Extraction of Inherent Amplitude Mode from a Light Beam

Zhiyang Xia, Xiaoyu Weng, Liwei Liu, Jun He, Changrui Liao, Yiping Wang, and Junle Qu*

Mode extraction is the inverse process of the double-beam superposition principle in classical optics. While polarization mode extraction has been successfully demonstrated using an *m*-order vector vortex beam, amplitude mode extraction remains a significant challenge due to the complex intertwinement of inherent amplitude modes. To address this challenge, a method is developed to extract arbitrary amplitude modes of a light beam in both the real and imaginary domains. By introducing competition between amplitude modes in these domains, the desired amplitude modes within a light beam can be selectively extracted in the focal region of an objective lens using an optical pen. This work demonstrates the principle of amplitude mode extraction, thereby potentially paving the way for multidimensional manipulation of light fields.

1. Introduction

Light beams with special polarization and amplitude exhibit unique propagation and focusing properties that play vital roles in a wide range of applications.[1–4] For example, radially polarized beams can form focal spots with sizes below the diffraction limit.[5] When the phase of a radially polarized beam is modulated, an optical needle can be realized in free space.[6] In terms of scalar light beams, anti-diffracting light beams, such as Airy beams and Bessel beams, have been demonstrated to be reliable illumination beams, which cannot only enlarge the field of view but also enhance the penetration depth of the imaging system.[3,7]

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Motivated by the above applications, the modulation of amplitude, phase, and polarization of light beams has attracted significant interest in the community of optics. Typically, one can achieve amplitude, phase, and polarization modulation of a light beam by superposing two light beams with different polarizations and phases. For instance, combining x and y linearly polarized beams results in a circularly polarized beam, while a radially polarized beam can be realized by superposing left and right circularly polarized beams with inverse vortex phases.[2] According to this double-beam superposition principle, a specific light beam can only be obtained when the parameters of the two orthogonally polarized beams are set. However, is it possible to achieve the inverse process of this conventional principle? In other words, can inherent modes be extracted from a single light beam?

Recently, the principle of polarization mode extraction has been demonstrated using a high-order vector vortex beam (VVB).[8] This allows for the selective acquisition of multiple VVB modes, such as radially and circularly polarized modes, in the focal region of an objective lens. However, polarization mode extraction relies on the presence of two independent orthogonal polarization modes. For instance, a high-order VVB can be regarded as a combination of two independent left and right circular polarization modes, or x and y linearly polarized modes. When modulated by a specific phase, different polarization modes exhibit distinct phase responses, enabling the extraction of one polarization mode from the other. In contrast, there are no independent amplitude modes within a light beam. When the phase of a light beam is modulated, all inherent amplitude modes respond identically. As a result, the inherent amplitude modes of a light beam are always intertwined, making it impractical to extract arbitrary inherent amplitude modes from a light beam.

Here, we extract arbitrary amplitude modes of a light beam in real and imaginary spaces. Two independent amplitude modes within a light beam are realized in the real and imaginary spaces, respectively. By introducing competition between amplitude modes in these spaces, arbitrary amplitude modes within a light beam are extracted at will in the focal region of an objective lens using an optical pen.[9] When combined with polarization mode extraction, this approach enables the creation of arbitrary amplitude, phase, and polarization modes without altering the polarization and amplitude of the incident vector beam. Therefore, this work addresses a significant gap in the principle of mode extraction, which may find valuable applications in optics.

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2. Results

2.1. Two Independent Amplitude Modes in Real and Imaginary Space

In classical optics, a light beam can be expressed as $\exp(i\phi)\mathbf{E}$, where ϕ and $\mathbf{E}$ are the phase and electric field, respectively. As shown in **Figure 1**, there are two independent amplitude modes: the amplitude mode $\cos\phi$ in real space and the amplitude mode $\sin\phi$ in imaginary space. By adjusting the phase ϕ, an increase in $\cos\phi$ leads to a corresponding decrease in $\sin\phi$. Consequently, during propagation in free space, the two amplitude modes intertwine, maintaining the overall amplitude of the light beam as constant. Since the inherent amplitude modes $\cos\phi$ and $\sin\phi$ reside in distinct spatial domains, they can be regarded as two independent amplitude modes of the light beam, analogous to orthogonal polarization modes.

2.2. Spatial Separation of Inherent Amplitude Modes

Although two independent amplitude modes are realized in real and imaginary space, both modes are intertwined together, see Figure 1. Thus, the key to amplitude mode extraction lies in eliminating the undesired amplitude mode in imaginary space without affecting the desired amplitude mode in real space. In theory, the light intensity of a light beam can be expressed as

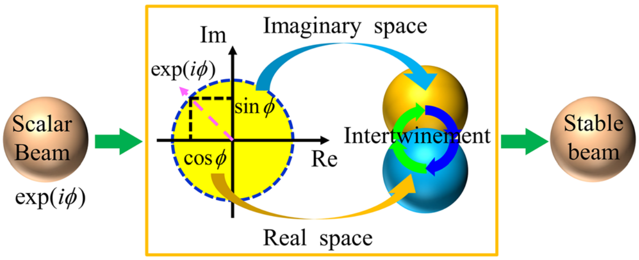

Figure 1. Schematic of the intertwinement of inherent amplitude modes within a light beam. Here, the amplitude mode $\cos\phi$ in real space and the amplitude mode $\sin\phi$ in imaginary space are two independent amplitude modes of the light beam.

$$I = \cos^2\phi + \sin^2\phi \tag{1}$$

Here, we name the amplitude mode $\cos\phi$ in real space and the amplitude mode $\sin\phi$ in imaginary space as Mode E and Mode F in **Figure 2**, respectively. From Equation (1), the above light beam can be divided into two pairs of amplitude modes, namely Mode A and Mode B in real space, and Mode C and Mode D in imaginary space. Therefore, Equation (1) can be rewritten as

$$I = |\text{Mode A}|^2 + |\text{Mode B}|^2 + |\text{Mode C}|^2 + |\text{Mode D}|^2 \tag{2}$$

where Mode A and Mode B are equal to $1/\sqrt{2}(+\cos\phi)$; while Mode C and Mode D are equal to $1/\sqrt{2}i(+\sin\phi)$ and $1/\sqrt{2}i(-\sin\phi)$, respectively.

According to Equation (2), the electric field of the light beam can be simplified as

$$\mathbf{E}_i = \left[1/\sqrt{2}(+\cos\phi)\; 1/\sqrt{2}(+\cos\phi)\; 1/\sqrt{2}i(+\sin\phi)\; 1/\sqrt{2}i(-\sin\phi)\right]\mathbf{E} \tag{3}$$

Here, the signs "+" and "−" in Equation (3) are no longer mathematical symbols but denote the 0 and π phase of amplitude modes in real and imaginary spaces, respectively. From this optical perspective, the amplitude modes $\sin\phi$ can be considered to be modulated by a pupil filter with a 0–π phase, while the other amplitude modes $\cos\phi$ remain unchanged. Finally, the electric field of the light beam in Equation (3) transforms into

$$\mathbf{E}_i = \left(\cos\phi + T_{\text{imag}}\, i \sin\phi\right)\mathbf{E} \tag{4}$$

where $T_{\text{imag}} = \exp(i\phi_{\text{imag}})$ and ϕ_{imag} denotes a binary phase with values of 0 and π. Note that the constant factor $1/\sqrt{2}$ is neglected.

According to Equation (4), both Mode A and Mode B represent the same amplitude mode $\cos\phi$, which is referred to as Mode E

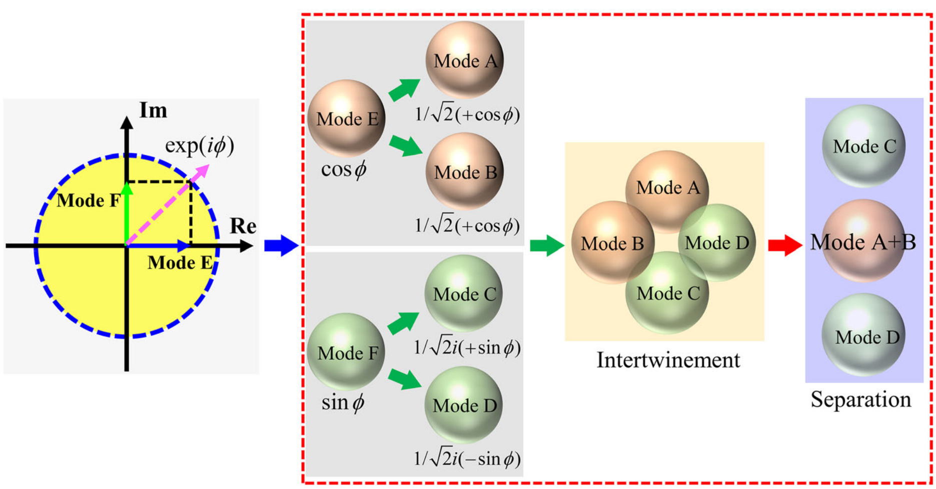

Figure 2. Spatial separation of inherent amplitude modes using Equation (4). Here, Mode E represents the inherent amplitude mode in real space, while Mode F represents the inherent amplitude mode in imaginary space.

in Figure 2. Mode F denotes the amplitude mode $\sin\phi$ with the modulation of T_{imag} in Figure 1, which is derived from Mode C and Mode D. In the case of $T_{\text{imag}} = 1$, Equation (4) simplifies to $\mathbf{E}_i = \exp(i\phi)\mathbf{E}$, and Mode E and Mode F are always intertwined, see Figure 2. In the case of T_{imag} with a 0–π phase, Mode F can be split into different parts in the focal region of the objective lens, namely Mode C and Mode D as shown in Figure 2, while Mode E (which is equal to Mode A + Mode B) remains unchanged. Although the sum of Mode F and Mode E in the focal region of the objective lens equals $\cos\phi$, their total light intensity remains normalized to unity. For this reason, Equation (4) represents the pure phase of an incident light beam. Unlike $T_{\text{imag}} = 1$, Mode E and Mode F are located at different positions, which makes it possible to extract the desired amplitude mode $\cos\phi$ using a phase-only spatial light modulator (SLM), as shown in Figure 2.

2.3. Amplitude Mode Extraction from a Light Beam

Figure 3 illustrates the optical setup for extracting amplitude modes from a light beam. A collimated x-linearly polarized beam with a wavelength of 633 nm passes through a phase-only SLM and two lenses (L_3, L_4) before being focused by an objective lens (OL) with a numerical aperture (NA) of 0.008. Arbitrary amplitude modes can therefore be generated in the focal region of OL, and their light intensities are captured using a CCD camera. Here, the polarization of the incident light beam is aligned to the horizontal direction using a polarizer (P) and a half-wave plate (HWP). The pupil plane of OL is optically conjugated to the phase-only SLM through the 4f system composed of L_3 and L_4. Consequently, the phase of the incident light beam in Equation (4) can be adjusted at will by the phase-only SLM.

Specifically, based on the Debye vectorial diffraction theory, the electric field in the focal region of OL in Figure 3 can be expressed as[10,11]

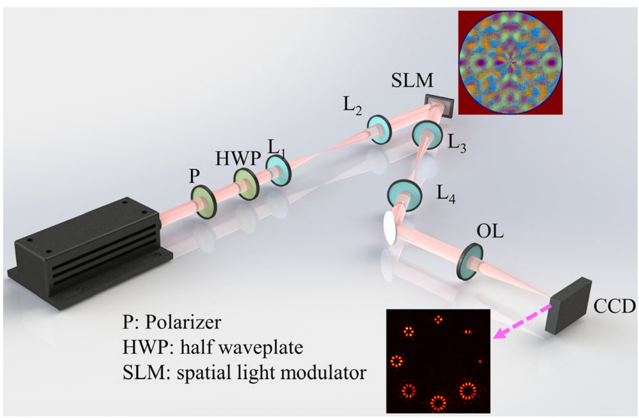

Figure 3. Schematic of the experimental setup for amplitude mode extraction. Here, $L_1 \approx L_4$ denote four lenses, and OL represents the objective lens. The polarization of the incident light beam can be adjusted using the polarizer (P) and a half-wave plate (HWP). The SLM is used to control the phase of the light beam. The light intensity of the amplitude mode is recorded using a CCD camera.

$$\mathbf{E} = -\frac{A}{\pi}\int_0^{2\pi}\int_0^{\alpha} \sin\theta\cos^{1/2}\theta T l_0(\theta)\mathbf{V}\exp(-ik\mathbf{s}\cdot\boldsymbol{\rho})\mathrm{d}\theta\,\mathrm{d}\varphi \tag{5}$$

where θ and φ are the convergent angle and azimuthal angle, respectively, and A is a normalized constant. $\alpha = \arcsin(\text{NA}/n)$, where NA is the numerical aperture of OL, and n is the refractive index in the focusing space. The wavenumber $k = 2n\pi/\lambda$, where λ is the wavelength of the incident beam, and $\boldsymbol{\rho} = (r\cos\phi, r\sin\phi, z)$ denotes the position vector of an arbitrary field point. The unit vector along a ray is expressed as $\mathbf{s} = (-\sin\theta\cos\varphi, -\sin\theta\sin\varphi, \cos\theta)$. $l_0(\theta)$ is the electric field amplitude of the incident beam, which can be expressed as[11]

$$l_0(\theta) = \exp\left[-\left(\beta_0\frac{\sin\theta}{\sin\alpha}\right)^2\right] \tag{6}$$

where the ratio of the pupil radius to the incident beam waist $\beta_0 = 1$ in this article.

According to Equation (4), the transmittance of SLM in Equation (5) can be written as

$$T = \cos\phi + iT_{\text{imag}}\sin\phi \tag{7}$$

Amplitude mode extraction is generally applicable to all light beams. For simplicity, we use an x-linearly polarized beam as an example to demonstrate amplitude mode extraction. Consequently, the propagation unit vector of the incident beam immediately after passing through the OL can be expressed as[10]

$$V = \begin{bmatrix} \cos\theta + (1-\cos\theta)\sin^2\varphi \\ -(1-\cos\theta)\sin\varphi\cos\varphi \\ \sin\theta\cos\varphi \end{bmatrix} \tag{8}$$

Ultimately, the light intensity of amplitude mode extracted from the x-linearly polarized beam can be obtained using $I = |\mathbf{E}|^2$. In the following simulations and experiments, $\text{NA} = 0.008$, $n = 1$. The unit of length in all figures is the wavelength λ, and the light intensity is normalized to the unit value.

Figure 4 presents the evolution process of extracting amplitude mode $\cos l\varphi$ in real space from a vortex beam $\exp(il\varphi)$. Specifically, $\phi = l\varphi$ in Equation (7). Taking the topological charge $l = 1$ as an example, the amplitude mode $\sin\phi$ in Equation (7) is modulated by an optical pen, and its phase can be expressed as[9]

$$\phi_{\text{imag}} = \text{Phase}\left\{\sum_{j=1}^{N}\left[\text{PF}\left(s_j, x_j, y_j, z_j, \delta_j\right)\right]\cos(\sigma\varphi)\right\} \tag{9}$$

Here, $\text{PF}(s_j, x_j, y_j, z_j, \delta_j)$ denotes the optical pen, see ref. [9]; $N = 2$, $s_j = 1$, $y_j = z_j = 0$, $\delta_j = 0$, $x_1 = -x_2 = d$. Due to the symmetrical parameters of optical pen, ϕ_{imag} turns into a binary phase with values of 0 and π. In this case, the desired mode $\cos l\varphi$ always located at the geometric focus of OL, while the undesired amplitude mode $\sin l\varphi$ is divided into two identical parts with different d. In Figure 4e–g, $d = 0$, 120, 400 and $\sigma = 0$. Their corresponding phases are shown in Figure 4a–c, respectively. Once d increases to a certain value, the intertwinement of inherent amplitude modes is overcome, thereby bringing the hope of extracting the desired amplitude mode $\cos l\varphi$ from a light beam.

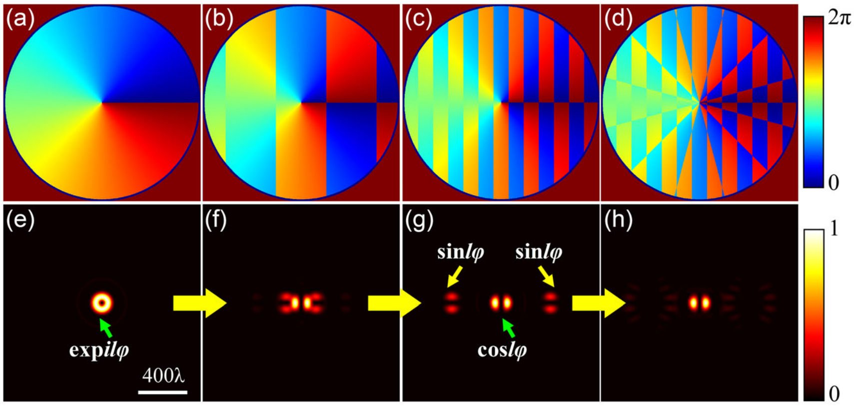

Figure 4. The evolution process of extracting amplitude mode in real space from a vortex beam $\exp(il\varphi)$. The undesired amplitude modes sin$l\varphi$ with different positions can be obtained by adjusting d. Here, e–g) $\sigma = 0$, $d = 0$, 120, 400, respectively; h) $\sigma = 3$, $d = 400$. Their corresponding phases are shown in a–d), respectively.

Although one can separate the desired mode cos$l\varphi$ from the undesired mode sin$l\varphi$, the light intensities of the undesired modes sin$l\varphi$ cannot be neglected in free space, as shown in Figure 4g. To further eliminate the undesired mode, we introduce amplitude mode competition between the desired mode cos$l\varphi$ and the undesired modes sin$l\varphi$. Because the undesired modes sin$l\varphi$ in Figure 4g are modulated by the phase in Equation (9), their energy densities can be adjusted by an additional factor $\cos(\sigma\varphi)$. A larger σ leads to lower energy densities of the undesired modes sin$l\varphi$. For example, the energy densities of the undesired modes sin$l\varphi$ in Figure 4h become low after modulating by the phase in Figure 3d with $\sigma = 3$. When normalized, the undesired modes sin$l\varphi$ can be ignored, and only the desired mode cos$l\varphi$ is retained in the focal region of OL.

More intuitively, we summarize the process of amplitude mode extraction in **Figure 5**. As discussed above, amplitude mode extraction involves two key factors: spatial separation of inherent amplitude modes and amplitude mode competition. Specifically, Mode E and Mode F represent the inherent amplitude modes in real and imaginary space, respectively. As shown in Figure 4a,e, the desired mode cos$l\varphi$ and undesired mode sin$l\varphi$ are always intertwined, leading to a stable vortex beam in free space. When modulated by the phase in Equation (7), both modes become spatially separated in free space as d increases. Although the total light intensities of the undesired modes are always equal to $1-\cos^2 l\varphi$, the energy density difference between the inherent modes in real and imaginary space can be adjusted by T_{imag}. Using this amplitude mode competition, one can find a suitable T_{imag} to retain the desired mode cos$l\varphi$, while the undesired mode sin$l\varphi$ can be effectively ignored. Note that the sum of Mode A and Mode B equals Mode E, while Mode F, the undesired amplitude mode, is divided into Mode C and Mode D, as shown in Figure 4.

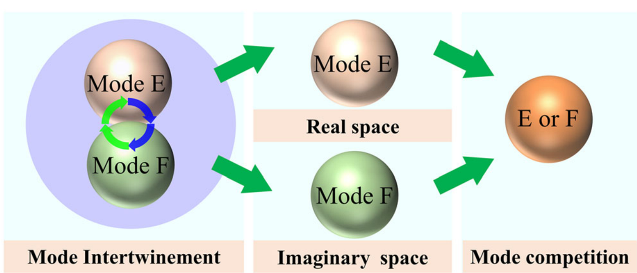

Figure 5. Schematic of inherent amplitude mode extraction from a light beam. Here, Mode E and Mode F represent two amplitude modes in real and imaginary space, respectively.

In order to verify the flexibility of amplitude mode extraction, **Figure 6** presents the simulation and experimental results of extracting the Chinese character "China" using an optical pen. The wavefront information of the incident light beam can be obtained by[9]

$$T_{\mathrm{op}} = \sum_{j=1}^{N} \left[\mathrm{PF}\left(s_j, x_j, y_j, z_j, \delta_j\right) \right] \tag{10}$$

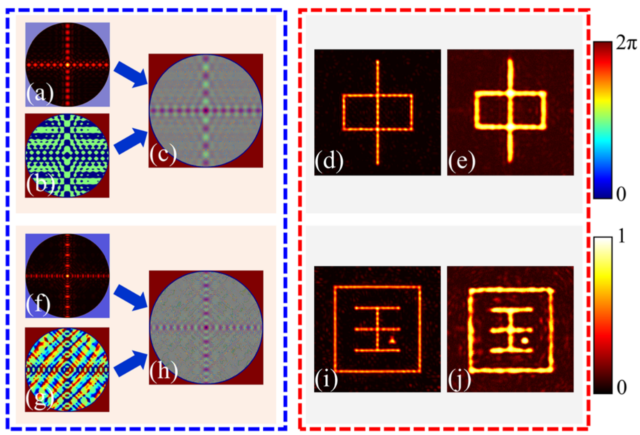

Figure 6. Extracting the light pattern "China" in Chinese. a,b,f,g) show the amplitudes and phases of the incident light beam, which are realized by the phases in c,h) based on amplitude mode extraction. d,i,e,j) present their corresponding simulation and experimental results, respectively.

Generally, Equation (10) can be simplified as

$$T_{\text{op}} = \cos\phi_{\text{amp}} \exp\left(i\delta_{\text{phase}}\right) \tag{11}$$

where $\cos\phi_{\text{amp}}$ and δ_{phase} denote the amplitude and phase of a light beam, respectively. According to the physical concept of the optical pen, the focal region of OL can be regarded as a drawing board, with each focus created by the optical pen acting as a paintbrush.[9] Therefore, one can create arbitrary light patterns by adjusting parameters N, s_j, x_j, y_j, z, δ_j. For example, the Chinese characters "中" and "国" shown in Figure 6 are created using this method. Here, $s_j = 1$ and $\delta_j = 0$, with $N = 73$ for the character "中" and $N = 125$ for the character "国". Their corresponding amplitudes and phases of the incident light beam are shown in Figure 5a,b,f,g, respectively.

Based on amplitude mode extraction, the amplitude mode in Equation (11) can be directly extracted from the incident light beam, and T in Equation (7) can be expressed as

$$T = \exp\left(i\delta_{\text{phase}}\right)\left(\cos\phi_{\text{amp}} + iT_{\text{imag}} \sin\phi_{\text{amp}}\right) \tag{12}$$

Here, $\exp(i\delta_{\text{phase}}) \cos\phi_{\text{phase}}$ and $\exp(i\delta_{\text{phase}}) \sin\phi_{\text{phase}}$ represent the desired and undesired modes, respectively. To eliminate the undesired mode, the phase of T_{imag} is adjusted to

$$\phi_{\text{imag}} = \text{angle}[J_{10}(30k \sin\theta / \sin\alpha) \cos(20\varphi)] \tag{13}$$

where $J_{10}(\bullet)$ is the Bessel function of the first kind with order 10. Specifically, the amplitudes and phases of the light beam in Figure 6a,b,f,g can be realized by the phases in Figure 6c,h, respectively. When focused by the OL, the amplitude modes in the imaginary space can be disregarded, retaining only the desired amplitude mode, as illustrated in Figure 6d,e,i,j. This allows for the direct extraction of any desired amplitude directly from a light beam.

3. Discussion

To further clarify, we would like to discuss the fundamental differences between amplitude mode extraction and previous studies.

3.1. Differences Between Amplitude Mode Extraction and Previous Studies

Numerous studies have investigated various techniques for generating desired amplitude modes within the focal region of an OL. Prominent among these are holography[12–14] and the checkerboard approach.[15,16] These methods, while innovative, often result in non-negligible light fields in the focal region, which can complicate the desired outcomes.[12] For instance, holographic techniques, despite their high resolution and versatility, can introduce unwanted light patterns. These patterns arise from the unwanted diffraction orders of the light beam and cannot be eliminated, which further affects the clarity of the final image.[12] In contrast, our method of amplitude mode extraction from a light beam introduces a novel and effective solution by leveraging two critical processes: spatial separation of inherent amplitude modes in real and imaginary space, and amplitude mode competition. First, we establish a direct one-to-one correspondence between the phase of the incident light beam and the amplitude mode in the focal region of OL. Second, by introducing amplitude mode competition, we can dynamically adjust the energy density difference between the amplitude modes in real and imaginary space. This flexibility enables the effective suppression of undesired amplitude modes, ensuring that they do not significantly interfere with the desired mode. Ultimately, after normalization, only the desired amplitude mode in real space is retained in the focal region of OL. This selective retention of the desired mode is a significant advancement over previous methods, which often struggle to achieve such precise control.

3.2. Differences Between the Amplitude Mode Extraction and Polarization Mode Extraction

Mode extraction is the inverse process of the principle of coherent superposition. Typically, coherent superposition enables the generation of a single specific light beam by superimposing two light beams with distinct polarizations and phases. In contrast, mode extraction offers a far broader range of possibilities. Analogous to mathematical operations, one can achieve not only $2 = 1 + 1$, but also $2 = 3 - 1$ or $2 = 5 - 3$. This inverse process thus provides numerous opportunities to selectively extract desired light beams in free space.

Despite sharing the same fundamental physical idea, amplitude mode extraction and polarization mode extraction exhibit two major differences. First, polarization mode extraction can only be achieved using a unique vector beam, such as an m-order VVB. This type of light beam exhibits distinct polarization responses in the focal region of OL. In contrast, amplitude mode extraction applies to any light beam. By modulating the phase of the undesired amplitude mode in imaginary space, one can always extract the amplitude mode from a light beam. Second, their mode competition mechanisms differ. For polarization mode extraction, competition between the desired and undesired polarization modes can only be achieved by increasing the order of VVB. In other words, the form of polarization mode competition is singular, determined by the polarization of incident m-order VVB. However, according to Equation (7), amplitude mode competition in this study is dependent on $T_{\text{imag}} = \exp(i\phi_{\text{imag}})$, where ϕ_{imag} represents a binary phase with values of 0 and π. Because ϕ_{imag} can be adjusted to arbitrary phase with 0 and π, amplitude mode competition exhibits a high degree of flexibility.

In conclusion, we have demonstrated both theoretically and experimentally the extraction of inherent amplitude modes from a light beam in the focal region of OL, using an x-linearly polarized beam as an example. The intertwining of inherent amplitude modes in real and imaginary space is overcome by modulating the amplitude mode in imaginary space and utilizing amplitude mode competition. As a result, arbitrary amplitude modes in real space can be extracted in the focal region of OL. Moreover, with the aid of an optical pen, one can create arbitrary light patterns. This work provides a versatile and precise tool for manipulating light fields, potentially enabling innovative applications in various fields of optics, including optical imaging and optical manipulation.

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Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Zhiyang Xia: investigation (equal); methodology (supporting). **Xiaoyu Weng**: conceptualization (equal); investigation (equal); methodology (equal); validation (equal); writing—original draft (lead); writing—review & editing (equal). **Liwei Liu**: supervision (equal); validation (equal). **Jun He**: validation (equal); writing—review & editing (equal). **Changrui Liao**: validation (equal); writing—review & editing (equal). **Yiping Wang**: supervision (equal); validation (equal); writing—review & editing (equal). **Junle Qu**: supervision (equal); validation (equal); writing—review & editing (equal).

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

amplitude mode, mode extraction, optical pen

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