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Influences of phase shift on superresolution performances of annular filters*

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This paper investigates the influences of phase shift on superresolution performances of annular filters. Firstly, it investigates the influence of phase shift on axial superresolution. It proves theoretically that axial superresolution can not be obtained by two-zone phase filter with phase shift π, and it gets the phase shift with which axial superresolution can be brought by two-zone phase filter. Secondly, it studies the influence of phase shift on transverse superresolution. It finds that the three-zone phase filter with arbitrary phase shift has an almost equal optimal transverse gain to that of commonly used three-zone phase filter, but can produce a much higher axial superresolution gain. Thirdly, it investigates the influence of phase shift on three-dimensional superresolution. Three-dimensional superresolution capability and design margin of three-zone complex filter with arbitrary phase shift are obtained, which presents the theoretical basis for three-dimensional superresolution design. Finally, it investigates the influence of phase shift on focal shift. To obtain desired focal shifts, it designs a series of three-zone phase filters with different phase shifts. A spatial light modulator (SLM) is used to implement the designed filters. By regulating the voltage imposed on the SLM, an accurate focal shift control is obtained.

Keywords: superresolution, filter design, focal shift, annular filters
PACC: 4230, 4225F, 4280B, 4283

1. Introduction

Airy spot is the diffraction-limited spot. Superresolution technique can make the diffraction spot smaller than Airy spot. Superresolution technique has been applied to many fields,[1−6] such as optical data storage, lithography, confocal microscopy etc. Since the first study of superresolution by Toraldo di Francia at 1952,[7] many kinds of superresolution filters have been proposed, and different superresolution performances have been investigated. Amplitude filters were firstly investigated for their simplicity.[8] Because phase-only filters yield better performance than amplitude filters, attention has been centred on pure-phase filters in recent years.[9−11] Complex filters have been investigated to achieve three-dimensional superresolution.[12] Recently, in order to gain a higher superresolution performance, continuous and discrete-continuous phase filters have been studied.[13,14]

Phase shift is an important parameter of pupil filters. If phase shift of a pupil filter changes, the filter's superresolution performances will change correspondingly. Annular filters are the most useful pupil filters for their simplicity and high superresolution performance.[1,2,5,6,9] Axial, transverse and three-dimensional superresolution performances of annular filters with phase shift π have been widely investigated.[10,12,15,16] But when phase shift of an annular filter is an arbitrary value in interval $[0, \pi]$, the superresolution performances are rarely studied. So it is meaningful to investigate influences of phase shift on superresolution performances of annular filters. We prove theoretically that axial superresolution can not be obtained by two-zone phase filter with phase shift π, and we get the phase shift with which axial superresolution can be brought by two-zone phase filter. We find that three-zone phase filter with arbitrary phase shift has an almost equal optimal transverse gain to that of commonly used three-zone phase filter, but it can produce a much higher axial superresolution

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gain. We get the three-dimensional superresolution capability and design margin of three-zone complex filter with arbitrary phase shift. At last, in order to obtain desired focal shifts, we design a series of three-zone phase filters with different phase shifts. By regulating the voltage imposed on a SLM which is used to implement the designed filters, an accurate focal shift control is obtained. We find that annular filters with arbitrary phase shift have higher superresolution capabilities, and our investigations present the theoretical basis for better superresolution performance control and superresolution filter design.

2. Theory for superresolution and filter design

According to scalar diffraction theory,[17] the normalized field distribution U in the focal region is written as

$$U(\nu,u)=2\int_0^1 P(\rho)J_0(\nu\rho)\exp\left(-\frac{\mathrm{i}u\rho^2}{2}\right)\rho\mathrm{d}\rho, \quad (1)$$

where $P(\rho)=T(\rho)\exp[\mathrm{i}\phi(\rho)]$ is the pupil function, $T(\rho)$ is the transmittance function, $\phi(\rho)$ is the phase function, ρ is the normalized radial coordinate. The variable $\nu=kr\sin\alpha$ is the transverse coordinate, $k=2\pi/\lambda$, r is the radial distance and $\sin\alpha$ is the numerical aperture of the optical system, The variable $u=4kz\sin^2(\alpha/2)$ is the axial coordinate, z is the axial distance. In the focal plane, the transverse field distribution can be written as

$$U(\nu,0)=2\int_0^1 P(\rho)J_0(\nu\rho)\rho\mathrm{d}\rho. \quad (2)$$

Along the axis, the axial field distribution can be expressed as

$$U(0,u)=2\int_0^1 P(\rho)\exp\left(-\frac{\mathrm{i}u\rho^2}{2}\right)\rho\mathrm{d}\rho. \quad (3)$$

For superresolution, there are four figures of merit: focal displacement U_F, which is the displacement of focus in axial direction; Strehl ratio S, which is defined as the ratio of the intensity at the focal point in superresolution pattern to that in Airy pattern; transverse gain G_T and axial gain G_A, which are defined as the ratio of the central spot radii in superresolution pattern to that in Airy pattern along transverse and axial directions respectively.

The nth moment of the pupil filter is defined as

$$I_n=\int_0^1 2P(\rho)\rho^{2n+1}\mathrm{d}\rho. \quad (4)$$

Within the second-order approximation, the figures of merit are written as[13]

$$U_\mathrm{F}=-2\frac{\mathrm{Im}(I_0^*I_1^)}{\mathrm{Re}(I_0I_2^*)-|I_1|^2}, \quad (5)$$

$$S=|I_0|^2-U_\mathrm{F}\mathrm{Im}(I_0^*I_1), \quad (6)$$

$$G_\mathrm{T}=2\frac{Re(I_0I_1^*)-U_\mathrm{F}\mathrm{Im}(I_0^*I_2)}{S}, \quad (7)$$

$$G_\mathrm{A}=12\frac{\mathrm{Re}(I_0I_2^*)-|I_1|^2}{S}, \quad (8)$$

where $*$ denotes the complex conjugate.

In this paper, annular filters are designed according to different superresolution performance requirement. We present a brief description to the filter design method using by us. As shown in Eqs.(4)–(8), figures of merit are functions of filter parameters. With these filter parameters, the concrete filter can be gained. According to the requirement for figures of merit, filter parameters can be obtained by an optimizing procedure. For instance, when transverse gain is required to be optimized and Strehl ratio is required to be a constant c, three-zone phase filter can be designed by the following optimizing procedure:

$$\max G_\mathrm{T}, S=c, \theta_1,\theta_2,\theta_3\in[0,\pi],$$

$$\rho_1<\rho_2\in[0,1], \quad (9)$$

where θ_1, θ_2, θ_3 and ρ_1, ρ_2 are phases and radius of the filter. The constrained nonlinear multivariable optimizing function named FMINCON is used in the paper for its flexibility and high efficiency.

3. Influence of phase shift on axial superresolution performance

Two-zone phase filter is the simplest phase filter. Phase shift of commonly used two-zone phase filter is π. According to Eqs.(4), (5), (6) and (8), axial gain G_A of the filter can be expressed as

$$G_\mathrm{A}=\frac{4(1-2\rho_1^6)(1-2\rho_1^2)-3(1-2\rho_1^4)^2}{(1-2\rho_1^2)^2}, \quad (10)$$

where ρ_1 is radii of the first zone. Let $a=4(1-2\rho_1^6)(1-2\rho_1^2)-3(1-2\rho_1^4)^2$ and $b=(1-2\rho_1^2)^2$ respectively, their difference $a-b$ can be simplified to

$$a-b=4\rho_1^2(\rho_1^2-1)(\rho_1^4-\rho_1^2+1). \quad (11)$$

Since $(\rho_1^2-1)<0$ and $\rho_1^4-\rho_1^2+1=(\rho_1^2-1)^2+\rho_1^2>0$, it can be verified that $G_{\rm A}=\dfrac{a}{b}<1$. From the above analysis, we can conclude that axial superresolution can not be obtained by two-zone phase filter with phase shift π.

Axial superresolution performance of two-zone phase filter with other phase shift has intrigued much interest. When phase shift of the filter is 0.6π, the axial superresolution performance has been investigated recently.[9] We investigate the axial superresolution performance of two-zone phase filter with arbitrary phase shift. Using ϕ to denote an arbitrary phase shift in interval $[0,\pi]$, we write the pupil function of the filter as

$$P(\rho)=\begin{cases}1, & 0<\rho<\rho_1\\ \exp(\mathrm{i}\phi), & \rho_1<\rho<1.\end{cases} \tag{12}$$

From Eq.(4), I_0, I_1 and I_2 of the filter can be expressed as

$$\begin{aligned} I_0 =&[\rho_1^2+(1-\rho_1^2)\cos\phi]+\mathrm{i}[(1-\rho_1^2)\sin\phi]\\ =&a_0+\mathrm{i}b_0, \end{aligned} \tag{13}$$

$$\begin{aligned} I_1 =&\left[\frac{\rho_1^4+(1-\rho_1^4)\cos\phi}{2}\right]+\mathrm{i}\left[\frac{(1-\rho_1^4)\sin\phi}{2}\right]\\ =&a_1+\mathrm{i}b_1, \end{aligned} \tag{14}$$

$$\begin{aligned} I_2 =&\left[\frac{\rho_1^6+(1-\rho_1^6)\cos\phi}{3}\right]+\mathrm{i}\left[\frac{(1-\rho_1^6)\sin\phi}{3}\right]\\ =&a_2+\mathrm{i}b_2. \end{aligned} \tag{15}$$

Substituting Eqs.(13)–(15) into Eqs.(5)–(8), we get

$$U_{\rm F}=\frac{-2(a_0b_1-a_1b_0)}{a_0a_2+b_0b_2-a_1^2-b_1^2}, \tag{16}$$

$$S=a_0^2+b_0^2-U_{\rm F}(a_0b_1-a_1b_0), \tag{17}$$

$$G_{\rm T}=\frac{2(a_0a_1+b_0b_1-U_{\rm F}(a_0b_2-a_2b_0))}{S}, \tag{18}$$

$$G_{\rm A}=\frac{12(a_0a_2+b_0b_2-a_1^2-b_1^2)}{S}. \tag{19}$$

According to Eq.(19), we obtain the axial superresolution region of two-zone phase filter with arbitrary phase shift, which is shown in Fig.1. Figure 1 shows that two-zone phase filter can produce axial superresolution when its phase shift is not π, and it can be seen that axial superresolution is only obtained in the white region enclosed by phase shift ϕ and radii ρ_1. The above conclusions present theoretical basis for two-zone phase filter's axial superresolution design.

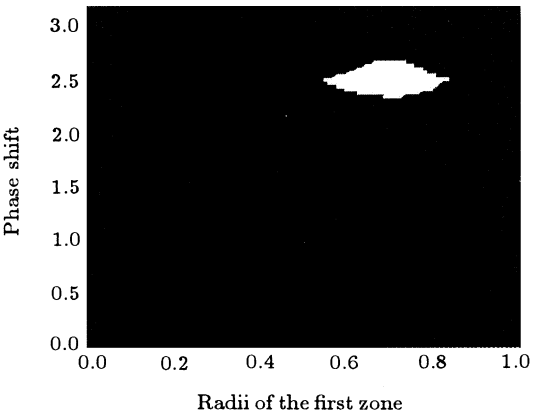


Fig.1. Region (white area) enclosed by radii ρ_1 and phase shift ϕ in which the axial superresolution can be obtained for a two-zone phase filter.

4. Influence of phase shift on transverse superresolution performance

Three-zone phase filter is the most useful phase filter for its simplicity and high superresolution performance.[1,5,6,10,12,15] Phase shift of commonly used three-zone phase filter is π, pupil function of the filter is given by

$$P(\rho)=\begin{cases}-1, & 0<\rho<\rho_1,\\ 1, & \rho_1<\rho<\rho_2,\\ -1, & \rho_2<\rho<1,\end{cases} \tag{20}$$

where ρ_1 and ρ_2 are radius of the first and the second zone. By Eqs.(4)–(8) and Eq.(20), figures of merit of the filter can be obtained.[10]

Recently, three-zone phase filter's optimal transverse gain has been obtained in Ref.[10]. We obtain the axial gain corresponding to the optimal transverse gain, which is shown in Fig.2. From Fig.2 , we find that the axial gain decreases dramatically with the increase of the optimal transverse gain. For example, the corresponding axial gain $G_{\rm A}=0.0919$ when the optimal transverse gain $G_{\rm T}=1.3643$. It can strongly decrease axial resolution, and damage axial imaging quality correspondingly. One can also find that the axial gain corresponding to the optimal transverse gain even turns to be negative. For instance, axial gain $G_{\rm A}=-1.0137$ when the optimal transverse gain $G_{\rm T}=1.6592$. Negative axial gain means that light intensity distribution does not present a peak at the focus position, it will present a well surrounded by annular bright lobs instead, which will damage the axial imaging quality strongly.

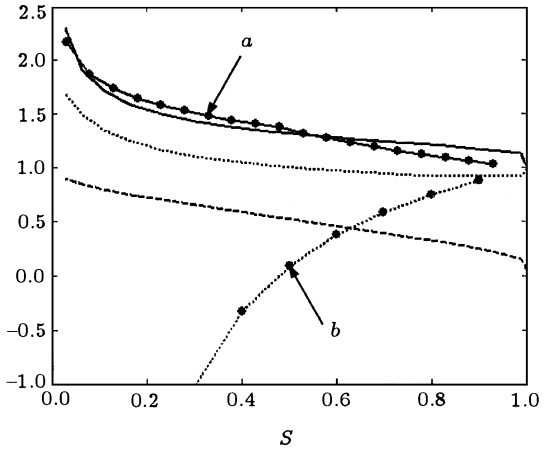


Fig.2. Optimal transverse gain (curve a) and its corresponding axial gain (curve b) of commonly used three-zone phase filter, the optimal transverse gain (solid line), the corresponding axial gain (dotted line) and the phase shift (dashed line, in units of π) of three-zone phase filter with arbitrary phase shift.

In the following, we study the optimal transverse superresolution of three-zone phase filter with arbitrary phase shift, and we compare the superresolution performance of the commonly used three-zone phase filter with that of three-zone phase filter with arbitrary phase shift. Using ϕ to denote an arbitrary phase shift in interval $[0, \pi]$, we can express I_0, I_1 and I_2 of the filter as

$$\begin{aligned} I_0 =&[\rho_1^2 \cos\phi + \rho_2^2 - \rho_1^2 + (1-\rho_2^2)\cos\phi] \\ &+ \mathrm{i}[\rho_1^2 \sin\phi + (1-\rho_2^2)\sin\phi] = a_0 + \mathrm{i}b_0, \qquad (21) \\ I_1 =&[(\rho_1^4 \cos\phi + \rho_2^4 - \rho_1^4 + (1-\rho_2^4)\cos\phi)/2] \\ &+ \mathrm{i}[(\rho_1^4 \sin\phi + (1-\rho_2^4)\sin\phi)/2] = a_1 + \mathrm{i}b_1, (22) \\ I_2 =&[(\rho_1^6 \cos\phi + \rho_2^6 - \rho_1^6 + (1-\rho_2^6)\cos\phi)/3] \\ &+ \mathrm{i}[(\rho_1^6 \sin\phi + (1-\rho_2^6)\sin\phi)/3] = a_2 + \mathrm{i}b_2. (23) \end{aligned}$$

Substituting Eqs.(21)–(23) into Eqs.(16)–(19), one can obtain the filter's figures of merit. We designate the maximal focal displacement 1.5. Using the constrained nonlinear multivariable optimizing method, we obtain the optimal transverse superresolution gain and the corresponding axial gain of three-zone phase filter with arbitrary phase shift, and they are shown in Fig.2. From Fig.2, one can see that the optimal transverse gain increases with the increase of the phase shift, and the corresponding axial gain increases with the increase of phase shift too. It can also be seen that the corresponding axial gain increases with the increase of the optimal transverse gain.

From Fig.2, we can draw the following conclusions: for three-zone phase filter with arbitrary phase shift, its optimal transverse gain is almost equal to that of commonly used three-zone phase filter, but its corresponding axial gain is much larger than that of commonly used three-zone phase filter. Moreover, the corresponding axial gains are mostly larger than 1. For example, when Strehl ratio is 0.3, the optimal transverse gain of commonly used three-zone phase filter is 1.6390, and the corresponding axial gain is –0.9250. The optimal transverse gain of three-zone phase filter with arbitrary phase shift is 1.4339, and the corresponding axial gain is 1.1076, which is much larger than –0.9250. The axial gain corresponding to the optimal transverse gain of commonly used three-zone phase filter is too small, and even turns to be negative. Three-zone phase filter with arbitrary phase shift has overcome the limitation.

In a word, three-zone phase filter with arbitrary phase shift has an almost equal optimal transverse superresolution to that of commonly used three-zone phase filter, but it can produce a much higher axial superresolution than that of the commonly used filter.

5. Influence of phase shift on three-dimensional superresolution performance

Recently, a very useful three-dimensional superresolution filter has been proposed in Ref.[12], and it is a three-zone complex filter. The radius of the three zones are ρ_1, ρ_2 and 1, where $\rho_1^2 + \rho_2^2 = 1$. Transmittances of the three zones are t, 1 and 1 respectively, the corresponding phase shift is 0.6π.

There are three degrees of freedom for three-zone complex filter, i.e. radii, transmittance and phase shift. In Ref.[12], only radii and transmittance are free, the phase shift is designated to 0.6π. We investigate the filter's three-dimensional superresolution performance when the filter's phase shift is an arbitrary value. Using ϕ to denote an arbitrary phase shift in interval $[0, \pi]$, we can express I_0, I_1 and I_2 of the filter as

$$\begin{aligned} I_0 =&[t\rho_1^2 \cos\phi + \rho_2^2 - \rho_1^2 + (1-\rho_2^2)\cos\phi] \\ &+ \mathrm{i}[t\rho_1^2 \sin\phi + (1-\rho_2^2)\sin\phi] = a_0 + \mathrm{i}b_0, \qquad (24) \\ I_1 =&[(t\rho_1^4 \cos\phi + \rho_2^4 - \rho_1^4 + (1-\rho_2^4)\cos\phi)/2] \\ &+ \mathrm{i}[(t\rho_1^4 \sin\phi + (1-\rho_2^4)\sin\phi)/2] = a_1 + \mathrm{i}b_1, (25) \\ I_2 =&[(t\rho_1^6 \cos\phi + \rho_2^6 - \rho_1^6 + (1-\rho_2^6)\cos\phi)/3] \\ &+ \mathrm{i}[(t\rho_1^6 \sin\phi + (1-\rho_2^6)\sin\phi)/3] = a_2 + \mathrm{i}b_2. (26) \end{aligned}$$

Substituting Eqs.(24)–(26) into Eqs.(16)–(19), one can obtain figures of merit of the filter.

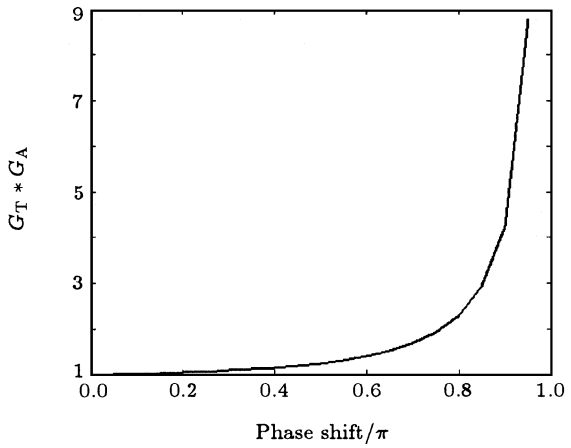


Fig.3. The optimal three-dimensional superresolution capability of three-zone complex filter varying with phase shift.

We study firstly the three-dimensional superresolution capability of three-zone complex filter with arbitrary phase shift. Three-dimensional superresolution capability can be expressed in terms of $G_T * G_A$ ($G_T > 1$ and $G_A > 1$). When the filter's phase shift is an arbitrary value in interval [0, π], we obtain the filter's optimal three-dimensional superresolution capability, which is shown in Fig.3. We can see that the filter's three-dimensional superresolution capability increases with the increase of phase shift. So in the filter's three-dimensional superresolution design, a larger phase shift should be chosen.

In three-zone complex filter's three-dimensional superresolution design, not only the three-dimensional superresolution capability but also the design margin should be considered. The filter's design margin can be expressed by the area of the filter's three-dimensional superresolution region, which is enclosed by radii a and transmittance t. When the filter's phase shift is an arbitrary value in interval [0, π], we obtain the areas of the filter's three-dimensional superresolution regions, which are shown in Table 1. It can be seen that area of the filter's three-dimensional superresolution region increases when phase shift increases from 0 to 0.85π, but decreases when phase shift increases in interval from 0.85π to π. A larger three-dimensional superresolution region means a larger design margin, so we conclude that three-zone complex filter's design margin is maximal when its phase shift is about 0.85π.

Table 1. Area of three-zone complex filter's three-dimensional superresolution region and the phase shifts.

Phase shift/π	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.75	0.8	0.85	0.9	1.0
Area	74	235	413	582	718	835	912	930	946	974	889	834

In a word, we obtain the relationship between three-zone complex filter's three-dimensional superresolution capability and its phase shift, and the relationship between the filter's design margin and its phase shift. The two relationships present theoretical basis for three-zone complex filter's three-dimensional superresolution design.

6. Influence of phase shift on focal shift of optical systems

Focal shift can be used to extend depth of focus of optical systems,[18] and focal shift is meaningful in dynamic focusing system. In this section, we investigate the influence of phase shift on optical systems' focal shift. The purpose of our study is to gain an accurate focal shift control by means of three-zone phase filters with different phase shifts.

We design a series of three-zone phase filters with different phase shifts, which can produce focal shift from 0 to 1.5 and guarantee transverse gains and axial gains invariable. The designed filters are shown in Table 2, where ϕ_1 and ϕ_2 are phase shifts and U_F is the focal shift which the designed filter can produce. Axial intensity distributions of the designed filters are shown in Fig.4. It can be seen that the designed filters can produce desired focal shifts in interval [0, 1.5]. And the axial gains corresponding to different focal shifts are almost invariable. Transverse intensity distributions of the designed filters are shown in Fig.5, and transverse intensity distribution with no filter is also depicted for comparison. It can be seen that the transverse gains corresponding to different focal shifts are almost invariable too.

Table 2. Designed three-zone phase filters with different phase shifts which produce defocusing amount from 0 to 1.5 and guarantee invariable transverse gains and axial gains.

ρ_1	ρ_2	ϕ_1	ϕ_2	U_F
0.3300	0.9730	0.3338	0.2460	0.25
0.7586	0.8995	0.3794	0.3313	0.5
0.5819	0.8816	0.7745	0.6523	0.75
0.5457	0.8678	1.4914	1.2642	1
0.5678	0.8684	1.5403	1.3093	1.25
0.6110	0.8850	1.4666	1.3750	1.5

By regulating the voltage imposed on a phase SLM, phase modulation degree of the SLM can be controlled. So we implement the designed filters with different phase shifts by a phase SLM.[19−21] That is to say, by regulating the voltage, three-zone phase filters with different phase shifts can be implemented, and different focal shifts can be obtained correspondingly. By this method, the accurate focal shift control can be obtained only by regulating the voltage imposed on a SLM. It is a focal shift control method without physical translation of optical systems' elements, so it can improve the accuracy of focal shift control greatly and can be implemented easily.

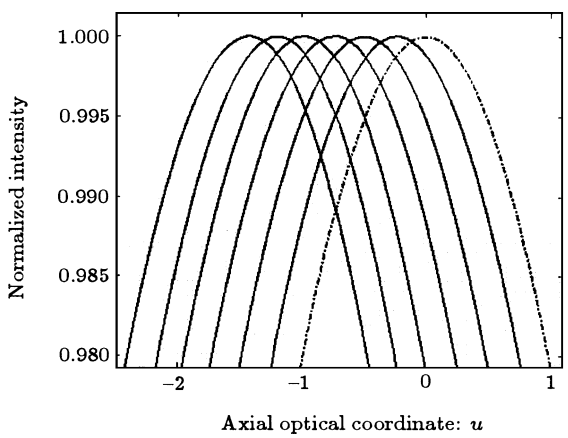


Fig.4. Axial intensity distributions of the designed three-zone phase filters that can produce focal shifts from 0 to 1.5.

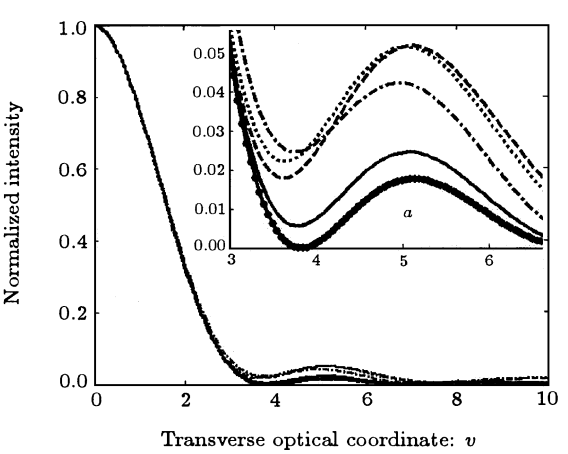


Fig.5. Transverse intensity distributions of the designed three-zone phase filters that produce focal shift 0.75 (solid line), 1 (dashed line), 1.25 (dotted line), and 1.5 (dash-dot line) respectively. Transverse intensity distribution with no filter is also shown by curve a for comparison.

In a word, in order to obtain different focal shifts with invariable transverse and axial gains, we design a series of three-zone phase filters with different phase shifts, and we use a phase SLM to implement the designed filters. By regulating the voltage imposed on the SLM, accurate focal shift control can be obtained.

7. Conclusion

In conclusion, phase shift is an important parameter of pupil filters, and annular filters are the most useful pupil filters. When annular filters' phase shift is an arbitrary value, their superresolution performances are rarely studied. So we investigate influences of phase shift on superresolution performances of some typical annular filters. Firstly, we investigate the influence of phase shift on axial superresolution performance of two-zone phase filter. We prove that the axial superresolution can not be obtained by two-zone phase filter with phase shift π. We get the phase shift with which axial superresolution can be brought by two-zone phase filter. Secondly, influence of phase shift on transverse superresolution performance of three-zone phase filter is investigated. We find that the three-zone phase filter with arbitrary phase shift has an almost equal optimal transverse superresolution capability to that of commonly used three-zone phase filter, however it can produce a much higher axial superresolution capability. Thirdly, we study the influence of phase shift on three-dimensional superresolution performance of three-zone complex filter. We obtain the relationship between the filter's three-dimensional superresolution capability and its phase shift, and we find the relationship between the filter's design margin and its phase shift. The two relationships present theoretical basis for three-dimensional superresolution design. At last, influence of phase shift on focal shift of optical systems is investigated. In order to obtain different focal shifts with invariable transverse and axial gains, we design a series of three-zone phase filters with different phase shifts. By regulating the voltage imposed on the SLM which is used to implement the designed filters, an accurate focal shift control is obtained. Our investigation finds that the annular filters with arbitrary phase shift have higher superresolution capabilities, and our investigation presents the theoretical basis for better superresolution performance control and superresolution filter design.

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