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Generating sub wavelength pure longitudinal magnetization probe and chain using complex phase plate

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A R T I C L E I N F O

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A B S T R A C T

Based on inverse Faraday Effect, the three dimensional magnetization field distribution induced by the azimuthally polarized annular multi Gaussian transmitted through a multi belt complex phase filter (MBCPF) is investigated numerically using vector diffraction theory. Numerical results shows that by properly adjusting the radii of different rings of MBCPF, one can achieve sub wavelength (0.286λ) pure longitudinal magnetic probe with ultra-long focal depth of (35λ). We also noticed that magnetization chain composed of eight, four and two magnetic spots of subwavelength scale is also achieved by properly modulating the radii of MBCPF. The authors expects such a pure ultra-long subwavelength magnetic probe and magnetic chain can be used to realize all optical magnetic recording (AOMR), multilayer magneto-optical data storage, ultra-compact optomagnetic devices, magnetic particle trapping and transportation, fabricating magnetic lattices for spin wave operation, as well as confocal and magnetic resonance microscopy.

1. Introduction

The increasing interest in developing ultra-compact optomagnetic devices has recently invoked intensive research attention on light-induced schemes, which are capable of steering longitudinal magnetization at the sub-wavelength scale in the magnetic materials. Magneto-optical material has attracted intensive research interest due to its potential and appealing applications in all optical magnetic recording (AOMR) [1–7]. Stanciu et al. first demonstrated the all-optical magnetic recording (AOMR) by a single 40 fs circularly polarized laser pulse by the inverse Faraday Effect (IFE) [8]. To further facilitate those fascinating and practical applications, it is highly desirable to obtain a super-long and sub-wavelength longitudinal magnetization needle, as well as an extra-long and sub-wavelength longitudinal magnetization chain. Based on the vector diffraction theory and the inverse Faraday Effect (IFE) in magneto-optic (MO) film, the circularly polarized beam allows a sub-wavelength magnetic confinement in the tight focusing condition [9–13]. Since then all optical magnetic recording become a topic of much research interest and number of experimental work on improvement in ultrafast magnetization reversal of optic-magneto materials induced by the inverse Faraday Effect was demonstrated [14–17]. Recently, it has been reported that this doughnut spot produced be the tightly focused azimuthally polarized beam can be changed into a significantly sharper focal spot when a vortical phase encoded on the azimuthally polarized beam [18,19], which shows the intriguing prospect in practical applications due to its sub-wavelength lateral spot size and purely transverse electric field [20–22]. Recently many novel methods such as using hybridly polarized beam and multi belt spiral phase plates are suggested to suppress the side lobe and to improve the focal depth of the transversely polarized focal field [23–27]. Jiang et al., calculated the light-induced magnetization of an azimuthally polarized vortex beam in a high numerical aperture (NA) objective lens [28]. They found that a sub-wavelength (0.508λ) and pure longitudinal magnetization spot is generated in the focal region. Since then generating a pure magnetization focal field using the azimuthally polarized vortex beam instead of the circularly polarized beam become a topic of great interest. The light-induced magnetization produced by tight focusing of azimuthally polarized beams with helical phase has

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received considerable attention and a lot of research groups participated in studying the magnetization generated by the interaction between phase singularity and polarization singularity under the tight focusing condition [29,30]. Afterwards, further melioration was reported to prolong the longitudinal magnetization extension (7.48λ) along the optical axis and simultaneously sharpen the transverse dimension (0.38λ) by means of an annular vortex binary filter, which corresponds to an aspect ratio of 20 [20]. Recently, Ma et al., demonstrated that with an azimuthally and radially modulated annular phase filter an extra-long longitudinal magnetization needle (28λ) with sub-wavelength (0.27λ) scale resolution can be achieved with relevant aspect ratio improved up to 103 [31]. The pure longitudinal magnetization needle with high aspect ratio above can be used to trap magnetic particles and realize high-density AOMR [32,33]. However they might be less useful for a desired number of atoms trapping and transport, as well as multilayer magnetic-optical recoding and storage. Recently Nie et al., proposed the possibility of obtaining a super-long (12λ) and sub-wavelength (0.416λ) longitudinal magnetization chain with single/dual channels in the focal region using 4Pi microscopy [34]. Later, using an azimuthally polarized vortex beam with proper amplitude modulation, Gong et al., found that a super-long (16λ) magnetization chain, composed of 19 sub-wavelength (0.44λ) spherical spots of longitudinal magnetization field, can be achieved in the focal volume of the objective lenses for a 4π tight focusing configuration [35]. However it is reported that the performance of 4Pi microscopy is significantly affected by aberration [36,37]. Since the 4Pi microscopy can naively be considered as two separate microscopes configuration to operate in conjunction with each other, different combination are associated with phase shift of the interfering counter propagating waves and leads to significant different focal intensities. It is also noted that parameter including polarization, chromatic aberrations, balance of intensities in the two arms and coherence of light have additional influence and need to be carefully considered in 4Pi configuration. Recently, radially polarized and amplitude-modulated annular multi-Gaussian beam mode is proposed for illuminating the pupil plane of the objective to achieve sub wavelength longitudinal beam with long focal depth [38]. Followed by this several work on tightly focused annular multigaussian beam to generated super long dark channel, transversely polarized focal segment and multiple focal spot structure are reported [39–42]. Recently Weichao Yan et al. proposed that by selecting optimized parameters of a multi-Gaussian beam and topological charge of a spiral phase plate, 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 [43]. In this paper, we proposed a new method to generate a highly confined longitudinal magnetic probe and magnetization chain of subwavelength scale using azimuthally polarized multi Gaussian vortex beam phase modulated by specially designed complex phase filter and focused with high NA objective.

2. Theory

The schematic diagram of the proposed system is shown in Fig. 1. An incident azimuthally polarized annular multi Gaussian beam (APMGB) travel through the vortex 0–2π phase spiral phase plate (SPP) and become an polarized annular multi Gaussian vortex beam (APMGVB). The APMGVB beam is then modulated with a multi belt complex phase filter (MBCPF) with 4 concentric belts and then subsequently focused with a high NA lens. In a tight focusing system, incident light in the entrance plane is an azimuthally polarized vortex multi-Gaussian beam. In the cylindrical coordinate system (ρ, φ, z_0), amplitude of the multi-Gaussian beam at the entrance plane ($z_0 = 0$) can be written as [38]

$$P(\theta) = \left(\frac{\theta}{\theta_0}\right)^m \sum_{n=-N}^{N} \exp\left[-\left(\frac{\theta - \theta_c - n\omega_0}{\omega_0}\right)^2\right] \quad (1)$$

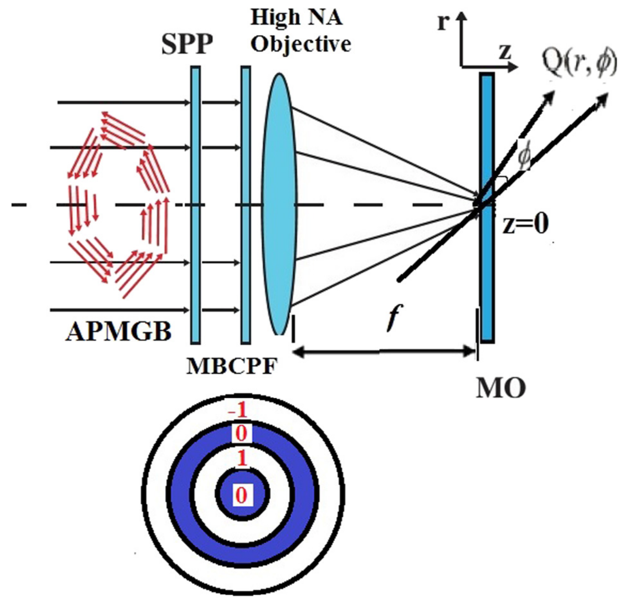

Fig. 1. Schematic diagram of a tight focusing system is illustrated. A MO film is placed at the confocal plane of the configuration and azimuthally polarized annular multi-Gaussian vortex beams focused by high NA objective lenses, MO denotes a magneto-optic film and MBCPF is Multi Belt Complex Phase Filter.

Here, θ is the converging semi-angle. We denote the maximum converging semi-angle as $\theta_{\max}$ which is related to objective numerical aperture by $\theta_{max} = arcsin(NA)$. θ_0 is an angle which, along with integer *m*, determines the shape of the modulation function.θ_0 is usually chosen to be slightly smaller than θ_{max}. θ_c determines the radial position translation of $P(\theta)$. Here we take $\theta_c = \theta_{max}/2$. w_0 is the waist width of single Gaussian beam which is calculated by the following formula

$$w_0 = 1/2 \times \frac{\theta \max}{N + \left\{1 - \ln\left[\sum_{n=-N}^{N} \exp\left(-n^2\right)\right]\right\}^{1/2}} \quad (2)$$

Eq. (1) describes an object beam. It is suitable to convert Eq. (1) from a function of angle into a function of radial polar coordinate. One may substitute θ with arcsin *(r/f),* where *f* is the focal distance of the objective. In Eq. (1), the factor (θ/θ_0) measures that the most of light energy is located on the annular edge of the pupil. Increasing the integer *m* concentrates more energy into the annular edge area in which the converging semi-angle is more than θ_0. The sum of $(2N + 1)$ spatially equally spaced Gaussian beams ensures that amplitude of the constructed annular multi-Gaussian beam decreases suddenly, when reaching the outer edge of the pupil. Such an amplitude modulated beam can be realized by encoding suitable phase mask on spatial light modulator. Based on Richards and Wolf's vectorial diffraction method widely used for high NA focusing systems at arbitrary incident azimuthally polarization [44], adopting the cylindrical coordinates r, z, ϕ and the notations [45], the electric field $E(r,\phi, z)$ in the vicinity of the focal region of an incident azimuthally polarized vortex beam can be written as,

$$E(r,\varphi,z) = \begin{bmatrix} Er \\ E\varphi \\ Ez \end{bmatrix} = \begin{bmatrix} -Ae^{i\phi}\left(I_0 + I_2\right) \\ -Ae^{i\phi}\left(I_0 - I_2\right) \\ 0 \end{bmatrix} \quad (3)$$

Where

$$I_n = \int_0^{\theta_{\max}} \sqrt{\cos(\theta)} \cdot \sin(\theta)\, P(\theta)\, e^{ikz\cos\theta} J_n(kr\sin\theta)\, d\theta \quad (4)$$

where A is relative amplitude, $\theta_{max} = arcsin(NA/n)$ that is the maximum aperture angle with (NA/n) is the ratio of numerical aperture (NA) and *n* is the index of refraction between the lens and the sample. *k*