2010-10-01

A Hybrid Highly Birefringent Fiber Optic Sensing System for Simultaneous Strain and Temperature Measurement

Piotr Lesiak
Warsaw University of Technology

Ginu Rajan
Technological University Dublin, ginu.rajan@tudublin.ie

Yuliya Semenova
Technological University Dublin, yuliya.semenova@tudublin.ie

See next page for additional authors

Recommended Citation

Lesiak, P. et al (2010) A Hybrid Highly Birefringent Fiber Optic Sensing System for Simultaneous Strain and Temperature Measurement. *Photonics Letters of Poland,* Vol. 2 (3), pp.140-142. doi:10.1109/JSEN.2011.2114650

Funder: Polish Ministry of Science and Higher Education through the National Centre for Research and Development. Enterprise Ireland under grant ERA-NET Matera. European Union framework of the European Social Fund through the Warsaw University of Technology Development Programme

Authors

Piotr Lesiak, Ginu Rajan, Yuliya Semenova, Gerald Farrell, Anna Boczkowska, Andrzej Domanski, and Tomasz Wolinkski

A hybrid highly birefringent fiber optic sensing system for simultaneous strain and temperature measurement

Piotr Lesiak[1*], Ginu Rajan[2], Yuliya Semenova[2], Gerald Farrell[2], Anna Boczkowska[3], Andrzej Domański,[1] and Tomasz Woliński[1]

[1]*Faculty of Physics, Warsaw University of Technology, Warsaw, Poland;*
[2]*Photonics Research Centre, Dublin Institute of Technology, Dublin, Ireland;*
[3]*Faculty of Materials Science and Engineering, Warsaw University of Technology, Warsaw, Poland;*
[4]*Faculty of Electronics and Information Technology, Warsaw University of Technology, Warsaw, Poland.*

Received September 28, 2010; accepted September 29, 2010; published September 30, 2010

Abstract—A novel hybrid fiber optic sensor based on integration of polarimetric fiber sensors for simultaneous strain and temperature measurement is presented in this paper. Two types of polarimetric fibers are used: a side-hole fiber and a polarization maintaining photonic crystal fiber. The disadvantage of each sensor type can be overcome by using the sensors in a complementary manner to measure temperature independently from average strain.

Highly birefringent (HB) polarization-maintaining (PM) fiber-based fiber-optic sensors are a new generation of sensors known as polarimetric fiber sensors which utilize polarization (phase) modulation within fibers to sense external perturbations [1]. HB polarimetric sensors can be made temperature insensitive but to measure strain they require means for setting a zero strain reference.

Polarimetric optical fiber sensors based on highly birefringent polarization-maintaining fibers have attracted great interest during the last decade [1, 2]. In HB fibers, the difference between the phase velocities for the two orthogonally polarized modes is high enough to avoid coupling between these two modes. Fibers of this type have a built-in, well-defined, high internal birefringence obtained by designing the core and/or cladding with a noncircular (mostly elliptical) geometry, or by using anisotropic stress induced by stress elements running along the length of the fiber.

The modal behaviour of the lowest-order mode HB fibers under various external deformations is of special interest for sensors and device applications. A number of physical quantities can be measured by sensors based on HB fibers: hydrostatic pressure, strain, vibration, temperature, acoustic waves, etc.

A symmetric deformation effect (X) influences the propagation constant β in every mode because of the changes in the refractive indices of the core and the cladding. In a single-mode regime, this leads to the changes in the phase $\Delta\Phi = \Delta\beta \cdot L$ (where L is the fiber length) between both polarizations of the fundamental LP_{01} mode along the fiber [1]:

$$\frac{\delta(\Delta\Phi)}{\delta X} = \Delta\beta\frac{\partial L}{\partial X} + L\frac{\partial(\Delta\beta)}{\partial X}, \tag{1}$$

where X stands for temperature (T), pressure (p) or longitudinal strain (ε) defined as: $\varepsilon = \Delta L / L$.

The effect of longitudinal strain on mode coupling is to modulate the relative phase retardation between the two orthogonal polarizations in the LP_{01} mode. The general formula describing the birefringence sensitivity to strain can be expressed in terms of an experimental parameter T_ε describing the amount of strain ε required to induce a 2π phase shift of polarized light observed at the output as [3]:

$$\Delta\beta(\varepsilon) = \Delta\beta^0 + \varepsilon\frac{2\pi}{T_\varepsilon L}, \tag{2}$$

where $\Delta\beta_L^0$ signifies the unperturbed modal (polarization) birefringence of a fiber.

Under the influence of longitudinal strain the first term on the right-hand side of expression (1) is negligible with respect to the second, so that:

$$\delta(\Delta\Phi) \cong \frac{\partial(\Delta\beta)}{\partial\varepsilon}L\,\delta\varepsilon = \frac{\partial(\Delta\beta)}{\partial\varepsilon}\delta L\,. \tag{3}$$

Hence the phase changes of the polarimetric responses are proportional to the absolute elongation δL and are independent of the length L of the sensing region. Under the influence of longitudinal axial strain, equation (3) can be approximated with the use of equation (2) in terms of the experimental parameter T_ε only:

$$\frac{\delta(\Delta\Phi)}{\delta\varepsilon} \cong sgn\frac{\partial(\Delta\beta)}{\partial\varepsilon}\cdot\frac{2\pi}{T_\varepsilon}. \tag{4}$$

The schematic of the hybrid sensing configuration is shown in Fig. 1. The phase change versus strain sensitivity of the polarimetric sensors is measured using a

* E-mail: lesiak@if.pw.edu.pl

polarimeter. A laser source with a wavelength of 1550nm is used as the input source. The fabricated composite material sample was 250mm-long, 35mm-wide and 2.5mm-thick. Both types of HB fibers are embedded in the same layer of the composite material (see Fig. 2). In the case of a side-hole fiber, both strain and temperature changes lead to a phase difference between both polarizations of the fundamental mode, while in the case of the HB PCF the phase difference originates only from longitudinal strain and is insensitive to temperature [4]. Thus by comparing outputs of the polarimetric sensors of both types, average strain and temperature can be obtained simultaneously.

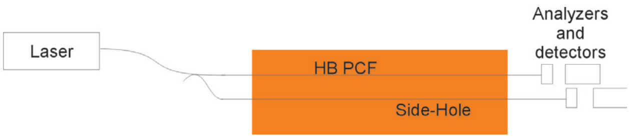

Fig. 1. Schematic of a hybrid sensing system in the intensity domain.

To introduce strain in the composite material sample, the sample is subject to bend deformation by applying a force in the middle region of the sample (Fig. 3). The stress-induced (ε) elongation of the sample as a function of deflection is given by the following formula:

$$\varepsilon = 6\frac{s \cdot d}{L^2} \qquad (5)$$

where s is the value of deflection, d is the distance between composite layers, L – length of the sample.

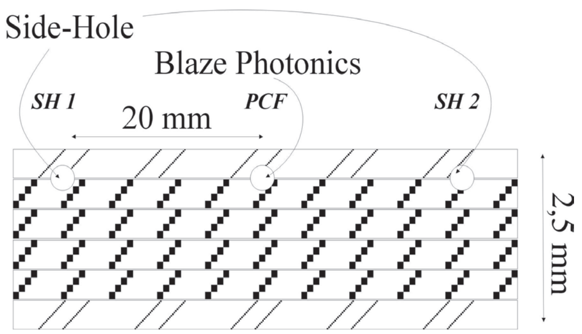

Fig. 2. Schematic (cross-section) of sensors distribution in a composite material.

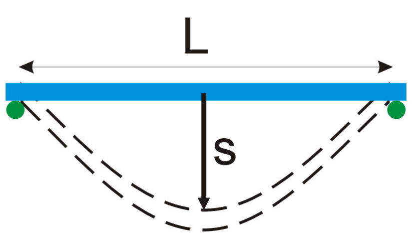

Fig.3. Scheme of deflection measurements.

Measurements made for side-hole fiber optic sensors show that strain sensitivities are different in all sensors after the lamination process (See Fig. 4).

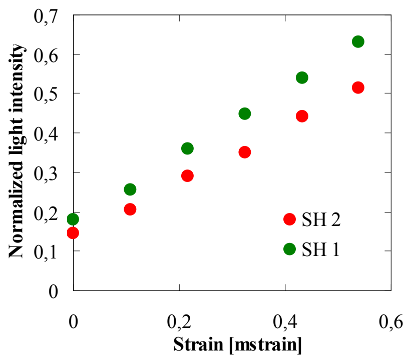

Fig. 4. Comparison between the characteristic of two side-hole sensors.

Additionally, after the lamination process the strain sensitivities for all fibers used in the experiment change dramatically. The measured strain sensitivity for both fibers before lamination (the side-hole fiber strain sensitivity is equal to 4rad/m*mstrain and for HB PCF it is 1.7rad/m*mstrain) shows that the strain sensitivity of the PM-PCF is much lower than that of the side-hole fiber. However, from Fig. 5 it is clear that for both sensors, output intensity variations are linear and have similar values.

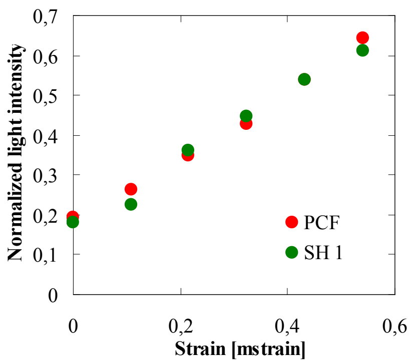

Fig. 5. Strain response of both polarimetric sensors in the hybrid configuration.

This suggests that the orientation of the polarization axes of the HB fibers in a composite material may be important for both types of the used HB fibers.

To measure the temperature sensitivity, the composite sample is attached to a Peltier cooler which is controlled by a temperature controller. The temperature of the sample is varied from 20^0C to 25^0C at intervals of 2.5^0C and the intensity outputs of both embedded sensors are monitored. The results are shown in Fig. 6. It is clear that the HB-PCF based polarimetric sensor is insensitive to temperature. Thus by configuring both sensor systems together as a hybrid sensor both strain and temperature can be measured simultaneously. The HB-PCF polarimetric sensor provides strain information and from the difference between the change in the output intensity of the HB-PCF sensor and the side-hole sensor, temperature information can be obtained.

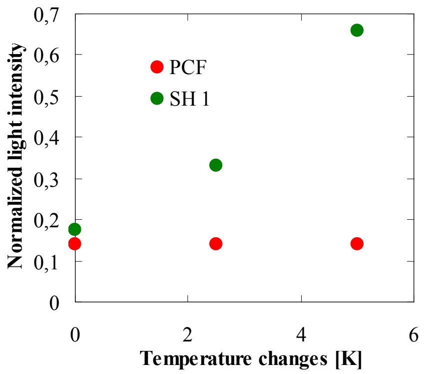

Fig.6. Temperature response of both polarimetric sensors in the hybrid configuration.

To conclude, in this letter a hybrid sensor is proposed and demonstrated by combining two types of polarimetric sensors that are based on Side-Hole fiber and HB PCF. Both sensors are strain sensitive but one of them (HB PCF) is temperature insensitive. This combination gives us the possibility to measure strain independently on ambient temperature. The proposed hybrid configuration can be effectively used for more reliable strain and temperature measurements and can be implemented in a wide range of sensing applications.

This work was supported by the Polish Ministry of Science and Higher Education through The National Centre for Research and Development and by Enterprise Ireland under the grant ERA-NET MATERA. It has been also supported by the European Union in the framework of the European Social Fund through the Warsaw University of Technology Development Programme, realized by the Center for Advanced Studies.

References

[1] T. R. Wolinski , Progress in Optics **XL**, 1-75 (2000).
[2] T. R. Wolinski, "Polarization Phenomena in Optical Systems" in *Enc. Opt. Engineering,* 2150-2175 (M. Dekker, New York, 2003).
[3] W.J. Bock, A.W. Domanski, T.R. Wolinski, Appl. Optics **29**, 3484-3488 (1990).
[4] D. H. Kim, J. U. Kang, Opt. Eng. **46**, 7(2007).

