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Imaging of sub-surface nanostructures by dielectric planer cavity coupled microsphere lens

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ABSTRACT

In this paper, a dielectric planar cavity between an object and a microsphere lens is fabricated and its effects on the imaging of sub-surface nanostructures have been studied. Using the dielectric planar cavity combined (DPCC) silica microsphere lens, our experimental results illustrate that the nanostructures of data-recorded Blu-ray disc can be clearly resolved. Optical images of the object with higher contrast and larger field of view (FOV) can be obtained, compared to the case when only a microsphere lens is used. For the 3.4 μm diameter microsphere lens combing a planar cavity with a thickness about 2.2 μm, the FOV is about 2.4 μm and the magnification is about 1.6. With the 3.4 μm diameter microsphere lens only, the FOV and magnification is 1.5 μm and 1.4 respectively. Theoretical analysis of the imaging properties is carried out by the characteristics of electric field distribution of microsphere lenses. The simulated results indicate that the dielectric planar cavity working as a Fabry-Pérot cavity can effectively enhance the coupling of optical information.

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1. Introduction

The optical resolution of a far-field microscopy is constrained by the diffraction limit of light, and the lateral resolution is limited to about half of the illumination wavelength according to Abbe's diffraction theory. To obtain super resolution imaging, a variety of techniques such as scanning probes [1], fluorescence microscopies [2], hyper-lenses and super-lenses [3], and microsphere lenses [4–14] have been proposed. Among these approaches, the microscopy assisted by microsphere lenses is an effective and simple imaging technique which can capture the fine structures of objects beyond Abbe's diffraction limit. The microsphere lens under a standard white light source can collect the near-field evanescent waves and transfer them to far-field propagating waves. Lee et al. have reported near-field focus and magnification by microscale and nanoscale hemispherical lenses and a virtual image forms below the object when it is closely contacted to the microlens by adjusting the focal plane of the objective-lens [4]. Wang et al. have demonstrated that transparent silica microsphere lenses with diameters 2–9 μm can collect and magnify sub-diffraction features with a lateral resolution down to 50 nm [5]. Recent studies have shown that the super resolution capability of microsphere lenses can be enhanced by using different immersing ways [7–12]. Li et al. have submerged both the microsphere and the objective-lens of the optical microscope and have successfully obtained direct white-light optical images of adenoviruses [7]. The contrast of the super resolution image of a low refractive index microsphere lens can be enhanced with a comparatively smaller magnification when the lens is semi-immersed in a liquid medium [8,9]. High refractive index microsphere lenses such as barium titanate glass microspheres or TiO2-BaO-ZnO microspheres totally immersed in medium with super resolution have also been experimentally demonstrated [10–12]. Moreover, the super resolution capability of the microsphere lens can be improved by using a laser confocal nanoscope system [13,14]. On the other hand, studies have shown that a dielectric planar cavity structure can effectively enhance the evanescent waves due to its resonant mode [15–17], but this idea has not been applied to the microsphere lens imaging area. In this letter, we introduce an approach which utilizes the dielectric planer cavity combined (DPCC) microsphere lens to resolve the sub-surface nanostructures (100–200 nm) of data-recorded Blu-ray discs (BDs). In combination with the microsphere lens, the dielectric planar cavity structure which is composed of a low refractive index silica (n∼1.46) layer and a high refractive index SU-8 (n∼1.6) layer, can work as a Fabry-Pérot cavity to enhance the background scattering. The experimental results show that optical images with high contrast and large field of view (FOV) can be obtained. Our method has the potential to promote the resolution of the microsphere assisted microscopy imaging.

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2. Experimental section

The configuration of the experimental setup is shown in Fig. 1(a), which illustrates that a conventional optical microscope (Leica DM2500 M) assisted by a DPCC microsphere lens is used to discern the object. The microscope is equipped with an objective lens ($100\times$ NA=0.9) and a CCD camera (Leica DFC 295). The object is a data-recorded BD with its protection film peeled off before use. A thin (50–100 nm) dielectric film still remains on the recording layer because there is no treatment of chemical etching. The observation of super resolution images is explored by adjusting the focus of the microscope under white-light illumination and reflective mode. The light generated from the microscope halogen lamp has passed through a filter before illuminating onto the sample and its peak wavelength is 540 nm. First, a thin layer of low refractive index silica with thickness about 95 nm was evaporated on top of the object, used as a coupling layer. Then, a high refractive index SU-8 layer with a thickness of 2.2 μm was spin-coated onto the silica layer, which is utilized as a cavity layer. The thickness of the SU-8 layer was measured by a step profiler (AMBios Technology, XP-1). Then, microsphere lenses with diameters 3.4 μm were spread on top of the SU-8 layer and semi-immersed in ethanol. The refractive index of the microsphere and ethanol is 1.46 and 1.37, respectively. Finally, a virtual image of the object could be obtained through the microscope and recorded by the CCD camera. As the scanning electron microscope (SEM) image Fig. 1(b) shown, the BD has periodic lines of about 300 nm, which are consisted of 200 nm stripes and 100 nm grooves with irregular recorded data spots on its surface.

3. Results and discussion

Fig. 2(a) is the image of a data-recorded BD directly obtained by a conventional optical microscope. It shows that both the periodic lines and the irregular data-recorded topographic changes can not be resolved due to the diffraction limit. Figs. 2(b) (c) (d) are the images of the object obtained by a microsphere in air, a semi-immersed microsphere lens and a DPCC microsphere lens, respectively. Fig. 2(b) shows that the patterns of the BD can not be discerned by the microsphere in air. However, if the microsphere lens is semi-immersed in ethanol, as the evanescent waves are less attenuated due to the higher refractive index of immersed medium, the resolution of the microsphere lens is improved [8], and the nanostructures of the sample can be resolved as shown in Fig. 2(c). Using the slightly immersed DPCC microsphere lens, an optical image with high contrast and more clear irregular recorded data spots can be obtained, which can be seen in Fig. 2(d) compared to Fig. 2(c), the immersed medium we use in our experiment is ethanol. In order to describe the imaging effect quantitatively, the frequency spectra of the images shown in Fig. 2 are calculated by Fourier analysis, and are shown in the insets of the figures. The frequency spectra shown in Fig. 2(d) illustrates that the image obtained by the DPCC microsphere lens has more high-frequency components, which located at the corner of the frequency spectra. While the frequency spectra shown in Figs. 2(a) (b) (c) has less high-frequency components, with the low-frequency components located at the center of the frequency spectra.

For semi-immersed microspheres, the improvement of image contrast is sacrificed on the loss of magnification [9]. Our experimental results show that the magnification of the microsphere lens with a diameters 3.4 μm (Fig. 2(c)) is about $1.4\times$. For the slightly immersed DPCC microsphere lens with the same diameter, the magnification is a little larger, which is about $1.6\times$, as shown in Fig. 2(d). Here, the magnification is defined as the ratio of the size of the observed periodic lines of BD in the FOV of microlens to its actual size with a value 300 nm. Considering the difficulty in defining the image plane and the consequent measuring error, the change of the magnification is unconspicuous. FOV is another important imaging property of microspheres, which is defined as the diameter of the sample area that can be observed by the microsphere lens. The image of the nanostructures of the BD is observed by using the semi-immersed microsphere lenses when the ethanol almost evaporates, and the FOV is about 1.5 μm. For the slightly immersed DPCC microsphere lens with a thickness 2.2 μm cavity layer, the FOV increases to about 2.4 μm. The increase of the FOV and enhancement of the image contrast indicate that the planer cavity structures contribute to the coupling of high-frequency components into the microsphere lens.

In our experiments, we have also studied the effects of the thickness of the cavity layer on the FOV of the imaging of sub-surface nanostructures obtained by the DPCC microsphere lens. Our experimental results reveal that both the fine structures of the data-recorded BD can be discerned with in our tested range (1.6–5.4 μm). Figs. 3(a) (b) (c) show that the FOV can maintain a relatively stable value of about 2.4 μm as the thickness of cavity layer

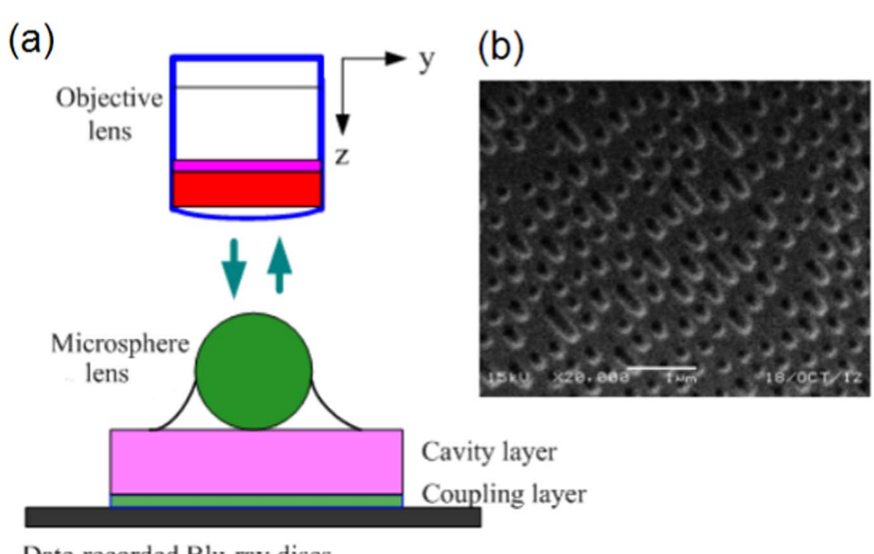

Fig. 1. (a) schematic of the DPCC microsphere lens imaging setup and (b) SEM image of the data-recorded Blu-ray disc.

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