Optics Communications 407 (2018) 217–226

Contents lists available at ScienceDirect

Optics Communications

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

Efficient tight focusing of laser beams optimally matched to their thin-film linear-to-radial polarization conversion: Method, implementation, and field near focus

Andrey G. Sedukhin *, Alexander G. Poleshchuk

Institute of Automation and Electrometry, Russian Academy of Sciences, Prospekt Akademika Koptyuga 1, Novosibirsk 630090, Russia

ARTICLE INFO

Keywords:
Diffraction
Superresolution
Tight focusing
Thin-film polarization converters
Radial polarization
Free-form optics

ABSTRACT

A method is proposed for efficient, rotationally symmetric, tight mirror focusing of laser beams that is optimally matched to their thin-film linear-to-radial polarization conversion by a constant near-Brewster angle of incidence of the beams onto a polarizing element. Two optical systems and their modifications are considered that are based on this method and on the use of Toraldo filters. If focusing components of these systems operate in media with refractive indices equal to that of the focal region, they take the form of an axicon and an annular reflector generated by the revolution of an inclined parabola around the optical axis. Vectorial formulas for calculating the diffracted field near the focus of these systems are derived. Also presented are the results of designing a thin-film obliquely illuminated polarizer and a numerical simulation of deep UV laser beams generated by one of the systems and focused in an immersion liquid. The transverse and axial sizes of a needle longitudinally polarized field generated by the system with a simplest phase Toraldo filter were found to be 0.39 λ and 10.5 λ, with λ being the wavelength in the immersion liquid.

1. Introduction

According to a well-established method, getting ultimately small focused laser spots in the far field requires the execution of three main steps: (i) the generation of a radially polarized illuminating beam, (ii) the separation of a narrow annular or donut-like opening in the plane perpendicular to the optical axis, and (iii) the axially symmetric convergence of the annular-shaped radially polarized beam to a far-field focus at high angles to the optical axis [see, e.g., [1–6]]. The corresponding optical systems enable one to obtain in their output focal planes such point spread functions, of which a dominant component of the time-independent slowly varying electric vector varies approximately as the zero-order Bessel function of the first kind, $J_0\left(k_w \rho \mathrm{NA}\right)$, where $k_w = 2\pi/\lambda_w$, λ_w is the working wavelength in free space, ρ is the radial coordinate, and NA is the numerical aperture of a focusing optics. Equating the square of the Bessel function to a value of 0.5, one can evaluate the approximate vectorial diffraction limit for the full width at half maximum (FWHM) of the focused spot as $0.36\lambda_w/\mathrm{NA}$ that is 1.4 times smaller than the Abbe scalar diffraction limit of a standard non-annular system, $0.51\lambda_w/\mathrm{NA}$. A further decrease of the focal spot size can be achieved by using the Toraldo di Francia concept of superresolution [7], which in extended treatment can be understood as adding one supplementary anti-phase spatial-frequency component [8,9], several anti-phase and in-phase components [10], or even a continuous set of such components [11–13]. These procedures are implemented by special filters in the form of either optimized binary-phase and binary-amplitude diffractive optical elements (DOEs) or axicons coupled with lenses and capable of generating near-Bessel–Gauss beams [13]. An even more prominent effect of such superresolution approach is that it enables one to extend the focal depth and to reshape significantly the axial form of the beams.

However, most known high-numerical-aperture optical systems with the use of illuminating radially polarized and annular shaped beams are rather expensive, bulky, and contain multiple optical units, which are often considered independently of one another. In particular, this concerns polarization converters. The shape of the point spread functions of these systems is normally deteriorated on account of such factors as the inaccuracy of fabricating and aligning their optical components as well as the imperfection of the spectral and polarization purity of focused wave fields. Moreover, these systems have often a poor total throughput because of the multiple light transformations with losses of energy. For example, significant losses may occur when separating

---

* Corresponding author.
E-mail address: sedukhin@iae.nsk.su (A.G. Sedukhin).

http://dx.doi.org/10.1016/j.optcom.2017.09.042
Received 25 May 2017; Received in revised form 21 August 2017; Accepted 10 September 2017

a narrow annular opening by blocking the central part of the beam with a beam stop [2,5,6]. Another sort of losses may be caused by the redistribution of light energy in a standard aplanatic objective lens (satisfying the sine condition), since the amplitude transmittance of this lens (the pupil apodization function) is described as $\sqrt{\cos(\theta)}$ [14] and therefore it decays if one selects high spatial frequencies by means of, e.g., a narrow annular mask with an effective value of θ close to $\pi/2$, where θ denotes the polar angle of the rays converged in the meridional plane to a focal point. A sloping profile of an input Gaussian laser beam (whose marginal part serves as a useful narrow annular opening) will of course introduce extra losses. Additionally, the limited performance of many optical systems prevents their usage in a number of applications, e.g., in high power laser systems and in the UV spectral region.

In an attempt to overcome the mentioned drawbacks for systems with rotational symmetry, in the present paper we propose a simple and efficient method for a tight subwavelength focusing of laser beams optimally matched to their thin-film conversion from a linearly polarized state to a highly uniform quasi-radially polarized state. As an illustration, two optical systems for implementation of this method are considered. An exact vectorial calculus treatment and a numerical simulation for the field generated by these systems are also given. To the best of our knowledge, this approach is developed for the first time, accounting rigorously for both useful and parasitic polarization components of the focused field.

2. Focusing systems integrated with selectors of radial polarization

To generate something close to a perfect radially polarized mode, we modified the method that was pioneered in [15–17] and based on the conversion of a linearly polarized beam to a circularly polarized one, the compensation of a helical phase component and the selection of the radially polarized component. In the Cartesian system (x_i, y_i, z_i), with the z_i-axis being the optical axis, the possibility of such polarization conversion can be clarified in 3D matrix form by the following decomposition of the circularly polarized beams:

$$\hat{\mathbf{e}}_{\pm}^{(i)} = \left(1/\sqrt{2}\right)[1,\ \mp i,\ 0]^T = \left(1/\sqrt{2}\right) \times \left\{[\cos(\psi),\ \sin(\psi),\ 0]^T \mp i[-\sin(\psi),\ \cos(\psi),\ 0]^T\right\} \exp(\mp i\psi), \tag{1a}$$

$$\hat{\mathbf{h}}_{\pm}^{(i)} = \left(1/\sqrt{2}\right)[\pm i, 1,\ 0]^T = \left(1/\sqrt{2}\right) \times \left\{[-\sin(\psi),\ \cos(\psi),\ 0]^T \pm i[\cos(\psi), sin(\psi),\ 0]^T\right\} \exp(\mp i\psi). \tag{1b}$$

Here $\hat{\mathbf{e}}_{+}^{(i)}$, $\hat{\mathbf{h}}_{+}^{(i)}$ and $\hat{\mathbf{e}}_{-}^{(i)}$, $\hat{\mathbf{h}}_{-}^{(i)}$ denote, respectively, the time-independent unit electric and magnetic vectors of the right (+) and left (−) circularly polarized incident fields, the matrices in the middle columns describe the x_i-, y_i-, and z_i-components of the mentioned vectors as sums of two waves linearly polarized in x_i- and y_i-directions, while the first and second matrices in square brackets on the right side of Eqs. (1a) and (1b) are, respectively, the wave components of the unit electric and magnetic vectors with radial and azimuthal polarization. The argument $\psi = \arctan\left(y_i/x_i\right)$ denotes here both the angle of rotation of the *p*-polarized radial and *s*-polarized azimuthal components of the unit electric and magnetic vectors in the transverse plane on a circle of unit radius $\sqrt{x_i^2 + y_i^2} = 1$ and a common helical phase delay of the last vectors described by the exponential terms in Eqs. (1a) and (1b). The generation of a right or left circularly polarized beam is performed by the normal passing of a linearly polarized laser beam through a quarter-wave plate (QWP), the fast axis of which is coincided with the x_i-axis and is oriented at an angle of $\psi_0 = \mp 45°$ to the plane of polarization of the incoming beam.

As can be seen from Eqs. (1a) and (1b), the selection of a radially polarized mode from a circularly polarized mode involves the resources of a compensating spiral phase plate with the transmittance $\exp(\pm i\psi)$ and a radial-type analyzer blocking the azimuthal component of polarization and passing the radial component [15–17]. However, many well-known analyzers that are designed to operate in the paraxial region (with small angles of inclination of the incident and outgoing rays) have usually specific restrictions and a poor performance: in particular, a poor polarization purity of selected modes. This is the case, e.g., for analyzers in the form of discrete properly oriented sectors patterned from a sheet polarizer or from a plate of birefringent material [16–18]. It was shown [19], that the presence of an even small residual azimuthally polarized component will give rise to an appreciable increase of the transverse size of the focused beam. To improve the polarization purity in systems with the above analyzers, one has to apply spatial bandpass filters decreasing the total throughput. Beyond that point, we may conclude that if one adds an auxiliary axicon filter behind the QWP, then the passage of the circularly polarized beam through it will only give rise to an added conical deflection of rays at a constant angle α to the optical axis. This does not cause any intermodulation distortions between the radial and azimuthal components of the electric and magnetic vectors behind the axicon and enables one to perform a high-optical-quality thin-film polarization splitting of an incident light at angle α close to or greater than the Brewster angle. As applied to distinctly different systems, such splitting has been demonstrated earlier for plate [20] and conical [21] surfaces. Besides, to match a variable polar angle θ of the focused rays to a desired constant angle of incidence of the rays onto the polarizing element, α, one may employ a freeform optics, which is currently being used to an increasing extent [e.g., [22,23]].

The essence of the proposed method is as follows: First, a linearly polarized laser beam is converted to a right (left) circularly polarized beam, e.g., with a QWP. Then the light is transmitted through beam-transforming optical elements (refractive or diffractive, one or several) which are used (i) to introduce the required vortex phase retardation for selecting pure radially and azimuthally polarized modes, (ii) to deflect the rays symmetrically out of the optical axis, preferably, at the Brewster or higher constant angle in order to make the optimum oblique illumination of a subsequent multilayer thin-film polarizer (TFP) and to provide an annular illumination in the far intermediate transverse plane, and (iii, optionally) to make the spatial frequency filtration and axial beam shaping in the focal volume. Having passed the beam through the TFP in the next stage, one isolates the necessary transmitted radially polarized mode (by filtering out the reflected azimuthally polarized mode) and, finally, using a proper annular reflector (AR), deflects the rays backward to the optical axis, converging them to a common focus F at high polar angles. This is performed in a ‘forward-reflecting’ regime, when the longitudinal component of the output wave propagation vector (behind AR) has the same sign as that of the input wave propagation vector (before AR) and one can provide both a high numerical aperture and a large working distance of the focusing system. The transmittance of the TFP is designed in such a way as to provide a desired extinction ratio between the suppressed reflected *s*-polarized components and the useful transmitted *p*-polarized components of the electric vector at a working angle of incidence of light onto the surface of the TFP. A large value and persistence of the working angle just mentioned, close to or greater than the Brewster angle, are known to be the necessary conditions for getting a high light efficiency, a high extinction ratio, and a not-to-small wavelength range of obliquely illuminated TFPs [24]. To satisfy these conditions, the working surface of the AR is distorted properly and becomes optimally matched to the TFP’s surface, with beam-transforming optical elements performing the function of the oblique illumination of the TFP under the required working angle.

Depending on the forms of optical components and other design factors, one can consider a multitude of similar optical configurations suitable for implementation of the proposed method. For performing two above-mentioned deflections of light rays in the meridional plane, with generation of an intermediate annular illuminated region, it will suffice to modify slightly, an already known two-component