Antiresonant-Guiding Photonic Crystal Fibers for Refractive Index Gradients Sensing

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Abstract: We propose, design and experimentally demonstrate a novel, simple, distributed refractometric sensor based on unique spectral properties of antiresonant-guiding photonic crystals fibers for measuring temperature gradients. Design optimization and potential applications will be discussed.

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1. Introduction

Photonic crystal fibers (PCFs) offer exceptional opportunities for manipulation of light propagation and realization of novel photonic devices. In particular, PCFs provide a new platform for the development of compact, multi-functional optical sensors [1-3].

Previously, we studied a sub-class of solid-core photonic crystal fibers with cladding air-holes filled with a liquid having a refractive index higher than that of the background material [4,5]. We found that the spectral response of such fibers consists of high and low transmission regions and can be explained by antiresonant guiding model. According to this model, the locations of the spectral minima are determined by the cutoff wavelengths of the modes of individual high-index inclusions (liquid-filled air-holes) and can be found from:

$$\lambda_m = \frac{2d}{m+1/2}\sqrt{n_h^2 - n_l^2}\,, \qquad (1)$$

where d is a diameter of the air-hole, n_l and n_h are refractive indices of the background (and core) material and that of the high-index inclusion, respectively, $m = 1,2,3...$ is an integer number. As follows from Eq. (1), λ_m are extremely sensitive to refractive index changes in the high-index inclusions and to the changes in the diameter of the high-index inclusions. Such strong sensitivity indeed was utilized in a number of PCF-based sensing devices [6-8].

2. Experiment

To date, a majority of PCF-based sensors has been designed for measuring uniform changes in the refractive index due to various factors, including temperature, concentration, etc. Here we describe a novel sensor design utilizing antiresonant-guiding PCFs for measuring refractive index gradients resulting from spatially non-uniform temperature distributions along the fiber.

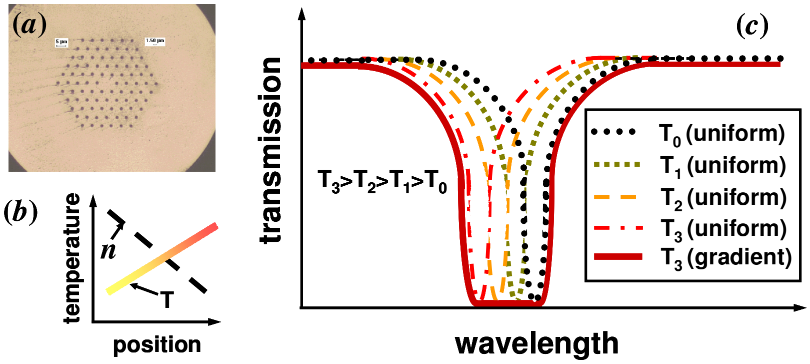

Fig. 1 (a) Image of the PCF used in our experiments, (b) and (c) basic principle of the device operation: temperature and refractive index of the high-index liquid as a function of position along the fiber (b) and transmission spectra corresponding to antiresonant-guiding PCF at room temperature T_0, shown by dotted line, a PCF uniformly heated to temperatures T_1, T_2, and T_3, shown by short dashed line, long dashed line, and dot-dashed line, respectively, and a PCF with a temperature gradient [T_0, T_3] applied along its length , shown by solid line.

Figure 1(a) shows an image of the PCF, manufactured by OFS Laboratories, which was used in the experiments. Figures 1(b) and 1(c) illustrate basic principle of the proposed device: temperature gradient, applied along the liquid-filled PCF length, results in the spatial gradient in the refractive index of the liquid. Such fiber can be considered as series of individual fiber segments each heated (cooled) uniformly to slightly different temperatures. Then, the overall spectrum of non-uniformly heated (cooled) fiber would be an envelope of the combination of spectra of the individual segments, as shown in Fig. 1(c).

The fiber used in experiments had an average hole diameter of d=1.5 μm, pitch of Λ=5.2 μm, core diameter of 8.9 μm, and 5 rings of holes surrounding the core. Figure 2(a) shows a schematic of the experimental setup. Liquid-filled PCF was mounted between two 3-Axis NanoMax stages. Light from white light source (ANDO/Yokogawa AQ4305) was launched into the PCF by butt coupling of cleaved on one end and connectorized on the opposite end standard single mode fiber (SMF) and collected at the output by the connectorized SMF spliced to the liquid-free end of the PCF. The collected light was measured using an optical spectrum analyzer (ANDO/Yokogawa AQ63187B).

We measured transmission through the PCF with high index liquid (Cargille Laboratories refractive index liquid nD=1.64), introduced into the air-holes by capillary effect, at room temperature and with various temperature gradients applied along the liquid-filled fiber length. Figure 2(b) shows measured spectra of the PCF at room temperature (solid black line), the spectrum corresponding to the PCF with temperature changing from room temperature to 64 °C (on the fiber surface) along the fiber length (dashed dark red line), and the spectrum corresponding to the PCF cooled using liquid nitrogen from room temperature to 0 °C (dot-dotted blue line).

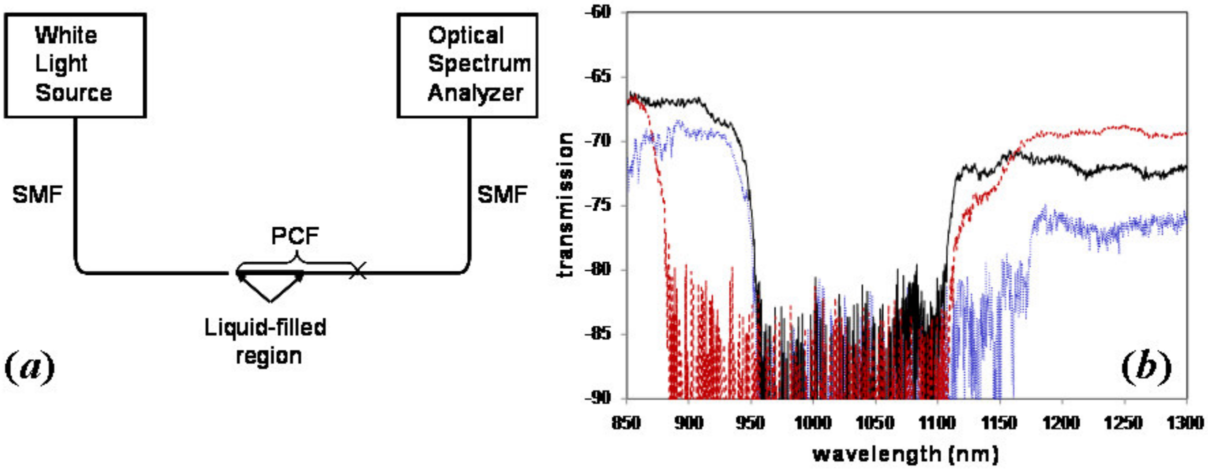

Fig. 2 (a) Block-diagram of the experimental setup, (b) measured transmission spectra corresponding to the liquid-filled PCF at room temperature (solid black line), with temperature spatially varying between room temperature and 64 °C on the fiber surface (dashed dark red line), and with temperature spatially varying between room temperature and 0 °C on the fiber surface (dotted blue line).

3. Summary

We demonstrated a novel distributed refractometric sensor based on unique spectral properties of antiresonant-guiding photonic crystals fibers for measuring refractive index gradients. Details of design optimization and a broad variety of potential applications of these sensors ranging from commercial to biological systems will be discussed in the presentation.

4. References

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