Optics Communications 399 (2017) 104–111

Contents lists available at ScienceDirect

Optics Communications

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

Large-area super-resolution optical imaging by using core-shell microfibers

Cheng-Yang Liu*, Wei-Chieh Lo

Department of Mechanical and Electro-Mechanical Engineering, Tamkang University, New Taipei City, Taiwan

ARTICLE INFO

Keywords:
Photonic nanojet
Microfiber
Super-resolution

ABSTRACT

We first numerically and experimentally report large-area super-resolution optical imaging achieved by using core-shell microfibers. The particular spatial electromagnetic waves for different core-shell microfibers are studied by using finite-difference time-domain and ray tracing calculations. The focusing properties of photonic nanojets are evaluated in terms of intensity profile and full width at half-maximum along propagation and transversal directions. In experiment, the general optical fiber is chemically etched down to 6 μm diameter and coated with different metallic thin films by using glancing angle deposition. The direct imaging of photonic nanojets for different core-shell microfibers is performed with a scanning optical microscope system. We show that the intensity distribution of a photonic nanojet is highly related to the metallic shell due to the surface plasmon polaritons. Furthermore, large-area super-resolution optical imaging is performed by using different core-shell microfibers placed over the nano-scale grating with 150 nm line width. The core-shell microfiber-assisted imaging is achieved with super-resolution and hundreds of times the field-of-view in contrast to microspheres. The possible applications of these core-shell optical microfibers include real-time large-area micro-fluidics and nano-structure inspections.

1. Introduction

Optical microscopy is the most significant non-destructive direct imaging technique in industrial applications. The spatial resolution of a traditional optical microscope is about 200 nm in ideal, however a 300 nm target is very difficult to be observed in practice. Therefore, how to beat the diffraction limit and improve the imaging resolution have become a popular research topic in photonics [1]. Scientists have proposed some methods to realize nano-scale imaging such as fluorescence photoactivation localization microscopy (FPLM), scanning electron microscope (SEM) and scanning near-field optical microscope (SNOM) [2–4]. These methods have their own limits in applications. FPLM works only with a single wavelength light source. SEM should be operated in vacuum and it is unsuitable for the observation of live viruses. SNOM takes a long time in the process to obtain the full-field imaging because SNOM is based on point-by-point scanning of a optical tip very close to the target surface. Therefore, a fast and direct super-resolution imaging technique is required to observe the nano-scale features in the visible light region.

Recently, an ultramicroscope by using microspheres to amplify the imaging intensity for nano-scale targets has been realized under the visible light illumination [5–20]. The observations of super-resolution images contain the employments of silica microspheres, high-index microspheres, dielectric slab with microspheres, microsphere locomotion and microspheres in the confocal mode. Anyway, the microsphere is the key element in these ultramicroscopy techniques. The strong focusing effect generated by microspheres is named the photonic nanojet. The image of nano-scale targets with the resolution of 100 nm is demonstrated by using microsphere-assisted imaging. The microsphere-assisted photonic nanojets with high intensity are also used to apply for subwavelength nano-patterning [21–25] and nanoparticle sensing [26–28]. However, microsphere-assisted imaging suffers from the shortcomings. Because the photonic nanojets are generated near the microsphere surface, the microspheres should be assembled on the objective surface and connect directly with the specimen. Therefore, it's very difficult to remove the microspheres from the objective surface and keep the specimen clean. Furthermore, the field of view (FOV) of microsphere-assisted imaging is limited by the diameter microsphere. When the super-resolution imaging is achieved by small microspheres, the FOV is restricted by sphere diameter on the order of few microns. The locomotion techniques can be used to move the microspheres along the objective surface, but the surface scanning capability requires complicated tools and has several technical difficulties in practice.

In this work, we first numerically and experimentally investigate the large-area super-resolution optical imaging by using core-shell microfibers in the visible light region. The power flow patterns for different core-shell optical microfibers are simulated by using the finite-differ-

* Correspondence to: Department of Mechanical and Electro-Mechanical Engineering, Tamkang University, No. 151, Ying-chuan Road, Tamsui District, New Taipei City, Taiwan.
E-mail address: cyliu@mail.tku.edu.tw (C.-Y. Liu).

http://dx.doi.org/10.1016/j.optcom.2017.04.047
Received 21 December 2016; Received in revised form 29 March 2017; Accepted 21 April 2017

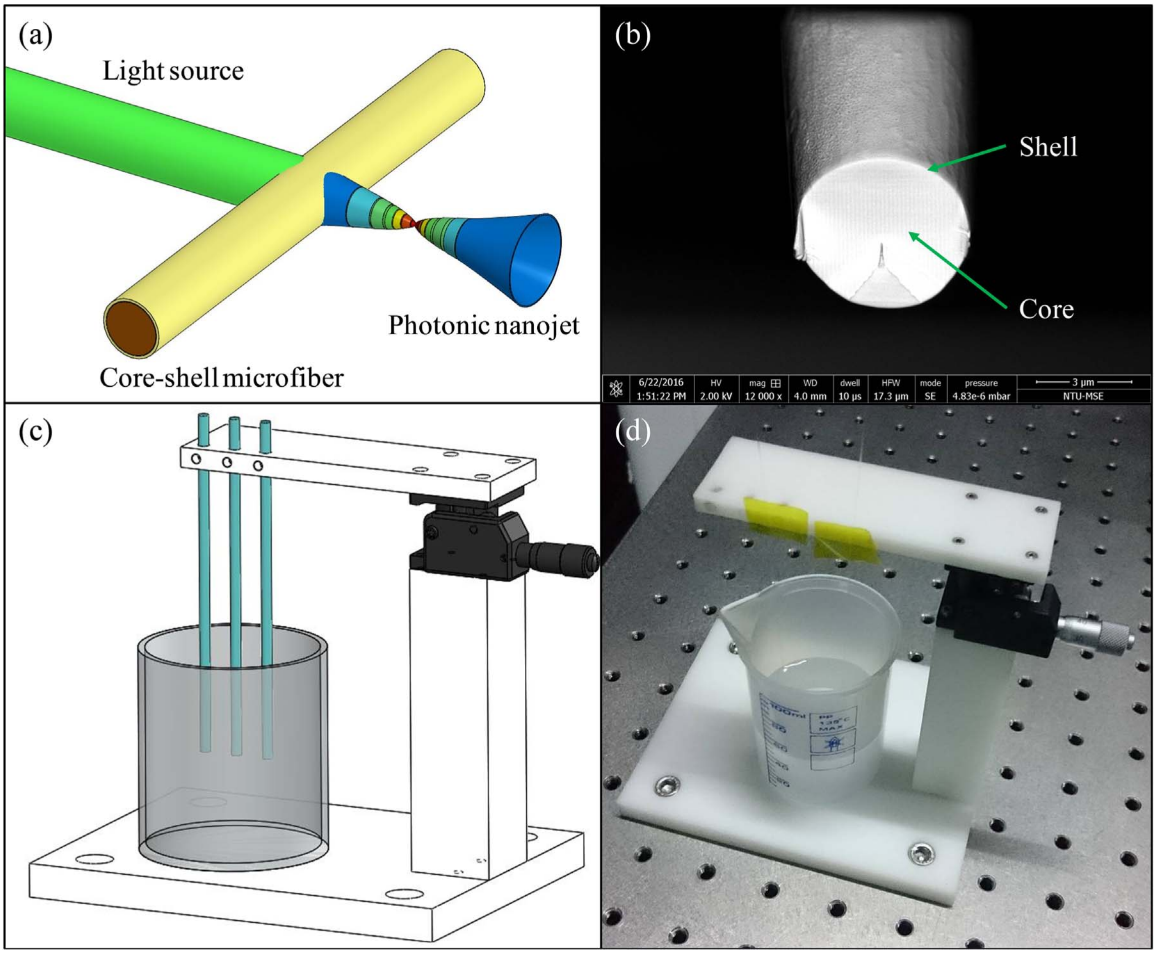

Fig. 1. (a) Schematic diagram of the proposed core-shell microfiber for photonic nanojet. (b) SEM image of a core-shell microfiber formed by FIB milling. Dynamic chemical etching of optical fiber: (c) schematic configuration and (d) photograph.

ence time-domain (FDTD) and ray tracing methods. The focusing properties of photonic nanojets are evaluated in terms of intensity profile and full width at half-maximum (FWHM) along propagation and transversal directions. In experiment, the general optical fiber is chemically etched down to 6 µm diameter and coated with different metallic thin films by using glancing angle deposition (GLAD). We show that the intensity distribution of a photonic nanojet is highly related to the metallic shell due to surface plasmon polaritons. The numerical approach and experimental verification are presented in Section 2 and Section 3. We also studied core-shell microfiber-assisted imaging of nano-scale gratings with different surface plasmon properties. The demonstrations for a combination of super-resolution and image magnification obtained through a core-shell microfiber are presented by the authors. The prospective studies and conclusion are briefly summarized in Section 4.

2. Numerical approach

In this present work, photonic nanojets generated by core-shell microfibers are found to be sensitive to the presence of nano-scale features in the optical microscope. The characteristics of photonic nanojets are demonstrated through comparisons between the FDTD models and their corresponding ray tracing calculations. The full Maxwell's equations FDTD calculations based on vector electromagnetic wave theory are employed in the simulations of light propagation in the core-shell microfibers [29,30]. The computational domain is a non-uniform triangular mesh and the perfectly matched layer is chosen as a boundary condition. After the convergence verification performed by the decrease of the step size, the mesh size in the core and surrounding medium is 10 nm and the mesh size in the shell region is 1 nm. The non-uniform triangular mesh can assure enough accuracy and high calculated speed. The space and time derivatives are both calculated by a second-order accurate centered difference. The time step is determined by the grid step size and selected to guarantee numerical stability and calculation speed. The electromagnetic distributions inside and outside the core-shell microfibers can be obtained by using discrete time and lattices. Fig. 1(a) depicts the schematic diagram of the proposed core-shell microfiber for photonic nanojet. The 6 µm core-shell microfiber is illuminated by a linearly polarized plane wave with wavelength of 532 nm and forms a photonic nanojet near its shadow surface. The refractive indices of the microfiber and surrounding medium are 1.5 and 1 (air). The refractive indices of the gold, silver and copper shells are 1.46+1.954i, 0.05+2.168i and 1.3+2.159i, respectively. The FDTD code is implemented on the personal computer with central processing unit of Intel Core i7 and random-access memory of 24 GB.

Fig. 2 depicts the simulations of normalized power flow patterns for the dielectric, gold coating, silver coating, and copper coating microfibers. It is numerically shown that the core-shell microfibers with core diameter of 6 µm and shell thickness of 5 nm create a elliptical spot near the microfiber surface. The shape of elliptical spot is similar to the shape of photonic nanojet generated by a microsphere [11]. The elliptical spot formed by a dielectric microfiber is small when the microfiber diameter is comparable with incident wavelength. For a dielectric microfiber, the intensity enhancement of photonic nanojet is possible only through an increase of microfiber diameter. However, the