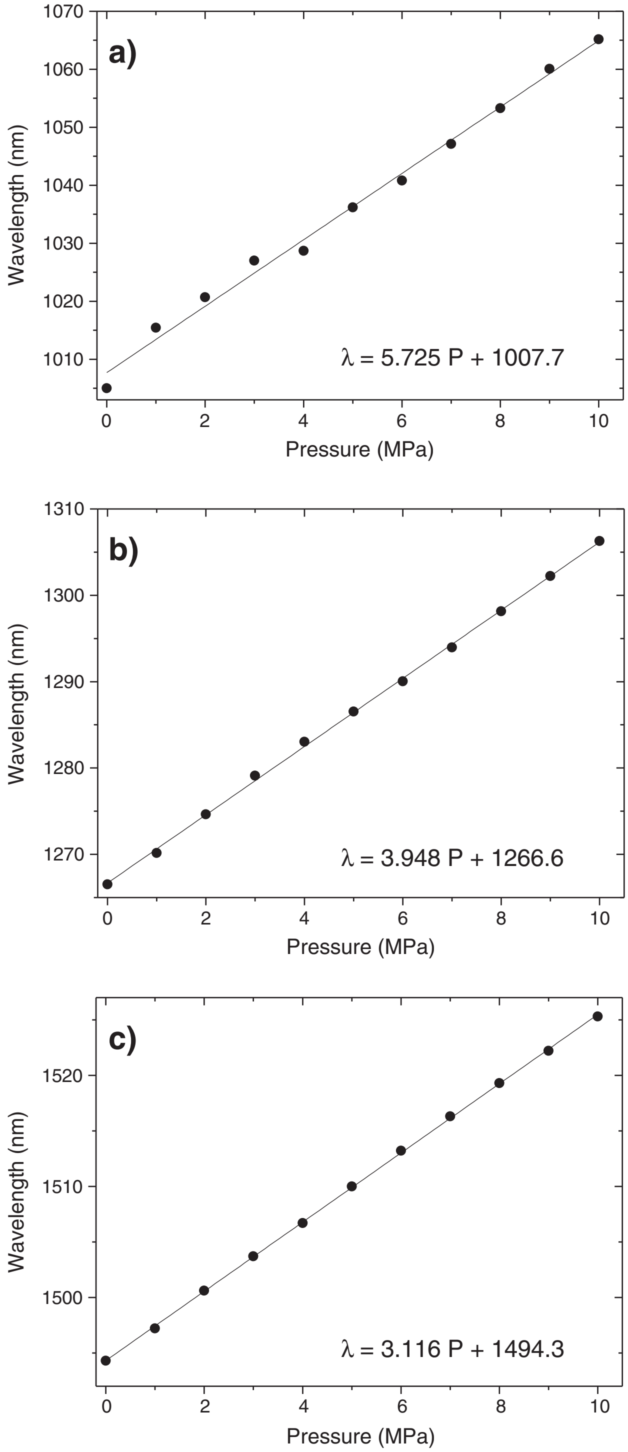

Fig. 9. Rocking filter resonant wavelength as function of pressure for: a) second resonance at ~1004 nm; b) third resonance at ~1265 nm; and c) forth resonance at ~1493 nm.

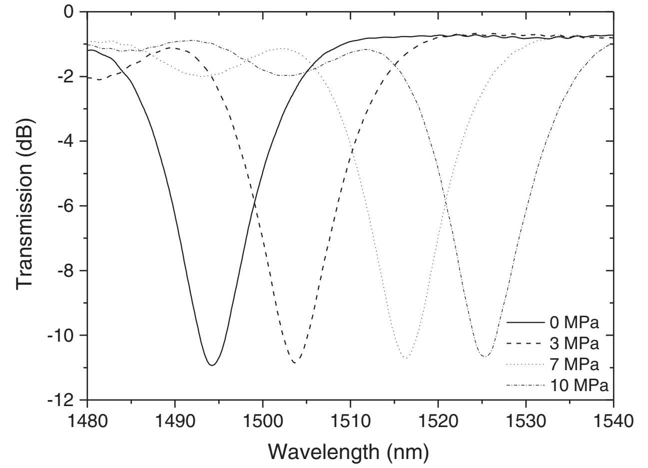

Fig. 10. Spectrum shift of the ~1493 nm resonance for different hydrostatic pressure values.

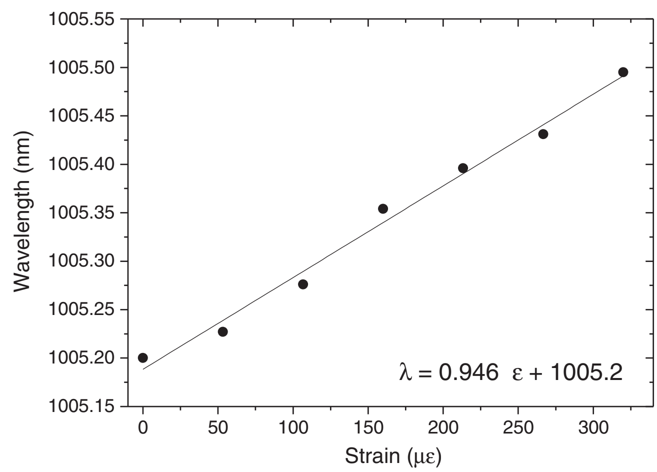

Fig. 11. Dependence of the rocking filter second wavelength resonance with applied strain.

was 0.946 pm/με, which is lower than the sensitivity of the LPGs in endlessly single mode PCFs (2.0–2.5 pm/με [11–13]). These sensitivity results make the rocking filter an adequate device for hydrostatic pressure measurements in view of the small cross-sensitivity to temperature.

Acknowledgments

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