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Generation of ultra-long pure magnetization needle and multiple spots by phase modulated doughnut Gaussian beam

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ABSTRACT

Based on vector diffraction theory and inverse Faraday effect (IFE), the light induced magnetization distribution of a tightly focused azimuthally polarized doughnut Gaussian beam superimposed with a helical phase and modulated by an optimized multi belt complex phase filter (MBCPF) is analysed numerically. It is noted that by adjusting the radii of different rings of the complex phase filter, one can achieve many novel magnetization focal distribution such as sub wavelength scale (0.29λ) and super long (52.2λ) longitudinal magnetic probe suitable for all optical magnetic recording and the formation of multiple magnetization chain with four, six and eight sub-wavelength spherical magnetization spots suitable for multiple trapping of magnetic particles are achieved.

1. Introduction

The possibilities of manipulating magnetization without any applied magnetic field have attracted the growing attention of researchers during the last fifteen years. The emerging Big Data era demanding the ever increasing speed and capacity to store and process information makes magnetization switching on ultra-short time scales a fundamentally challenging topic with implications for magnetic data storage [1]. Gerrits et al. [2] demonstrate that circularly polarized femtosecond laser pulses can be used to non-thermally excite and coherently control the spin dynamics in magnets by way of the IFE. Stanciu et al. [3] first demonstrated the all-optical magnetic recording (AOMR) by a single 40 fs circularly polarized laser pulse by the IFE. Since then all optical magnetic recording become a topic of much research interest and number of experimental works on improvement in ultrafast magnetization reversal of optic-magneto materials induced by the IFE was demonstrated [4–10]. Recently, Berritta et al. [11] introduced the first materials specific ab initio theory of the magnetization induced by circularly polarized laser light in metals and compute the effective optomagnetic fields that corresponds to the induced magnetizations. They showed that the IFE is strongly materials and frequency dependent and demonstrated the existence of both spin and orbital induced magnetizations. Freimuth et al. [12] suggested that the ultrafast demagnetization in 3d transition metal ferromagnets is dominated by transverse spin fluctuations rather than by a reduction of the exchange splitting. In All optical Magnetic Recording (AOMR), the magnetization reversal induced by focusing a circularly polarized beam with an objective has been demonstrated to be an essential method for the longitudinal magnetization recording. Since ultra fast high density data storage demands a highly confined pure longitudinal magnetic probe of sub-wavelength scale, several methods utilizing amplitude and phase modulation to the input circularly polarized beam has been suggested for reduction of magnetization spot size and to improve the probe depth [13–16]. However generating pure longitudinal magnetization of ultra-long focal depth within a sub-diffraction limited region by the IFE has remained a challenge toward sub-wavelength AOMR. Recently, Jiang et al. [17] showed that the interaction between the polarization singularity of an azimuthally polarized beam and optical vortices in the tight focus cannot generate longitudinal electric components, which results in the generation of pure longitudinal magnetization. They

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demonstrated that sub-wavelength (0.508λ) pure longitudinal magnetization throughout the entire focal plane of a high NA objective is possible when an azimuthally polarized beam is superposed with an optical vortex. However, the aspect ratio of the focal voxel is restricted to approximately 3 due to the lack of the capability to extend the constructive interference beyond 1.29λ. In order to overcome this problem Wang et al. [18] suggested an annular vortex binary filter to modulate the incident azimuthally polarized beam and numerically demonstrated ultra-long (7.8λ) needle-like beam with pure longitudinal magnetization and much sharpen transverse dimension of 0.38λ. They observed that the corresponding needle aspect ratio of 20 which is twice as large as the longitudinal magnetization needle generated by electron beam lithography. Followed by this, Ma et al. [19] numerically demonstrated that by applying both azimuthally and radially modulated annular phase filters an ultra-long longitudinal magnetization needle (28λ) with a narrower lateral size (0.27λ) having aspect ratio about 103 can be generated Nie et al. [20–21] theoretically proposed a novel method to yield sub-wavelength pure longitudinal magnetization chain in the focal region through tightly focusing an azimuthally polarized Bessel-Bessel Gaussian (BG) beam phase modulated by specially designed vortex binary filters and by using radially polarized vortex beam under 4π focusing. Later Gong et al. [22] theoretically demonstrated that by changing the phase difference between the two counter propagating azimuthally vortex beams in the 4π system, one could flexibly control the movement of the magnetization filed along the optical axis. They numerically proved the possibility of generating a super long (16λ) magnetization chain composed of 19 sub-wavelength (0.44) with longitudinal magnetization filed in the focal volume. Recently, Yan et al. [23] demonstrated that by selecting optimized parameters of a multi-Gaussian beam and topological charge of a Spiral Phase Plate (SPP), not only a super-long and sub-wavelength longitudinal magnetization needle with single/dual channels for a single-lens high numerical aperture focusing system, but also an extra-long and three-dimensional super-resolution longitudinal magnetization chain with single/dual channels for a 4π high numerical aperture focusing system can also be achieved in the focal region. Recently, a new kind of beam called doughnut Gaussian (DG) beam is introduced in a high NA focusing system. The DG beam is similar to a hollow Gaussian beam and it was reported that the radially polarized DG beam can be used to generate sub-wavelength focal structure of longitudinal polarization [24–26]. Recently, Sundaram et al. [27] showed that an azimuthally polarized DG beam can generate transversely polarized optical needle with highly confined lateral spot size of 0.48λ and extremely large focal depth around 49λ under high NA focusing and with a dedicated vortex filter. In the present work, we theoretically proposed novel method to generate sub-wavelength pure longitudinal magnetic probe of ultra-long focal depth and a method to achieve multiple magnetic spots using azimuthally polarized doughnut Gaussian vortex beam modulated by specially designed complex phase filters.

2. Theory

The schematic diagram is shown in Fig. 1(a). An incident azimuthally polarized doughnut Gaussian beam travel through the SPP and becomes an azimuthally polarized doughnut Gaussian vortex (APDGV) beam. The SPP is a kind of phase encoding element that delays the phase of the incident beam from 0 to 2π along the angular direction at the cross section of the beam. Mathematically, the phase transmittance of the SPP with topological charge m is expressed as $T(\varphi) = \exp(im\varphi)$. The APDGV beam is then modulated with complex phase DOE with N concentric belts. The modulated APDGV beam is then focused with high NA lens. The electric field of the DG beam at the output pupil is defined as follows [27]

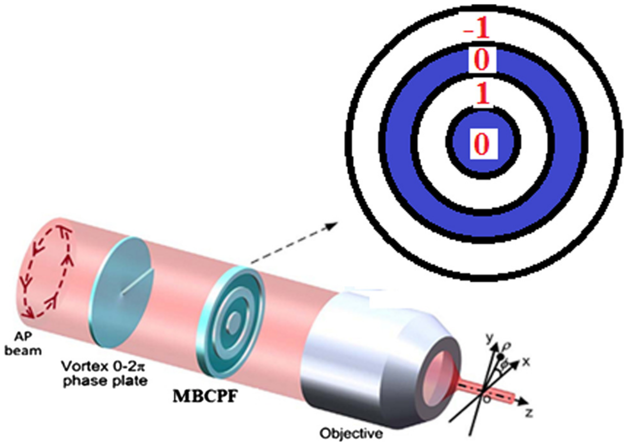

Fig. 1. Schematic diagram of the proposed system azimuthally polarized Doughnut Gaussian beam passes through a MBCPF and is subsequently focused by a high NA lens.

$$A(\theta) = \exp\left[-\left(\frac{\sin(\theta) - \theta_0}{w}\right)^2\right], \tag{1}$$

where w_0 reflects the beam size at the beam waist of the Gaussian beam. θ_0 relates with the radius of the DG beam. θ is the variable of the function. Obviously, the shape of the defined doughnut Gaussian beam is determined by θ_0 and w_0. To be more specific, the position of the maximum field intensity depends on θ_0 and the width of the DG beam is determined by w_0. Based on Richards–Wolf vector diffraction theory [28], in the cylindrical coordinate system (r, φ, z), the electric field distribution of the phase modulated azimuthally polarized vortex beam in the focal region can be described as [18]

$$E(r,\varphi,z) = \begin{bmatrix} E_r \\ E_\varphi \\ E_z \end{bmatrix} = A_0 i^m \int_0^\alpha T(\varphi) \begin{bmatrix} V_1 \\ iV_2 \\ 0 \end{bmatrix} A(\theta) e^{ikz\cos\theta} \sqrt{\cos\theta}\sin\theta d\theta, \tag{2}$$

where

$$V_1 = J_{m-1}(kr\sin\theta) + J_{m+1}(kr\sin\theta), \tag{3}$$

and

$$V_2 = J_{m-1}(kr\sin\theta) - J_{m+1}(kr\sin\theta). \tag{4}$$

Here, r, φ, and z are the cylindrical coordinates in the focal space and A_0 is the relative amplitude. J_{m-1} and J_{m+1} denotes Bessel functions of the first kind. Eq. (2) is represented in cylindrical vector components and it indicates that the filter transforms a beam with pure azimuthal polarization into a beam with radial and azimuthal polarization components that are essential to obtaining longitudinal magnetization at the focus. Based on the IFE, the magnetization field induced by tightly focusing azimuthally polarized beams with helical phase near the focal point is defined as [18]

$$\vec{M} = i\gamma \vec{E} \times \vec{E}^*, \tag{5}$$

where γ is a real constant proportional to the susceptibility of the material [29–31], $\vec{E}$ is the electric field and $\vec{E}^*$ is its conjugate. By substituting Eqs. (2)–(4) into Eq. (5), the magnetization field can be given by

$$M_z = 2\gamma |A_0|^2 \mathrm{Re}(I_1 * I_2), \tag{6}$$

with