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Real-space observation of nanojet-induced modes in a chain of microspheres

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ABSTRACT

The three-dimensional real-space observation of photonic nanojet-induced modes in a chain of microspheres with different diameters is reported. The optical transmission properties of a chain of microspheres are studied by using high resolution finite-difference time-domain calculation. The photonic nanojet-induced modes in different chains of microspheres are measured by using a scanning optical microscope system with an optical-fiber probe. We observe the photonic nanojet-induced modes from optical microscope images for chains of 3 μm, 5 μm, and 8 μm microspheres deposited on a patterned silicon substrate. The incident beam can be periodically reproduced in chains of dielectric microspheres giving rise to lossless periodically optical focusing with period of two diameters. Detailed theoretical and experimental data on the transmission, scattering loss, and field-of-view are presented. This waveguide technique can be used in biomedical microscopy, ultra-precise laser process, microfluidics, and nanophotonic circuits.

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1. Introduction

The optical waveguide is the fundamental element that interconnects the various components of an optical integrated circuit. Lightwaves travel in the waveguide in distinct optical modes by different physical phenomena [1–4]. Generally, optical waveguides consist of a dielectric core with higher refractive index surrounded by a cladding with lower refractive index. Three-dimensional (3-D) calculation is necessary to investigate the transmission mechanism of optical waveguides. Recently, it was demonstrated that a dielectric microsphere produces a narrow focused beam with subwavelength lateral sizes, termed photonic nanojet [5–12]. Such a photonic nanojet propagates with little divergence and elongated shape for several wavelengths into the surrounding medium. This phenomenon is attractive for designing focusing components with high optical transmission properties. However, the photonic nanojets from a single microsphere require strictly conical illumination which is not readily available in many applications. In order to solve this problem, the concept is based on the use of microsphere chains. Initial researches have concentrated on the optical coupling effects between the microspheres, termed whispering gallery mode [13,14]. Then, it has been investigated the mechanism of optical transport by using photonic nanojet coupling. The optical coupling leads to formation of photonic nanojet induced mode with the periodicity of the focused beams corresponding to the diameter of two microspheres and with very small propagation losses [15–17]. The transmission analysis of photonic nanojet induced modes in chains of microcylinders with metallic coating is reported by the authors [18]. The photonic nanojet induced modes are dramatically enhanced by the metallic coating. Therefore, highly efficient optical transport is achieved in a chain of metallic coating microcylinders. The chains of microspheres can be used in contact surgery with strongly absorbing tissue, since focusing of lightwave is accomplished primarily inside the chain [19]. The advantages of a chain of microspheres are easy integration with flexible hollow waveguides and ability to focus multi-mode lightwaves. The more understanding of photonic nanojet induced modes is nevertheless needed to fully exploit the application of microsphere chains as a flexible optical delivery system.

In this paper, we theoretically and experimentally demonstrate the 3-D real-space observation of nanojet-induced modes in a chain of microspheres illuminated by a light source with wavelength of 633 nm. The finite-difference time-domain (FDTD) method is used to execute the numerical calculation for a chain of microspheres. The beam focusing in chains of microspheres is characterized with the periodicity of photonic nanojets. The photonic nanojet-induced modes in chains of microspheres have been measured by using a scanning optical microscope system with an

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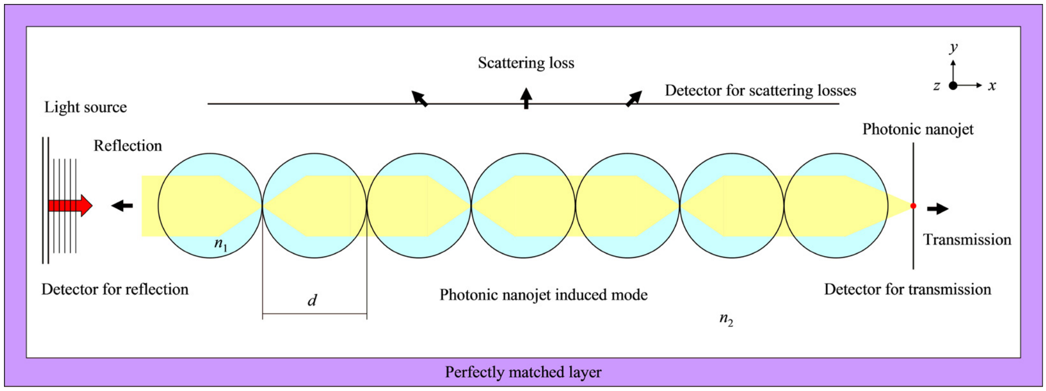

Fig. 1. Schematic diagram of the illumination of a chain of microspheres.

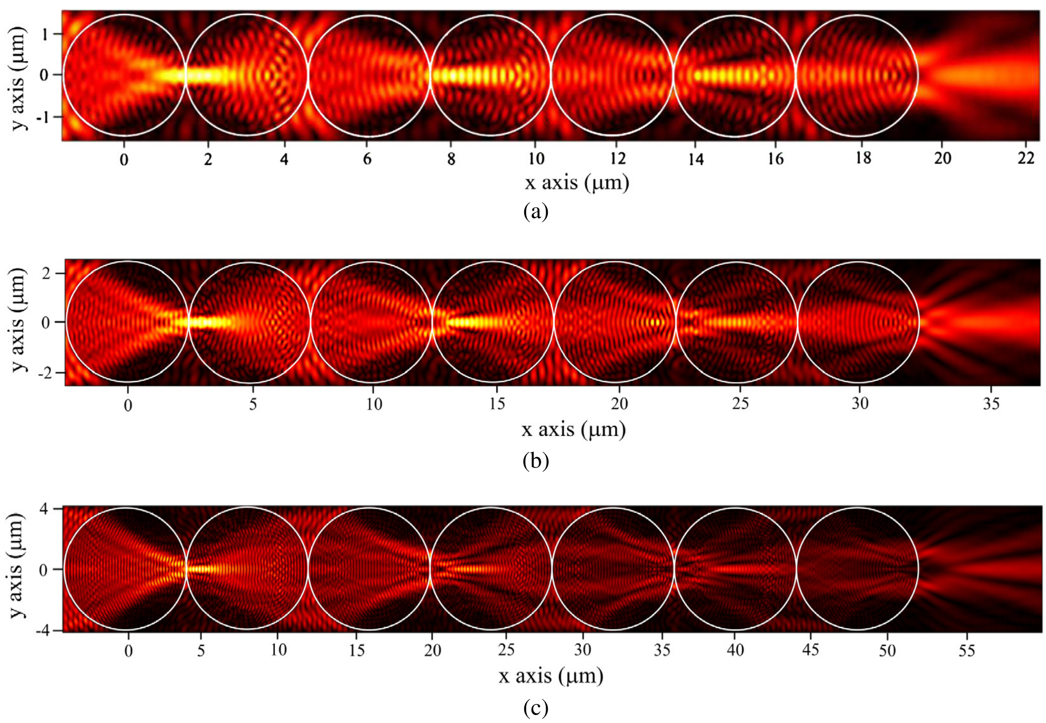

Fig. 2. Normalized electric field distribution of a chain of microspheres at diameter (a) $d = 3$ µm, (b) $d = 5$ µm, and (c) $d = 8$ µm. All microspheres have a refractive index $n_1 = 1.6$. Light source with wavelength 633 nm propagates from left to right. The white circles show the microsphere rim.

optical-fiber probe. The dielectric microspheres can be assembled inside hollow structure and may provide a novel optical waveguide technique for photonic circuits. The 3-D numerical calculations of photonic nanojet-induced modes are presented in Section 2. The experimental configuration and measurement data are shown in Section 3. The conclusion and the potential applications for the chains of microspheres are summarized in Section 4.

2. Numerical approximation

Recently, photonic nanojet-induced modes have emerged as a new concept for describing beam focusing and optical transport properties in the chains of dielectric microspheres. The FDTD method based on vector electromagnetic wave theory can accurately demonstrate lightwave propagation in the microspheres [20]. We have conducted FDTD codes with high resolution on photonic nanojet calculations for core-shell microcylinders and graded-index microspheres [21–24]. The enhancements of photonic nanojets and nanojet-induced modes generated by a single core-shell microcylinder and chains of core-shell microcylinders are reported. The ultra-elongation of photonic nanojets produced at the shadow side surfaces of a graded-index microellipsoid illuminated by a plane wave is also reported. Since the 3-D FDTD method can provide a rigorous solution to the photonic nanojet-induced mode, we select it to make our numerical simulation. The fundamental photonic nanojet-induced modes are schematically illustrated in Fig. 1. In 3-D simulations, the computational region is a cubic box with the perfectly matched layer boundary condition [25]. In order to ensure enough accuracy and high calculation speed, the space step is 10 nm. The refractive index and the diameter of microspheres are $n_1 = 1.6$ and d. The chains of microspheres is placed in air, the refractive index is assumed to be $n_2 = 1$. A plane wave illumination with a wavelength of 633 nm in the x direction is incident from the left and impinges on the chains of microspheres. When the focal length of photonic nanojets is $d/2$, the photonic nanojet-induced modes propagate effectively in the chains of microspheres. If the total number of microspheres is odd number, the photonic nanojet will arise at the shadow side of the last microsphere.

Fig. 2 depicts the normalized electric field distribution of a chain of microspheres at diameter $d = 3$ µm, $d = 5$ µm, and

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