Sensors and Actuators B 196 (2014) 663–669

Contents lists available at ScienceDirect

Sensors and Actuators B: Chemical

journal homepage: www.elsevier.com/locate/snb

# Side-polished fiber as a sensor for the determination of nematic liquid crystal orientation

Yuqi Han [b], Zhe Chen [a,b,*], Dong Cao [b], Jianhui Yu [a,b,*], Haozhi Li [b], Xiaoli He [b], Jun Zhang [a,b], Yunhan Luo [a,b], Huihui Lu [a,b], Jieyuan Tang [a,b], Hankai Huang [b]

[a] *Key Laboratory of Optoelectronic Information and Sensing Technologies of Guangdong Higher Education Institutes, Jinan University, Guangzhou 510632, China*

[b] *Department of Optoelectronic Engineering, Jinan University, Guangzhou 510632, China*

ARTICLE INFO

*Article history:*
Received 3 October 2013
Received in revised form 18 February 2014
Accepted 20 February 2014
Available online 2 March 2014

*Keywords:*
Fiber optics
Side-polished fiber
Optical fiber sensing
Nematic liquid crystal
Orientation change
Optical transmission power

ABSTRACT

The orientation change of nematic liquid crystal (NLC) has been the essential mechanism for various high sensitive sensors. In this paper, a side-polished fiber (SPF) is proposed to sense the orientation change of NLC. We successfully designed the liquid crystal cell embedded with a SPF that enabled us to mechanically rotate the orientation of NLC on the polished surface of the SPF. Our experimental results showed that the orientation change of NLC can indeed be sensed by monitoring the output optical power transmitted through the SPF. The increment of the transmitted optical power through the SPF was measured as large as 28.10 dB with the mechanical rotation from 0° to 90°. Within the angle range from 0° to 30°, the response was almost linear. The average response slope was about 0.359 dB/°, which indicated relatively high sensitivity. These experimental results indicate that SPF can be used to determine the orientation change of NLC. In particular, there exists a possibility that a SPF overlaid with NLC on its polished surface can potentially be made into a small transducer of a biosensor.



## 1. Introduction

The orientation of liquid crystal (LC) is highly sensitive to external fields and environment including shear stress, electric and/or magnetic fields, biomolecular binding events, and surface structure imposed alignment [1,2]. The sensitivity of liquid crystal qualifies itself as a "sensitive element". Liquid crystal has recently been reported as a transducing element in various sensors [3,4], especially biosensors [5–8]. Based on the LC orientation changes induced by the anchoring transition, Abbott's group successfully demonstrated using liquid crystal as a "molecular magnifying glass" to optically amplify and transduce biomolecular binding events [9]. They used a polarizing microscopy to observe light transmittance or optical texture changes through a liquid crystal cell in order to determine the LC orientation change induced by anchoring transitions in surface structure of substrates [10–15].

Side-polished fiber (SPF) has already found various applications in all fiber-optic devices and sensors [16,17], due to its well known advantages, including low cost, immunity to electromagnetic interference, multiplexing, and small size. One of the benefits for SPF is that sensing material(s) can be easily deposited or incorporated onto its polished area. Another benefit is the interaction length between light and the deposited matter can be increased by increasing the polished fiber section length, thus potentially enabling higher sensitivity [18,19]. The third one is that its mechanical structure with a thickness of about 70 μm is stronger than that of the etched fiber with a diameter of only 8 μm [20]. Because the evanescent field of guided light wave in SPF could leak beyond the polished surface, SPF is very sensitive to the refractive index change of overlaid materials on its side polished surface [21,22]. SPFs overlaid with liquid crystal have been made into optical polarizer [23], modulator [24] and filter [25] et al. SPF overlaid with hybrid photoresponsive liquid crystal has also been demonstrated as light sensors [26–29].

In this paper, we report a liquid crystal cell embedded with a side-polished fiber (SPF) that enabled us to sense the change of the liquid crystal (LC) orientation on the polished surface of the SPF. The LC orientation change is induced by the anchoring transition of the substrate using mechanical rotation. In comparison of using the polarizing microscopy, the LC orientation change can be quantified by the output optical power transmitted through the SPF. Moreover the influence to the transmitted optical power resulting from the LC orientation changes can be substantially enhanced

* Corresponding authors: Department of Optoelectronic Engineering, Jinan University, Guangzhou 510632, China. Tel.: +86 020 85223428 403.
*E-mail addresses:* thzhechen@jnu.edu.cn (Z. Chen), kensomyu@gmail.com (J. Yu).

http://dx.doi.org/10.1016/j.snb.2014.02.076
0925-4005/

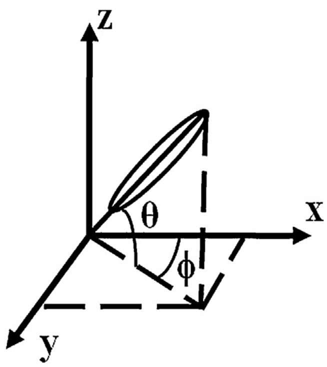


**Fig. 1.** The orientation of nematic liquid crystal director in a Cartesian coordinate system.

along the fiber length by taking advantage of the relatively long side polished section. As a result of this enhancement, the optical sensitivity of SPF is no longer limited to the orientations change in the liquid crystal with a thickness of only 1–20 μm, as demonstrated by Abbott's group. By monitoring the output optical power transmitted through the SPF, we found that the SPF sensor can sensitively determine the change of liquid crystal orientation. Therefore, as an alternative to polarizing microscopy, SPF overlaid with nematic liquid crystal can not only optically amplify and transduce the LC orientation change, but also overcome some shortcomings of polarizing microscopy, such as semi-quantitative assessment, large size, non in situ measurement, complicated operation and the difficulty of integration into or with other device(s). As a potential application, our SPF optical sensor overlaid with nematic liquid crystal could perhaps be integrated with a microfludic channel to amplify the binding of bio-molecules and transduce the binding event into optical signals.

## 2. Operating principle and experimental design

Optical properties of liquid crystal are determined by the spatial orientation of composing molecules. The molecular shape of nematic liquid crystal (NLC) is like a rigid rod. A unit vector along the long molecular axis, named director, describes the local orientation of liquid crystal. The direction of the director can be defined by the azimuth $\phi$ and tilt angle $\theta$ in a Cartesian coordinates [1,2], as shown in Fig. 1. A liquid crystal (LC) director can be orientated or anchored along a preferred direction by external factors, especially the microstructure of solid surfaces. Subsequent anchoring transitions to different directions can be induced by changes in the surface microstructure of the liquid crystal cell – substrate interface [30]. In our experiments, NLC samples are separated from an external medium by the plane surfaces of substrates. When liquid crystal molecules are strongly anchored at the boundaries, the orientation of liquid crystal could be described by the director of the bulk terms only. As shown in Fig. 2(a), the rubbed polyimide (PI) films spin-coated on two substrates of the liquid crystal cell can form the microstructure and be able to strongly anchor the liquid crystal along the rubbing direction. In the SPF-embedded LC cell, the unpolished cladding of the SPF will shelter its polished surface from the anchoring impact of the PI film on the bottom substrate 1. Consequently, the LC orientation on the polished surface mainly depends on the anchoring direction of the PI film on the top substrate 2. The LC orientation can be considered to approximately equal to the anchoring direction of the top substrate 2. Therefore, mechanical rotation of the top substrate 2 can quantitatively control the azimuth of the LC orientation next to the polished surface. Despite its possible instability and inhomogeneity, the mechanical rotation can provide an actuating method that can more

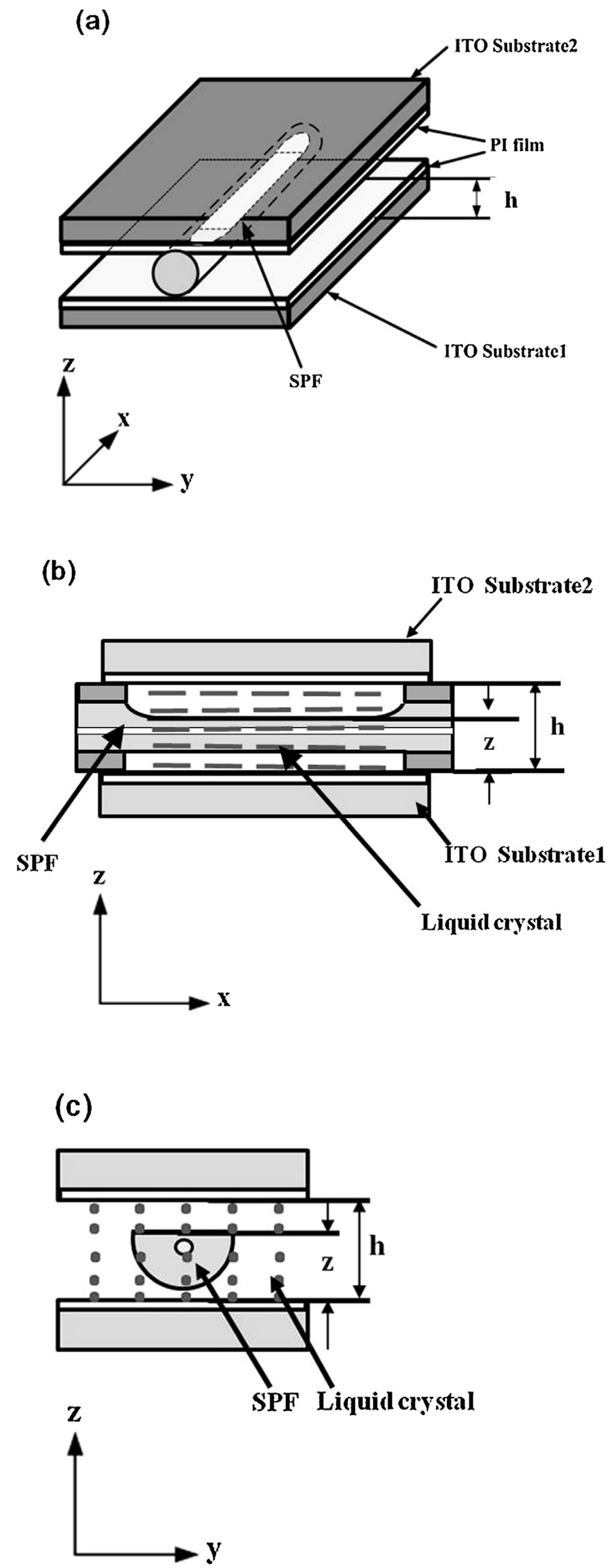


**Fig. 2.** Schematic diagram of a SPF-embedded liquid crystal cell. (a) Three-dimensional perspective view. There are five parts of the cell: top substrate 2 coated with a layer of indium tin oxide (ITO), polyimide (PI) film, nematic liquid crystal, PI film and bottom ITO substrate 1. (b) Cross sectional view along the SPF. (c) The cross-sectional view across the polished area of the SPF.