Modulation for focusing properties of vector beams in imaging systems

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Abstract

Vectorial properties of light have significant effects on the focusing properties, especially for the case of tightly focusing, where the requirements on the ratio of the longitudinal field to the traverse fields (RLT) are different for various applications, such as particle acceleration, micronano-fabrication, fluorescent imaging, determination of three dimensional orientation of individual molecules and so on. Here, utilizing inhomogeneous polarization modulation (IPM) method, we demonstrate how to adjust the numbers of focal spots, the RLT, and the depth of focus (DOF) in terms of requirements and create successfully single or multiple focal spots with dominant transverse or longitudinal fields and small size. In terms of this method, not only the asymmetry of the focal spot for linearly polarized illumination with IPM can be obviously decreased, but also its size is the same as that of the short axis of the elliptical focusing spot for the case without IPM. Moreover, it can not only produce the focal spot with dominant transverse field, low sidelobe, and size slightly smaller than that of the radial polarization, but also can realize the identical resolutions in the transverse direction. In addition, for a focal spot with dominant transverse or longitudinal field, both the subdiffraction sizes (0.4λ or 0.5λ) and the DOF of 6.92λ are also achieved.

1. Introduction

In the last few years, the utilizations of vectorial properties of light in order to achieve excellent performances in various applications have received considerable attentions [1–10]. Moreover, the focusing properties determined by the vectorial properties of light play a key role in further improving performances of optical systems. For example, strongly localized electromagnetic waves govern behaviours of nanoscale optical devices [3–5]. The focusing of radially polarized light is used for particle acceleration, microscopy, and second-harmonic generation owing to the unique focusing properties with both a longitudinal field larger and a resolution higher than those for a linearly polarized illumination [8–10]. In 2009, Sheppard et al. present a Bessel beam with special polarization that can create a central lobe width 9% narrower than that for radially polarized illumination [11]. The polarization-sensitive imaging is used to realize sub-100 nm resolution for the illumination light with the wavelength of 1530 nm [6,7], which is based on the intensity along the short axis of the asymmetric focal spot caused by a linearly polarized illumination [12,13].

In the focusing fields, the numbers of focal spots, the ratio of the longitudinal field to the traverse fields (RLT), and the depth of focus (DOF) are three primary factors that are specifically required by various applications. For example, the RLT will determine the local polarization of tightly focused light, where the larger longitudinal field, the better in application of the particle manipulation. If we can adjust those three factors in terms of requirements and understand the corresponding regulars, some special aims and applications will be more easily achieved. Here we report a modulation method for focusing properties with inhomogeneous polarization modulation (IPM) and find the regulars to adjust those elements. We successfully create single or multiple focal spots with both dominant transverse or longitudinal fields and small size. Here the focal spot with dominant transverse field denotes its size (i.e., the size of the bright spot) is majorly determined by the transverse field, namely, the bigger the transverse field, the smaller the size of the focal spot, whereas the focal spot with dominant longitudinal field is just opposite to the dominant transverse focal spot. A case in point of the former is the focusing spot of the optical system illuminated by the linearly or circularly polarized light, whereas that of the latter is the radially polarized light. In terms of this method, the asymmetry of the focal spot for the linearly polarized illumination can be obviously decreased. Here, the asymmetry of the focal spot decreases 17% and its size is the same as that of the short axis of the elliptical focusing spot for the linearly polarized illumination without IPM. Moreover, it can not only produce the focal spot with dominant transverse field, low sidelobe, and size slightly smaller than that of the radial polarization, but also can realize the identical...
2. Focusing of light with inhomogeneous polarization modulation

As we know, in theory, arbitrary polarized beams may be considered as the coherent superposition of two orthogonally polarized beams, which is called the IPM, such as cylindrical vector beams [15] and vector–vortex beams [16,17]. For the cylindrical vector beams [15], they are inhomogeneous polarized and equivalent to the coherent superposition of two linearly polarized beams with sine and cosine amplitude modulations of one-order. It is expected that if the sine and cosine amplitude modulations are higher order or the azimuth modulation (the definition is given later) is not one-order as used in the cylindrical vector beams [15], more complicated inhomogeneous polarization will be created. At this time, some interesting focusing properties might exist. Similarly, if two orthogonally circularly polarized beams (i.e., right- and left-hand circular polarizations) or other orthogonally polarized beams are used to compose a vector beam, some unexpected phenomena might happen. Therefore, it will open a new way to study vectorial properties of light by utilizing IPM instead of pupil filters [8,19,20] or some specifically polarized light [9,10,16,18].

Here we will focus on the vector beam with IPM formed by the coherent superposition of two linearly polarized beams, whose electric field at the incident pupil (see Fig. 1) is \( E_0 = P \rho(h) A_0(h) \) with polarization \( P = x e_x \cos \phi + y e_y \sin \phi \), \( e_x = \pm 1, \pm j \), and a constant phase \( \phi_0 \). \( A_0(h) = \exp(-h^2/\omega^2) \) denotes a Gaussian field with waist radius \( \omega \) in a cylindrical coordinate system \((h, \phi)\). The non-negative integer \( n \) is called the amplitude modulation factor that determines the power of the sine and cosine amplitude modulation. The integer \( m \) is azimuth modulation factor that can cause the vortex polarization of the incident beam [16]. The modulation term \( B(h) \) denotes a pupil filter with cylindrical symmetry. If \( B(h) \) is a real, pure imaginary, or complex number, it represents an additional amplitude, phase, or complex pupil filter, respectively. For various parameters \( m, n, e_x, e_y \) and \( \phi_0 \), the vector \( P \) is inhomogeneous polarization.

In terms of the series expansions of cosine functions with \( n \) order, when \( n = 2n + 1 \) is odd, there are

\[
\cos^n(m \phi + \phi_0) = \frac{1}{2^n} \sum_{k=0}^{n} \binom{n}{k} C_k \cos ((2n-2k+1)(m \phi + \phi_0)).
\]

With a combination function \( C_k = \frac{m!}{k!(n-k)!} \). When \( n = 2n \) is even, the similar series expansions exit, namely

\[
\sin^n(m \phi + \phi_0) = \frac{1}{2^n} \sum_{k=0}^{n} \binom{n}{k} C_k \cos ((2n-2k)(m \phi + \phi_0)) + \frac{1}{2^{n^2}} C_0.
\]

When the vectorial beam \( E_0 \) is focused by the imaging system shown in Fig. 1, and both the time dependence \( \exp(i\omega t) \) and Eqs. (1a, 1b) and (2a, 2b) are used, by a well-known procedure described in prior publications [12,13,21], the focusing electric fields of an arbitrary point \((\rho, \phi, z)\) in the image space are expressed as

\[
E_\rho(s_h) = -j A \sum_{k=0}^{n} \binom{n}{k} C_k e_{x} (D_{+}\cos \phi - D_{-}\cos \phi) + D_{+}\cos \phi - D_{-}\cos \phi, (3a)
\]

\[
E_\phi(s_h) = -j A \sum_{k=0}^{n} \binom{n}{k} C_k e_{y} (D_{+}\sin \phi - D_{-}\sin \phi) + D_{+}\sin \phi - D_{-}\sin \phi, (3b)
\]

with both \( \phi = \pm (n-2k)(m \phi + \phi_0) \pm b \phi, l = 0, 1, 2 \) and

\[
A_{c} = \frac{\int_{0}^{\pi} \cos^{1/2} \theta_1 \sin \theta_1(T^* + T) \cos \theta_1 \theta \rho \theta_1 d \theta_1}{\sin \theta_1}, (4a)
\]

\[
B_{c} = \frac{\int_{0}^{\pi} \cos^{1/2} \theta_1 \sin \theta_1 \cos \theta_1 \theta_1 \rho \theta_1 d \theta_1}{\sin \theta_1}, (4b)
\]

\[
D_{c} = \frac{\int_{0}^{\pi} \cos^{1/2} \theta_1 \sin \theta_1 (T^* - T) \cos \theta_1 \theta \rho \theta_1 d \theta_1}{\sin \theta_1}, (4c)
\]

with \( \rho = J_f(\alpha \rho) I_f \sin \rho k_0 a \rho \exp(i \psi) \), \( \psi = (n-2k)m \phi + \phi_0 \), \( \alpha = k_1 \cos \theta_1 \cos \theta_1 \cos \theta_2 \cos \theta_2, (2b) \), \( T^* = 2n \phi \cos \theta_1 \cos \theta_1 \cos \theta_2 \cos \theta_2, (1) \), \( T = 2n \phi \cos \theta_1 \cos \theta_1 \cos \theta_2 \cos \theta_2, (1) \), and \( A = \pi f \alpha \lambda_1^2 \frac{2^{2n+1}}{2^{(2n+1)}}, (1) \). For the case of the odd number \( n = 2n + 1 \), \( \sin \theta_1 = \cos \phi \) and \( \sin \theta_1 = \tan \phi \), whereas for the case of the even number \( 2n \), \( \sin \theta_1 = -\sin \phi \) and \( \sin \theta_1 = \cos \phi \). \( J_0 \) is the Bessel function of the first kind and order \( \ell \). \( \phi \) is the maximum aperture angle. \( \lambda_1 \) and \( k_1 \) separately denote the wavelength and wave number in image space, whereas \( k_0 \) is the wave number in sample.

When \( n = 0 \) and the combination function \( C_0 = 1 \), the focusing fields described by formulas (3) are identical to formulas (27) of image fields in Ref. [13]. For the inhomogeneous polarization \( P, n = 0 \) means that there are not polarization modulations. Meanwhile, \( P \) is linearly polarized for \( e_x/e_y \) or \( e_x/e_y = \pm 1 \) and circularly polarized for \( e_x/e_y = \pm j \). When \( n = 1 \) and \( e_x = e_y = 1, P \) is radially polarized for \( \phi_0 = 0, \pi \) and azimuthally polarized for \( \phi_0 = 0.5 \pi, 1.5 \pi \) under the case of \( m = 1 \), respectively. For \( m \neq 1, P \) is vortex polarized [16]. Therefore, formulas (3a–3c) and (4a–4c) describe a universal imaging model of aplanatic systems for various polarized beams. Moreover, the sine and cosine amplitude modulation with any order and the pupil filters with cylindrical symmetry described by the additional modulation term \( B(h) \) are also involved.
3. Results and discussions

3.1. Numbers of focal spots

Compared with the extensive use of polarization [6–10,14–17], the inhomogeneous polarization $\mathbf{P}$ has more parameters ($n$, $m$, $e_x$, $e_y$, and $\varphi_0$) optimized for specific purposes. In terms of the simulation calculations, we find that the realization of multifocus is majorly determined by the parameters $n$ and $m$. The parameters $e_x$ and $e_y$ only determine whether the longitudinal field or the transverse fields plays dominant role in the focusing fields. The phase $\varphi_0$ only has minor effect on the realization of multifocus.

In simulation calculations, the Gaussian field $A_0(h) = \exp\left[-(\beta \sin \theta_1/\sin \Phi)^2\right]$ and the pupil filter $B(h) = (\sin \theta_1/\sin \Phi)^n$ are used, where $\beta$ is the ratio of the radius of the incident pupil to the waist radius. Although $\sin \Phi = 0.95$ and $\beta = 0.2$ are used in this paper, the following conclusions are regardless of those two parameters.

Simulation calculations show that the numbers of focal spots are separately $2(m - 1)$ for $m > 1$ and $2(m|n| + 1)$ for $m < 0$ when $n$ is odd and $e_x = e_y = 1$. However, for all the cases of $m > 1$, such as $m = 3$, the contrast between the light intensity of the main bright spots and that of the annular background spot is very low [see Fig. 2(a)]. In order to obtain multifocus with high contrast, $m < 0$ with $\varphi_0 = 0$, $\varphi_0 = n$ are used [see Fig. 2(b)]. Moreover, in the case of $e_x = e_y = 1$ and $\varphi_0 = 0$, the multifocus is majorly determined by the longitudinal field (see Fig. 2). In addition, in order to create multifocus with high contrast, the RLT can be adjusted by the amplitude modulation factor $n$. In Fig. 2, the RLTs are 1.23, 2.62 and 0.5 for Fig. 2(a)–(c), respectively. Obviously, the contrast in Fig. 2(c) is lower than that in Fig. 2(b), whose reason is RLT in Fig. 2(c) is too low. This shortcoming can be improved to a certain extent by increasing the amplitude modulation factor $n$, which is because that bigger $n$ means higher pass filter realized by the pupil filter $B(h)$ [22]. Therefore, similar to the focusing properties of a radially polarized light [18], the multifocus with dominant longitudinal field can be obtained by the IPM, which will be helpful for micronano-fabrication with multifocus parallel processing [23,24].

When $n$ is even and $e_x = e_y = 1$, the focusing properties are unfavorable for multifocus except for the case of $m = 1$. We find that, for an arbitrarily even number $n$, the double focuses with high contrast can be created as long as $m = 1$ (see Fig. 3). The double focuses are arranged along the 45° direction with respect to the x axis and the longitudinal field plays dominant role in the focusing fields. As the numbers of focal spots are $2(m - 1)$ for $m > 1$ and $2(m|n| + 1)$ for $m < 0$ when $n$ is odd and $e_x = e_y = 1$, the double focuses with high contrast cannot be obtained for the case of odd number $n$ and the vector–vortex Bessel–Gauss beams given by Ref. 16.

When $e_x = 0$ and $e_y = 1$ or $e_x = 1$ and $e_y = 0$, the focusing fields are dominated by the transverse fields. Moreover, the numbers of focal spots are $2m|n|$ when $n \neq m \neq 0$ and $n$ is odd. For the even number $n$, the multifocus cannot be created. Shown in Fig. 4(a)–(c), the transverse fields play dominant role in the focusing fields. However, the multifocus cannot be completely separated [see Fig. 4(c)] because the longitudinal field in the focal spots is too big. Note, for the multifocus with dominant transverse field, the smaller the longitudinal field the better. In terms of simulation calculations, this phenomenon is also true for other various $m$. As the amplitude of the longitudinal electric field is reduced by the ratio of the dielectric constants of the two media and the transversal electric field is continuous through the interface [8], the multifocus can be separated when the focusing fields transmits through the low–high refractive index interface [see Fig. 4(d)]. For the multifocus with dominant transverse field, it is beneficial that the refractive index of the sample is slightly higher than that of the objective coupling medium. Therefore, the multifocus with dominant transverse field will be more suitable for imaging than the multifocus with dominant longitudinal field because of the refractive index mismatch between the objective coupling medium and the sample. For example, it may improve the imaging speed of STORM [25] with multifocus imaging.

![Fig. 2](image-url) Total focusing light intensity at the focal plane for the case of $\varphi_0 = 0$, $n_1 = n_2 = 1$, (a) $m = 3$, $n = 5$, (b) $m = -1$, $n = 5$, and (c) $m = -1$, $n = 1$.

![Fig. 3](image-url) Light intensities of the (a) transverse and (b) longitudinal fields and the total light intensity (c) at the focal plane for the case of $n = 6$, $m = 1$, $\varphi_0 = 0$, and $n_1 = n_2 = 1$. 
3.2. Improvement of the asymmetric focusing field

For the optical system with high numerical aperture (NA), the polarization of light has significant effects on the focusing properties. When a linearly polarized illumination is used, the distribution of the focusing fields at the focal plane is asymmetric and nearly elliptical [12,13]. Resolutions in the two transverse directions are different and the resolution of the imaging system is determined by the long axis of the elliptical focal spot. If a circularly polarized beam is used, the focal spot is circularly symmetric, but the resolution of the imaging system is lower than that for a linearly polarized illumination [13]. The focusing spot of a radially polarized beam has a resolution higher than that for a linearly polarized illumination [13]. The focusing spot is asymmetric, but the resolution of the imaging system is lower than that for a linearly polarized illumination [13]. The focusing spot of a radially polarized beam has a resolution lower than that for a linearly polarized illumination [13], but the focal spot is broadened by the presence of the low-high refractive index medium interface, getting larger as the difference of the refractive indices becomes larger [8], which limits the applications of a radially polarized beam in imaging. For this very reason, based on the intensity along the short axis of the asymmetric focal spot caused by a linearly polarized illumination, the polarization sensitive imaging is used to realize sub-100 nm resolution for the illumination light with the wavelength of 1530 nm [6,7]. However, the polarization sensitive imaging technology will make the imaging speed reduced in half. If the asymmetry of the focal spot under the case of the linearly polarized illumination can be obviously decreased and, simultaneously, its size is as small as possible, it will be interesting.

Shown in Fig. 5(a)(c), the asymmetric focal spot is majorly determined by the longitudinal fields. The reason that the light intensity of the transverse fields at the focal plane deviates slightly from the circular distribution [see Fig. 5(b)] is due to the asymmetric distribution of linear polarization at the pupil. For a linearly polarized illumination, as the longitudinal field is not small enough compared with the transverse fields, the double focuses formed by the longitudinal field further elongate the focal spot given by the total fields.

In this paper, we find that the single focal spot with dominant transverse field can be created by IPM, where the parameters \( n = 2, \ m = \pm 1, \ \epsilon_x = \epsilon_y = 1, \) and \( \varphi_0 = 0.5\pi, 1.5\pi \) [see Fig. 5(d)(f)]. Other parameters \( [A_0(h), B(h), \beta \text{ and } \sin \phi] \) used in Fig. 5 are the same as those used in Fig. 3. Meanwhile, the light intensity of the longitudinal field spreads to a large range at the focal plane and decreases obviously compared with that of the transverse fields. In Fig. 5(d)(f), the ratio of the transverse components to the longitudinal component is 16.2 in the focal plane, whereas it is only 5.4 for the linearly polarized light [see Fig. 5(a)(c)]. It is expected that the asymmetry of the focal spot caused by the longitudinal component will be negligible. The asymmetry of the focal spot is only derived from the asymmetric distribution of polarization at the pupil. Here, for the linearly polarized illumination [Fig. 5(c)], the full width at half maximum (FWHM) along \( x \) and \( y \) axes are 0.51\( \lambda \) and 0.74\( \lambda \), respectively. For the IPM [Fig. 5(f)], the FWHMs along the 45° and 135° directions with respect to the positive \( x \) axis are 0.43\( \lambda \) and 0.52\( \lambda \), respectively. The asymmetric degree defined as the ratio of the FWHM along the long axis to that along the short axis of the nearly elliptical focal spot is 1.45 for the linear polarization, whereas it is only 1.2 for the IPM. The asymmetry of the focal spot may decrease obviously (about 17%). Moreover, shown in Fig. 5(g), the FWHM along the long axis of focal spot for the IPM is almost equal to the FWHM along the short axis of focal spot for the linearly polarized illumination. Therefore, this IPM light has an advantage over the linearly polarized light and may substitute the polarization sensitive imaging [6].

Fig. 5(h) describes the distribution of the light intensities and polarizations of the used IPM at the entrance pupil. Its polarization is symmetric about the 45° direction with respect to the \( x \) axis. When \( n=1, \ m=1, \ \epsilon_x = \epsilon_y = 1, \) and \( \varphi_0 = 0.5\pi, 1.5\pi \), the IPM becomes azimuthally polarized [15]. Although the IPM used in Fig. 5(h) is a little like the azimuthally polarized light because of the production of the focal spot with dominant transverse field, its focusing spot is not a doughnut like of that of the azimuthally polarized light. The IPM with proper parameters is conducive to decrease the asymmetry of the focal spot for the linearly polarized illumination and construct a focal spot with both dominant transverse field and small size, which is very helpful to simultaneously achieve high resolution at the two transverse direction of the focal plane for imaging.

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**Fig. 4.** Light intensities of the (a) transverse and (b) longitudinal fields and the total light intensities [(c) and (d)] at the focal plane for the case of \( n = 1, m = 2, \varphi_0 = 0, \epsilon_x = 0, \epsilon_y = 1, n_1 = 1, (c) n_2 = 1, \) and (d) \( n_2 = 1.5 \).
Shown in Fig. 6, for the IPM with proper parameters that can improve the asymmetry of the focusing field for the linearly polarized illumination, the FWHM along x (red solid curve) is the same as that along y (green dotted curve) axes. Moreover, the resolutions along the x and y axes are identical and slightly smaller than those of the 45° (cerulean dash-dotted curve) direction with respect to the positive x axis and the radial polarization. In addition, although the IPM may be considered the composition of two orthogonally linearly polarized beams with amplitude modulations \(\sin^2(\phi + 0.5\pi)\) and \(\cos^2(\phi + 0.5\pi)\), the maximum intensity of the sidelobes of the IPM is only 31.7% and far smaller than that (51.7%) of the linear polarization with amplitude modulations \(\sin^2(\phi + 0.5\pi)\) [see the blue dashed curve in Fig. 6(a)]. Therefore, if the IPM is used for imaging, such as the confocal laser scan microscopy, it can not only produce the focal spot with dominant transverse field, low sidelobe, and size slightly smaller than that of the radial polarization, but it can also realize the identical resolutions in the transverse direction (XY plane).

3.3. Focus with both dominant longitudinal or transverse field and long depth of focus

As indicated before, we have introduced how to generate multifocus and control the RLT so as to obtain single focus or multifocus with dominant longitudinal or transverse field. In the applications of focusing fields, another important problem is the DOF in imaging systems with high NA, because the DOF decreases with increase of NA. As the focus with long DOF can be used as a non-diffracting beam, it may reduce the diffraction angle of the particles accelerated and make it more easily for focusing in second-harmonic generation polarization microscopy [14]. In order to create a focus with both dominant longitudinal field and long DOF, a complicated binary-phase optical element with five or more belts is designed [14], where they generate a focus with dominant longitudinal field, subdiffraction size (0.4\(\lambda\)), and long DOF (4\(\lambda\)).

Actually, for many of applications requiring long DOF, such as non-diffracting beam, particle acceleration, optical tweezers, and...
micronano-fabrication with laser direct writing, illuminating the mask like of optical projection lithography is not needed, therefore, an annular beam formed by negative cones [26] can be used to elongate the DOF. Moreover, the narrower the size of the annular belt, the longer the DOF. In Ref. [14] as the incident light is the Bessel–Gaussian beam, it can also be regarded as an annular beam.

Fig. 7 describes the DOF for various vectorial beams under the condition of the annular beam illumination. Simulations show that the size of the annular belt has same effect on the improvement of the DOF for various vectorial beams. Here the annular belt is determined by \( B(h) \) equivalent to 1 for \( \Omega < \sin \theta_1 < \sin \phi \) and 0 for others. When \( \Omega = 0.9 \), all DOFs are 6.92\( \lambda \) (see Fig. 6) and all transverse size of the focal spot are the same as that of Fig. 1(b), Fig. 2(c) and Fig. 5(f). When \( \Omega = 0.85 \), all DOFs are 4.12\( \lambda \), where the simulation figures are not given for the sake of simplicity. Therefore, the single focus or multifocus with both dominant longitudinal or transverse field and long DOF can be obtained by the annular beam. During the course of the optimization of the annular belt, the effects of improving DOF are same for different IPM. Moreover, for the binary-phase optical element [14], the conclusions still remain unchanged.

### 4. Discussions about the generation of IPM

Up to now, utilizing the IPM, we have researched theoretically how to adjust the numbers of focal spots, the RLT, and the DOF in terms of requirements and drawn corresponding regulars. The generation of IPM is a little difficult, but there is a basic method for

**Fig. 6.** The FWHMs along \( x \) (red solid curve), \( y \) (green dotted curve) axes, and the 45\( ^\circ \) (cerulean dash-dotted curve) and 135\( ^\circ \) (violet plus curve) directions with respect to the positive \( x \) axis for the IPM. (a) The FWHMs along \( x \) (blue dashed curve) and \( y \) (black star curve) axes for the linear polarization with amplitude modulation \( \sin^2(\phi + 0.5\pi) \). (b) The FWHM along \( x \) axis for the radial polarization (blue dashed curve). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

**Fig. 7.** Contour plots for the focal spots along \( xz \) plane [(a) and (b)] and \( rz \) plane [(c) and (d)] for the radially polarized light [(a): \( n = 1, e_x = e_y = 1, \phi_0 = 0, \phi \)] and the IPM light with parameters same as those of (b): Fig. 2(b) and (c); Fig. 3(c) and (d); Fig. 5(f) except for \( B(h) \) equivalent to 1 for \( \Omega < \sin \theta_1 < \sin \phi \) and 0 for others.
creating the IPM. As we know, the cylindrical vector beams are inhomogeneous polarized and equivalent to the coherent superposition of two linearly polarized beams with sine and cosine amplitude modulations of one-order (i.e., TEM\(_{01}\) and TEM\(_{10}\) laser modes) \([15,27]\). A very popular and simple method for generating the cylindrical vector beam is the combinations of the optical element creating the two orthogonally polarized beams and the interference technology. For example, firstly, the orthogonally polarized TEM\(_{01}\) and TEM\(_{10}\) laser modes are created by a binary diffractive optical element \([27]\), a thin wire across the center of the cavity \([28]\), or a spatial light modulation (SLM) \([29]\). Then the Mach–Zehnder interferometer \([27]\), the Sagnac interferometer \([28]\), or the so-called stabilized version of the interferometer \([29]\) combines the two modes and creates the cylindrical vector beams.

Similarly, as indicated in Section 2, the IPM can be considered as the coherent superposition of two orthogonally linearly polarized beams with sine and cosine amplitude modulations. Therefore, a basic method for generating IPM is also the combinations of the optical element creating the two orthogonally polarized beams and the interference technology. The sole difference between the IPM discussed in this paper and the cylindrical vector beams is that the sine and cosine amplitude modulations in the former might be higher order instead of the one order in the latter. However, on the basis of optimal parameters of IPM, these two orthogonally linearly polarized beams with sine and cosine amplitude can still be created by SLM \([29]\) or nanolithography technology \([30]\). Then utilizing the Mach–Zehnder interferometer or other interference configurations, the above two orthogonally linearly polarized beams can compose the designed IPM.

5. Conclusions

In conclusion, we have proposed a modulation method for focusing properties with IPM and successfully created single or multiple focal spots with both dominant longitudinal or transverse field and small size. In terms of this method, how to decrease the asymmetry of the focal spot for linearly polarized illumination is indicated. Moreover, compared with the linear and radial polarization, the IPM can not only produce the focal spot with dominant transverse field, low sidelobe, and size slightly smaller than that of the radial polarization, but also can achieve identical resolutions in the transverse direction (XY plane). In addition, for a focal spot with dominant transverse or longitudinal field, both the subdiffraction sizes (0.4\(\lambda\) or 0.5\(\lambda\)) and the DOF of 6.92\(\lambda\) are also achieved. On the basis of the comprehensions on the modulation regulars on the focusing fields, we will be able to make the optimal choice of vectorial properties of light.

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