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Invited Paper

An integrated nematic liquid crystal in-fiber modulator derivates from capillary optical fiber

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ABSTRACT

A novel liquid crystal integrated modulation-depth-adjustable in-fiber modulator is proposed. The liquid crystal is encapsulated in a specially designed capillary optical fiber with tubular structure. The experimental results show that the liquid crystal under the electric field can influence the light intensity in the tubular core of the fiber. The light at 632.8 nm in the circular waveguide can be modulated by only 2.71×10^{-2} nL of the liquid crystals under electric field. The wide range of modulation-depth from 23% to 50% can be obtained by adjusting the strength of the external electric field. In addition, the modulator shows good stability and repeatability. This work has great potentials in integrated in-fiber optical devices such as tunable modulators, optical switches and electric field sensors.

1. Introduction

Optical modulators are significant components in the laser engineering and electro-optical system. Then, many forms of optical modulators have been developed [1–3]. Especially, optical fiber modulators are essential in many fields such as WDM system, optical fiber laser system and integration photoelectric system, because of their special properties such as very low insertion loss [4–6]. On the other hand, there is a tendency towards constructing optical integrated systems to minimize the volume of the devices. For example, fiber-optic integrated devices achieve internal modulation and manipulation of light propagation in the fiber. They are important in the fields of optics communication modules and optical fiber sensors [7,8]. Especially, microstructured optical fibers (MOFs) is important in the advanced sensor components and devices by infiltrating the microholes with gas, liquid and biological samples [9–13]. They allow the interaction between the guided light and the operation materials via evanescent field of the core and have an inherent advantage to hold small volumes for microsystems and to simplify the experimental setup of optical fiber sensors [14–16].

Liquid crystals (LCs) are very interesting materials in that they exhibit both fluid and crystalline characteristics, which exist in nematic, smectic, cholesteric, and ferroelectric forms [17]. One of the most important properties of them is the crystalline reorientation based on externally applied fields, which include electric, magnetic, and optical electric fields. In the presence of the external field, a corresponding interaction, due to the anisotropy of the material, changes the alignment of the LCs [18]. This inherent property can readily be applied to sensors measuring an externally applied field that comes from an electric voltage. Because it possesses unusual characteristics, over the past decades, there have been a number of studies on the optical properties of LCs, such as attenuators, filters and spectrometers. With these spectacular and useful properties, LCs show great prospect in the development of various optical devices such as optical switches and electric-field sensors.

In this paper, we encapsulate LC into a specially designed capillary optical fiber (COF) with a tubular structure to propose an in-fiber integrated modulator. In this design, the optical fiber with the hollow structure is filled with trace amount of LC in the volume of nano-liter. Under the effect of external electric field, the interaction between the LC and the circular waveguide will be greatly affected and the light in the waveguide can be modulated. In previous similar devices such as the modulators, and the switches based on PCF [19–22], the integration has been obviously improved. The LC is inhaled into the air holes of the optical fibers to change the guiding properties of the fiber from an index guiding fiber to a photonic band gap guiding fiber. However, the LC inhaled

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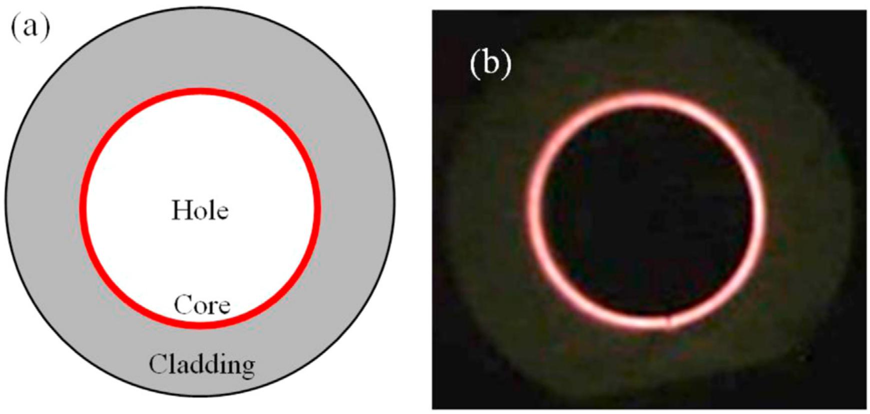

Fig. 1. (a) The sketch of the capillary optical fiber (b) The cross section of the capillary optical fiber.

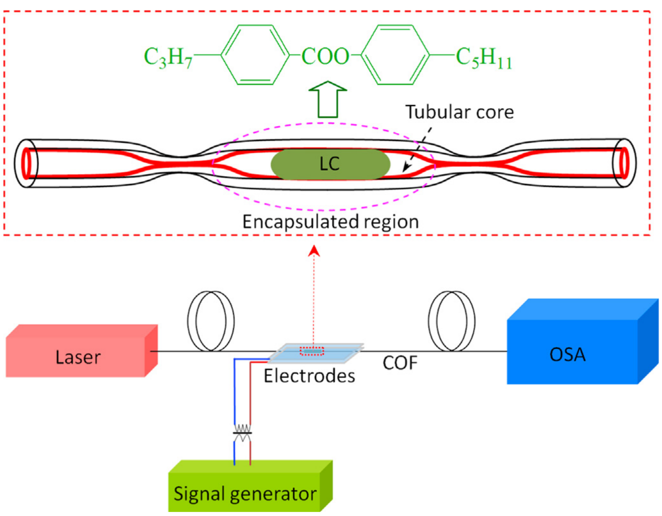

Fig. 2. Experimental setup for the in-fiber integrated capillary optical fiber modulator (insert: the chemical structure of benzoic acid, 4-propyl-, 4-pentylphenyl ester).

into the holes is not encapsulated and is flowable. This will lead to the instability of the system during use. Compared with the PCF fibers, the capillary optical fiber have a tubular waveguide and we can encapsulate the LC by melting the two ends of the region filled with LC. This will immobilize the position of the LC and enhance the stability of the device. Simultaneously, the optical fiber in the paper is low cost than the PCFs. So, the device in the paper is more economic.

2. Experiment

The experimental setup is shown in Fig. 1. A piece of COF with the length of 6 cm designed by us is used as the fundamental element of the modulator. It has a tubular structure, consisting of an inner air channel. The outer diameter of the COF is 125 μm and the inner diameter is 48 μm. There is a tubular core and a tubular cladding. The thickness of the core is about 7 μm and that of the cladding is 31.5 μm. A nematic LC of benzoic acid, 4-propyl-, 4-pentylphenyl ester which refractive indices is 1.543 at 25 °C is used in the experiment. The structure of the LC molecule is shown in the insert of Fig. 2. In the air channel, a trace amount of the LC (2.71×10^{-2} nL) is filled to modulate the light (the loss of the LC itself in the fiber is about 8 dB). The length of the LC column is 1.5 cm (the loss of the fiber filled with the LC is about 12 dB). This region of the tubular structure is melted using welding machine to encapsulate the LC and prevent the flowing of it. The intensity of the output light is detected with an optical spectrum analyzer. The part of COF which filled with LC was coated on a pair of glass substrates deposited with ITO (Indium Tin Oxide). The distance between them is 1 mm. The electric field is created through a signal generator (0–10 V, 80 Hz). The strength of the applied field is adjusted by a transformer and monitored with a voltmeter. The corresponding real-time variation of transmission loss is recorded by single wavelength tracking at 632.8 nm.

3. Results and discussion

In general, the alignment of the nematic LC in the core is highly dependent on the LC-container interface interaction. In common silica capillaries, the nematic director tends to align along the axis of the fiber and the nematic director can be realigned by the external electric field. In this experiment, when voltage is applied to the electrode, the nematic director aligns along the direction of the applied electric field as shown in Fig. 3. This is an inherent property of nematic LC. As a result, the external voltage can change the effective refractive index of LC near the tubular core by means of the electrode.

The modulation characterization of the LC in the tubular core of

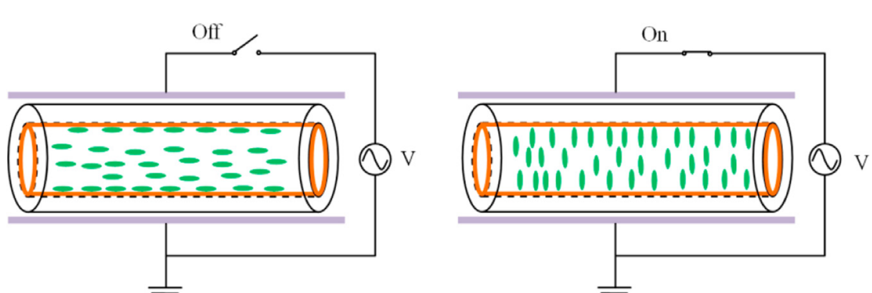

Fig. 3. Schematic diagram of the arraying direction of LC molecules near the tubular core under the electric field.