Optics Communications 334 (2015) 253–257

Contents lists available at ScienceDirect

Optics Communications

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

Rapid super-resolution imaging of sub-surface nanostructures beyond diffraction limit by high refractive index microsphere optical nanoscopy

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ARTICLE INFO

Article history:
Received 7 July 2014
Received in revised form
18 August 2014
Accepted 19 August 2014
Available online 4 September 2014

Keywords:
Super-resolution
Diffraction limit
Mie theory
Microsphere
Photonic nanojet

ABSTRACT

Sub-surface nanostructures cannot be observed by scanning electronic microscopy or standard scanning probe microscopy. They are also outside the resolution limit of standard optical microscopes. In this paper, we demonstrate super-resolution imaging of sub-surface nanostructures beyond the optical diffraction limit. Sub-surface Blu-ray recorded data structures (100–200 nm) have been observed directly with submerged microsphere optical nanoscopy (SMON) using TiO_2–BaO–ZnO glass microspheres (refractive index = 2.2) of 60 μm diameter immersed in water coupled with a standard optical microscope. Theoretical analysis of the imaging phenomena was carried out by the characteristics of electrical field Poynting vectors and photonic nanojets.

1. Introduction

Sub-surface nanostructures or nanostructures that do not have chemical or topographical differences cannot be observed using scanning electron microscopes or standard scanning probe microscopes. They are also beyond the resolution of a standard optical microscope defined by the optical diffraction limit. Such limitation of the optical resolution is about the half of the light wavelength. For visible light illumination at 400–700 nm wavelength, the ultimate far field imaging resolution is 200 nm. To overcome the far field diffraction limit of optical resolution, perfect superlenses were theoretically introduced by using a negative refractive index medium that restores evanescent waves [1]. The metamaterial optical superlens (FSL) resolves sub-diffraction-limited objects by the conversion of near field evanescent waves into far-field propagating waves [2–6]. However, the magnification of such an FSL was approximately 1. This magnification does not allow them to be captured with a standard optical microscope [7]. The optical hyperlens can overcome this limit by adapting curved anisotropic metamaterial optical lenses that can magnify the near field evanescent waves during the transformation to far field propagating waves [8–10]. The microsphere optical nanoscopy also demonstrated super-resolution imaging by magnifying and transferring the near field evanescent waves to propagating waves in the far field in combination with a standard optical microscope through a fused silica dielectric microsphere in air [11], with semi-immersing liquid [12,13], and the use of barium titanate glass microspheres in water and other liquids such as isopropyl alcohol [14,15]. The scanning laser confocal microscope combined with the 5 μm fused silica microsphere to achieve 25 nm resolution in 408 nm wavelength [16]. The effect of microsphere size on the super-resolution imaging using was reported by Lee et al. showing little difference in image magnification factors for the 30–100 μm polystyrene microspheres, but the focal plane is different for different sphere sizes with the optimum about two to three times of the microsphere diameters below the target surface [17]. A water immersed microsphere nanoscope has been successfully used to observe viruses at a size of 75 nm [18]. Optical super-resolution of sub-surface structures below a transparent surface layers was realized by scattering-type scanning near-field optical microscopy (s-SNOM) [19], and scanning tunnelling optical microscopy [20]. The imaging is through point-by-point scanning of a laser illuminated atomic force microscope tip induced sub-diffraction light spot below the target surface. The technique is, however, slow in capturing the images, thus not suitable for real time inspection of sub-surface nanostructures in industrial components. In this paper, we report a rapid super-resolution imaging of sub-surface nanostructures beyond optical diffraction limit by the submerged microsphere optical nanoscopy (SMON) technique.

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http://dx.doi.org/10.1016/j.optcom.2014.08.048
0030-4018/

The image resolution and magnification are compared with the SEM images of nanostructures in data-recorded and blank Blu-ray discs. The simulation of the photonic nanojet and the characteristics of near-field Poynting vectors were carried out to understand the phenomena.

2. Methods

The data-recorded and blank Blu-ray discs were used as target materials. The soft protection film of the Blu-ray discs was removed by pealing from the edge of the disks. Chemical etching was not applied to the Blu-ray discs so that a thin (50–100 nm) dielectric film ($ZnS–SiO_2$) remained on the recording layer (SbTe). TiO_2–BaO–ZnO glass microspheres of a 60 μm diameter (refractive index $n=2.2$) were used as the micro-lenses. The microspheres were spread on the target surfaces of the Blu-ray discs with water drops. A standard optical microscope (LEICA DM 2500 M) with a ×100 NA:0.85 objective lens was used for the observation of super-resolution images through the microspheres at the reflective mode illuminated with halogen white light. During the imaging, both the optical microscope objective lens and the microsphere were immersed in water (refractive index $n=1.33$). The focal image position was placed below the target surface. It was measured at 1 μm resolution of the microscope z-axis of the objective lens. The magnification and image resolution were examined for each imaging condition. The experimental setup is shown in Fig. 1.

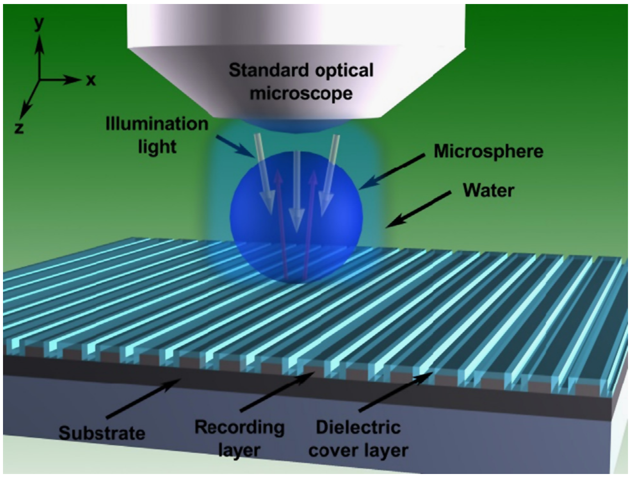

Fig. 1. Schematic of the SMON imaging experimental setup.

In the simulations, Mie theory and Poynting vector flows were used. The $d=60$ μm diameter TiO_2–BaO–ZnO glass microsphere was used during the calculation of the electromagnetic field. The incident plane waves of 400 nm, 500 nm, 600 nm, and 700 nm wavelengths were transmitted through the dielectric microsphere along the z coordination, and two-dimensional distribution was calculated in the x–z plane. Directional vector arrows were used to indicate the flow of the field and colour coding was used to indicate the electric field intensity. Since the photonic nanojet supports the super-resolution imaging induced by enhanced backscattering [21–23], the waist of photonic nanojets was theoretically determined and compared with the optical diffraction limit.

3. Results and discussion

The optical images captured using the SMON technique was compared with the SEM images as shown in Fig. 2. The SEM image in Fig. 2(a) shows the data-recorded Blu-ray disc surface. The SEM observation of the blank Blu-ray disc in Fig. 2(b) shows periodic lines of about 300 nm pitches with 120 nm (dark colour) and 180 nm (bright colour) lines. However, the irregular recorded data

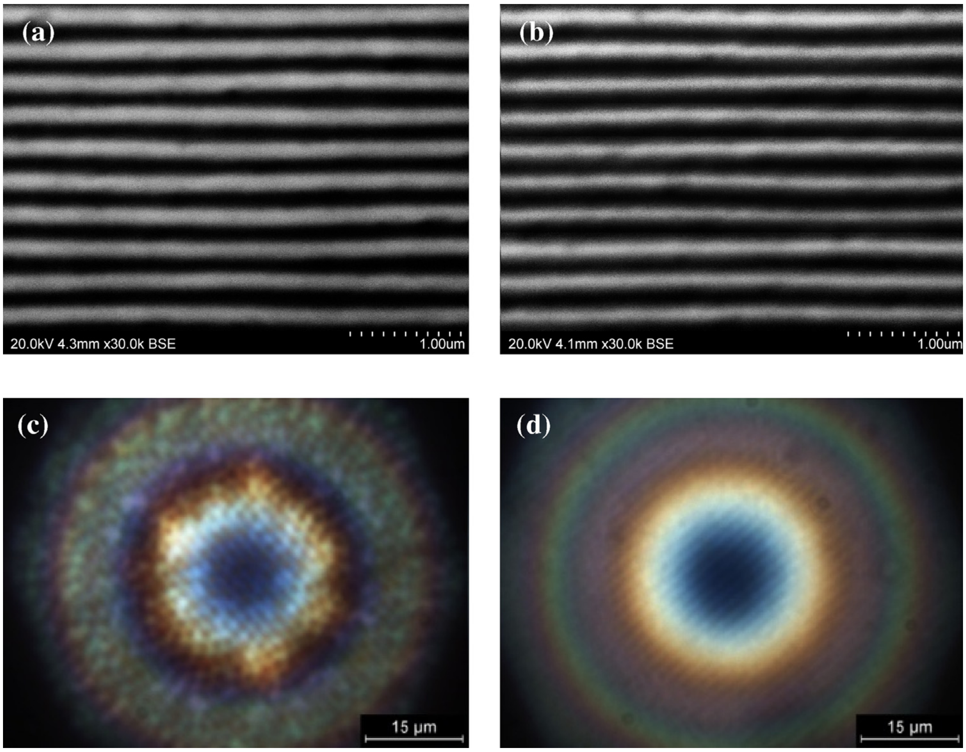

Fig. 2. A comparison of scanning electron microscope (SEM) and optical super-resolution images of data-recorded and blank Blu-ray discs. The Blu-ray disc nanostructures are observed with a focal plane position of 130 μm below the Blu-ray disc top surface. (a) a SEM image of a data-recorded Blu-ray disc surface; (b) a SEM image of a blank Blu-ray disc; (c) an optical image of the data-recorded Blu-ray disc using the SMON technique; (d) an optical SMON image of blank Blu-ray disc.