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Tunable nanojet-induced mode achieved by coupled core–shell microcylinders with nematic liquid crystals

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ABSTRACT

The tunable nanojet-induced mode achieved by coupled core–shell microcylinders with nematic liquid crystals is reported. The optical transmission properties of touching core–shell microcylinders with nematic liquid crystals are studied by using high resolution finite-difference time-domain simulation. We identify two rotation mechanisms of liquid crystal in terms of the coupling efficiency between neighboring core–shell microcylinders. The nanojet-induced guided modes depend strongly on the directors of liquid crystals. The optical transport can be continuously tuned in the core–shell microcylinder by controlling the directors of liquid crystals. The coupled core–shell microcylinders can be assembled inside hollow structures to build tunable optical waveguides for effective and low-loss guiding of photons.

1. Introduction

During the past two decades there has been considerable interest in the optical waveguides. Optical waveguides can be produced by using different physical phenomena such as total internal reflection in layered arrangements, photonic bandgaps in photonic crystal structures [1], and high quality microcavities in coupled resonator waveguides [2]. In recent years, the concept of photonic nanojets has been disclosed by many science researchers [3–9]. The photonic nanojets are received on the shadow side of a dielectric microcylinder or microsphere under plane wave illumination and focused spots with elongated shape and subwavelength lateral sizes. The optical coupling and transport through chains of dielectric microcylinders are described by using the generalized Mie theory and tight-binding method [10,11]. The perfect whispering gallery mode is achieved to propagate through a chain of coupled microcylinders. The Fabry–Pérot fringes with low propagation losses are observed in the transmission spectra of long chains. Besides, it has been shown that the photonic nanojets can be periodically reproduced along a chain of microcylinders. Such periodical patterns of coupled photonic nanojets, termed nanojet-induced guided modes, have been observed in chains and clusters of microspheres [12,13]. The nanojet-induced guided modes are directly observed in very long chains consisting of several tens of microspheres with diameters in the 2 μm to 10 μm. By measuring attenuation at long distances from the light source, the propagation losses for nanojet-induced guided modes are very small as ~ 0.1 dB per microsphere [14]. Furthermore, author presents the ultra-high transmission of nanojet-induced modes in chains of microcylinders with metallic coating [15]. The nanojet-induced modes are dramatically enhanced by the metallic coating. Therefore, highly efficient optical transport is achieved in such a metallic coating microcylinder chain.

The tunable devices are very important for utilization of photonic circuits [16]. The tunable propagation of lightwave in a photonic crystal structure modulated by a nematic liquid crystal (LC) is presented by the authors [17–19]. We proposed the infiltration of the LCs in photonic crystal structure with different lattices, and guided modes based on the orientation of LCs can be controlled by adjusting the applied electric field in the optical waveguides. Furthermore, the electro-optical switching in the photonic crystal linear waveguides, waveguide bends, resonators, and microcavities is also presented by the author [20–22]. The lightwave modulation is a variation of the electric conductivity of the inner cylinders in the waveguides or resonators and the guided modes can be controlled. Such devices offer novel building blocks for ultracompact photonic integrated circuits based on electrically controlled modulators and dividers. Recently, a tunable photonic nanojet achieved by a single core–shell microcylinder with nematic LC is reported by the author [23]. The location of photonic nanojet can be continuously tuned in the core–shell microcylinder by rotating the directors of LC. It would be crucial to the detection sensitivity of nanoscale specimens in far field optical systems.

In this paper, we theoretically demonstrate the tunable transmission of nanojet-induced guided modes in coupled core–shell microcylinders illuminated by a plane wave. The focusing of

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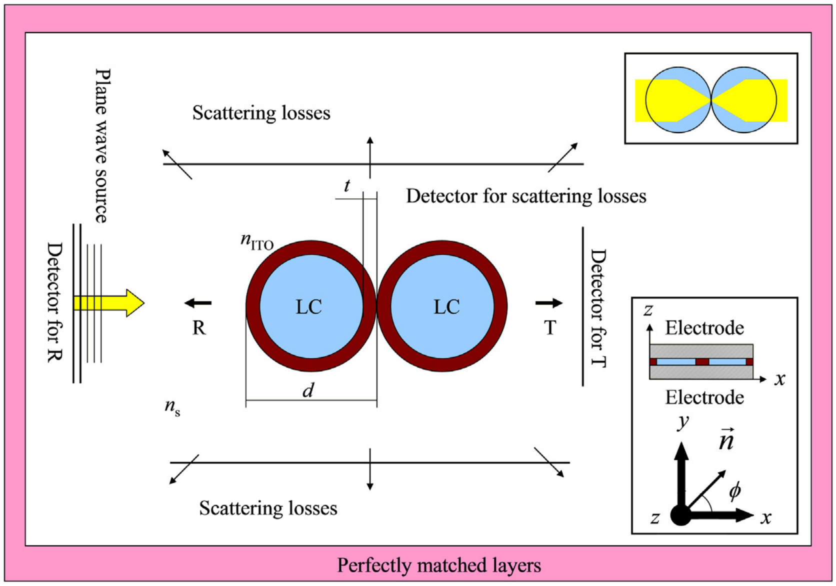

Fig. 1. Schematic diagram of the coupled core–shell microcylinders with nematic liquid crystal. Blue and brown shaded regions indicate liquid crystal core and indium tin oxide shell, respectively. The top insert indicates geometrical optics model of coupled microcylinders with the focal length $d/2$. The bottom insert indicates the director of a liquid crystal and the configuration of electrodes. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this paper.)

lightwave in coupled core–shell microcylinders is characterized with the periodicity of nanojets by using finite-difference time-domain (FDTD) method. The touching core–shell microcylinders are efficiently coupled to collimate incident lightwave. The nanojet-induced guided modes depend strongly on the directors of LCs. The optical transport can be continuously tuned in the core–shell microcylinder by rotating the directors of LCs. The numerical approximation for tunable nanojet-induced mode is presented in Section 2. The numerical results of coupled core–shell microcylinders with LC are shown in Section 3. Finally, we summarize the conclusion and consider the potential utilizations in Section 4.

2. Numerical approximation

Optical transmission properties can be calculated via many different methods [24]. A unique calculation technique is needed for a core–shell microcylinder. The FDTD technique is one of the most popular methods of finding the electromagnetic properties [25]. Recently, we have conducted FDTD program with high resolution on superenhanced photonic nanojet by core–shell microcylinders [26]. The enhancements of nanojet at resonance and off-resonance conditions of core–shell microcylinders are investigated. In this paper, our simulations employ the FDTD calculation based on the rigorous electromagnetic theory. The computational modeling space is meshed into a uniform two-dimensional (2D) mesh with the perfectly matched layer [27] as boundary condition and the grid cell size is 1 nm. The time sampling is calculated by the Courant limit to guarantee numerical stability of the algorithm. Fig. 1 depicts a numerical model of the coupled core–shell microcylinders with LC. In the 2D geometry, we have utilized an incident lightwave, linearly p-polarized, namely with its magnetic vector perpendicular to the propagation plane. The lightwave propagation is along the x-axis direction. We use the FDTD calculation to investigate the internal electromagnetic field distributions of the coupled core–shell microcylinders with LC. LC materials generally have two dielectric constants [28]. The ordinary dielectric constant is ε^o and the extraordinary dielectric constant is ε^e. The lightwave propagations with electric fields perpendicular and parallel to the director of LC possess ordinary and extraordinary dielectric constants, respectively. Jones matrix method is a powerful approach for dealing with lightwave transmission problem of a LC component at normal incidence. When the director of LC rotates on the propagation plane, the dielectric tensor is generally given by

$$\varepsilon = \begin{bmatrix} \varepsilon_{x,x} & \varepsilon_{x,y} \\ \varepsilon_{y,x} & \varepsilon_{y,y} \end{bmatrix} \tag{1}$$

where

$$\begin{aligned} \varepsilon_{x,x} &= \varepsilon^o \cos^2\phi + \varepsilon^e \sin^2\phi, \\ \varepsilon_{y,y} &= \varepsilon^o \sin^2\phi + \varepsilon^e \cos^2\phi, \\ \varepsilon_{x,y} &= \varepsilon_{y,x} = \left[\varepsilon^e - \varepsilon^o\right]\cos\phi\sin\phi. \end{aligned} \tag{2}$$

Here, the rotation angle of the LC director is ϕ. The LC director is presented by $\vec{n} = (\cos\phi, \sin\phi)$. When the optical medium is isotropic material, ε^o is equal to ε^e.

Our FDTD computational program has been compared with the exact solution for the light scattering of the small spheres [29]. The detailed treatment of the FDTD method and LC calculation can be obtained in Refs. [25–29].

3. Coupled core–shell microcylinders with LC

The photonic nanojets can be periodically reproduced along a chain of microcylinders. The propagation losses of nanojet-induced guided modes are shown to be 0.1 dB per microcylinder for a broad range of visible light. These properties indicate great potential for use of coupled microcylinders in applications. We present the quantitative studies to demonstrate tunable optical coupling mechanism by nanojet-induced guided modes for coupled core–shell microcylinders with LC. Fig. 1 depicts several parameters of the coupled core–shell microcylinders with LC. Blue and brown shaded regions exhibit LC core and indium tin oxide (ITO) shell, respectively. The top insert indicates geometrical optics model of coupled microcylinders with the focal length $d/2$ in the rules of geometrical optics. When the focal length of photonic nanojet is $d/2$, the nanojet-induced mode is a perfect propagation. The bottom insert shows the director $\vec{n}$ of a LC, the rotation angle ϕ of the LC director to the x-axis and the configuration of electrodes. The dielectric core of microcylinder is created by the infiltration of LCs into the air cavity. The diameter of core–shell microcylinder is d and the shell thickness of ITO is t. In the case of nematic LCs, the