Optics and Laser Technology 108 (2018) 551–557

Contents lists available at ScienceDirect

Optics and Laser Technology

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

Full length article

Super-resolution optical microscopic imaging using a structure of surface plasmon resonant cavity

Ti Sun [a,b], Haiyang Chen [a,b], Song Yang [a,b], Jingpei Hu [c], Chinhua Wang [a,b,*]

[a] College of Physics, Optoelectronics and Energy and Collaborative Innovation Center of Suzhou Nano Science and Technology, Soochow University, Suzhou 215006, China
[b] Key Lab of Modern Optical Technologies of Education Ministry of China and Key Lab of Advanced Optical Manufacturing Technologies of Jiangsu Province, Soochow University, Suzhou 215006, China
[c] Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800, China

ARTICLE INFO

Article history:
Received 23 March 2018
Received in revised form 27 June 2018
Accepted 14 July 2018

Keywords:
Super-resolution
Optical microscopic imaging
Surface plasmon resonant cavity
Tunable

ABSTRACT

We report on an observation of a novel super-resolution optical microscopic imaging technique using a surface plasmon resonant cavity (SPRC) in which surface plasmonic waves (SPWs) with a much larger wave vector than that of either the direct illumination light of the same frequency or the SPWs without the SPRC structure are generated to serve as the illumination of the microscopy. Numerical results show that an imaging resolution of 21 nm can be achieved based on the proposed SPRC method under an illumination of 532 nm light, which is 10.4-fold, 4.4-fold or 4.1-fold better than that of conventional high numerical aperture fluorescence microscopy, grating structured illumination microscopy using proximity projection scheme or conventional surface plasmon excitation, respectively. It is also found that the wave vector of the SPRC structure and hence the resolution of the microscopy can be tunable by varying either the cavity height or the thickness of the cavity wall (i.e., silver thin film). The physical origin of the much enhanced resolution and also the tunability of the proposed method are analytically confirmed by the dispersion relation derived from the SPRC system.

1. Introduction

Studies of the biological samples and many other scientific research and application fields require high resolution optical microscopy. However, the resolution of optical microscopy is fundamentally limited by optical diffraction that is directly related to the illuminating wavelength, which means that objects with separations smaller than the diffraction limit cannot be resolved. Much efforts have been devoted to improve the resolution of optical microscopy and many novel imaging techniques have been proposed, such as stimulated emission depletion microscopy [1–3], photoactivation localization microscopy [4], and near-field scanning optical microscopy [5–7]. Compared with the super-resolution methods mentioned above, the structured illumination microscopy (SIM) does not require complex, bulky, and expensive architectures, which has a large field of view and high-imaging speed [8,9]. The optical resolution of SIM system is essentially determined by the spatial frequency or the periodicity of the illumination pattern, which is directly related to the wavelength of illumination. To achieve higher resolution, smaller periodicity of the illumination pattern, i.e., shorter wavelength of illumination is required. Surface plasmon polaritons are essentially electromagnetic waves trapped at the metal/dielectric interface due to the collective oscillation with the free electrons of the metal, which attracts much attention in recent years [10]. The wave vector of SPPs can be significantly larger than that of the free space illuminating light at the same frequency. Because of this unique property, SPPs are widely used in nanophotonic subwavelength scale applications, such as super-resolution photolithography [11], superlens imaging [12,13], and far-field hyperlens imaging [14]. Most recently, standing wave surface plasmon resonance fluorescence microscopy (SW-SPRF) [15] and plasmonic structured illumination microscopy (PSIM) [16,17] have been proposed and have shown their capability for microscopic resolution enhancement. In 2014, Wei et al. [17] demonstrated a surface plasmon assisted super-resolution imaging using PSIM. A slit array patterned plasmonic structure which was made of Ag grating on SiO_2 substrate was employed in the PSIM. Compared with conventional fluorescence microscopy, PSIM achieves a 2.6-fold resolution improvement due to the excited illumination of surface plasmon polaritons, which is solely determined and thus limited by the metallic material (e.g., silver) employed in the grating structure. Compared to PSIM, a proximity projection grating scheme (PPGS)

* Corresponding author at: College of Physics, Optoelectronics and Energy and Collaborative Innovation Center of Suzhou Nano Science and Technology, Soochow University, Suzhou 215006, China.
E-mail address: chinhua.wang@suda.edu.cn (C. Wang).

https://doi.org/10.1016/j.optlastec.2018.07.032
0030-3992/

is also proposed and demonstrated by *See et al* in which the resolution of conventional SIM can be further enhanced significantly [18,19] and a sub-100 nm resolution of the PPGS-based SIM can be obtained.

In this paper, a novel super-resolution optical microscopic imaging technique using a slide of surface plasmon resonant cavity (SPRC) is proposed and numerically demonstrated. The slide of SPRC is made of a dielectric (Al_2O_3) cavity with two cavity walls being a metallic grating mask and a metallic thin film deposited on a dielectric substrate, respectively. It is found that surface plasmon waves (SPWs) with a much larger wave vector than that of either the direct illumination light of the same frequency or the SPWs without the SPRC structure can be generated with the introduction of a SPRC structure, which breaks the limitation of wave vector being solely determined by the material in the conventional SPPs excitation schemes. Numerical results show that an imaging resolution of 21 nm can be achieved based on the proposed SPRC method under an illumination of 532 nm light, which is 10.4-fold, 4.4-fold or 4.1-fold better than that of conventional high numerical aperture fluorescence microscopy, PPGS-based SIM or conventional surface plasmon excitation, respectively [16,17,19]. In addition, it is also found that the wave vector of the SPRC structure and hence the resolution of the microscopy can be tunable by varying either the cavity height (i.e. the thickness of the Al_2O_3 material) or the thickness of the cavity wall (i.e., silver thin film), although the period of the metallic mask is fixed and much larger than the illumination wavelength. The physical origin of the much enhanced resolution and also the tunability of the proposed method are analytically confirmed by the dispersion relation derived from the SPRC system.

2. Methods

The schematic of a super-resolution surface plasmon resonant cavity (SPRC) microscopy is presented in Fig. 1. A collimated illumination light is incident from the bottom of a SPRC device (slide) with a wavelength of λ_0 = 532 nm and *p*-polarization. The incident angle of the collimated light onto the SPRC structure can be adjusted by a reflector shown in Fig. 1(a). A sample is sitting on the slide of SPRC, and the signals of the sample can be collected by using a traditional objective and captured by a charge-coupled device (CCD) camera in far field, as shown in Fig. 1(a). The SPRC is formed by a diffraction-limited Ag grating mask sitting on a SiO_2 substrate and a backing Ag thin film separated by an Al_2O_3 layer with a thickness d_3, as shown in Fig. 1(b) and (c). As a comparison, a conventional PSIM structure is shown in the inset of Fig. 1(c), in which a sample is directly placed on the metallic Ag grating. Numerical simulations are performed using the FDTD Solutions (Lumerical of Canada). In the calculation, the refractive indices of SiO_2 and Al_2O_3 are 1.50 and 1.77, respectively, and the permittivity of Ag is $-11.75 + 0.37i$ [20]. The period and thickness of the Ag grating is assumed to be 840 nm (T) and 100 nm (d_2), the slit width of the grating is fixed at 30 nm (w), and the thickness of backing Ag film (d_4) and the cavity height of Al_2O_3 layer (d_3) can be tunable (The detailed effect of the parameters of Ag grating on the performance is given in "Supplementary material"). A biological sample with aqueous environment (H_2O) is assumed to be sitting on the SPRC structure, which serves as the objective plane in a SPRC optical microscopy.

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.optlastec.2018.07.032.

3. Principle of a super-resolution SPRC optical microscopy (SPRC-OM)

Fig. 2 shows the electric field (*x*-component) distributions of the SPRC structure with different cavity heights (d_3) and as comparison, the electric field distribution of a conventional PSIM structure at plane $Y = 0$. The thickness of the backing Ag film (d_4) is assumed to be 20 nm. In Fig. 2(a), (b), (c), (d), (e), (f), (g), and (h), the thickness of the cavity layer (Al_2O_3) is 170 nm, 140 nm, 43 nm, 26 nm, 18 nm, 15 nm, 12 nm and 0 nm, respectively, and Fig. 2(i) is the

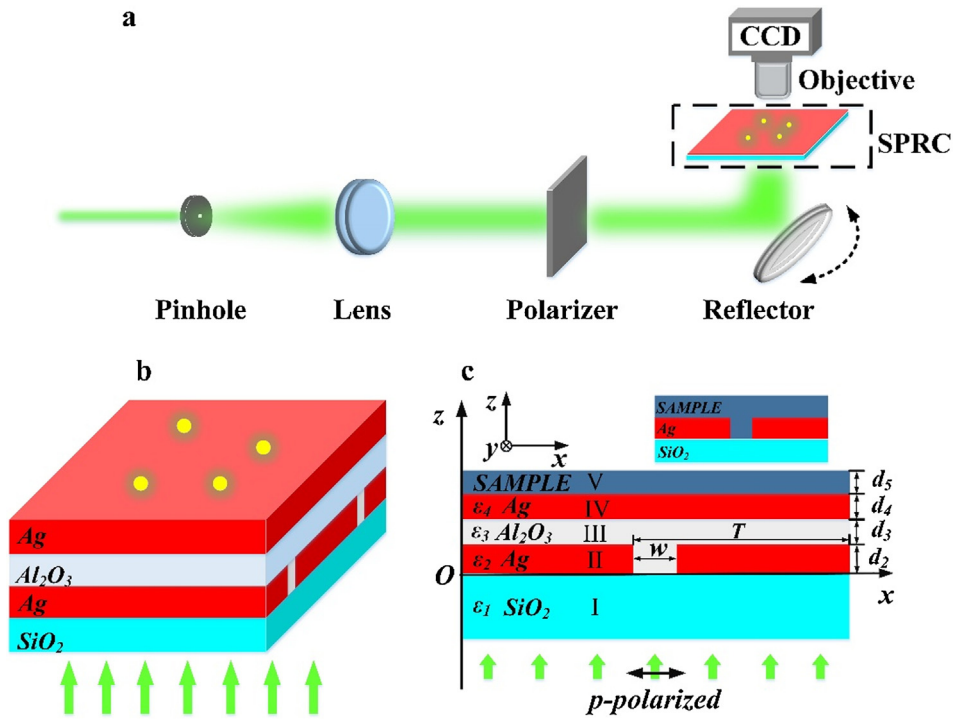

Fig. 1. (a) Schematic of a super-resolution SPRC optical microscopy (SPRC-OM); (b) overall side view of the proposed SPRC structure; (c) section view of the proposed SPRC structure.