Nonlinear optical vortex coronagraph

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Implementing selective edge enhancement in nonlinear optics

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Abstract: Recently, it has been demonstrated that a nonlinear spatial filter using second harmonic generation can implement a visible edge enhancement under invisible illumination, and it provides a promising application in biological imaging with light-sensitive specimens. But with this nonlinear spatial filter, all phase or intensity edges of a sample are highlighted isotropically, independent of their local directions. Here we propose a vectorial one to cover this shortage. Our vectorial nonlinear spatial filter uses two cascaded nonlinear crystals with orthogonal optical axes to produce superposed nonlinear vortex filtering. We show that with the control of the polarization of the invisible illumination, one can highlight the features of the samples in special directions visually. Moreover, we find the intensity of the sample arm can be weaker by two orders of magnitude than the filter arm. This striking feature may offer a practical application in biological imaging or microscopy, since the light field reflected from the sample is always weak. Our work offers an interesting way to see and emphasize the different directions of edges or contours of phase and intensity objects with the polarization control of the invisible illumination.

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1. Introduction

Edge enhancement technique can highlight the contour of the object in optical information processing, and it has been widely used in image processing [1,2], microscopy and biological imaging [3–6], fingerprint recognition [7] and, astronomical exploration [8–10]. The theory of edge detection was proposed in 1980 [10], while the experimental attempt was made not until 1992 by Khonina et al. [11]. One of the basic methods to achieve edge enhancement optically is Hilbert transform, which brings a shift effect of $\pi$ radians on the negative and positive frequency components of the input image [12]. After that, Davis et al. introduced a radially symmetric Hilbert transform with a vortex phase plate in a 4f optical system [13], also called vortex filtering. According to the characteristics of vortex filters, vortex filtering can be generally divided into scalar and vector, which provides isotropic and anisotropic filtering effect [14,15]. To achieve scalar vortex filtering, only spiral phase is needed in the Fourier plane of a 4f system [1,13,16]. But for a vectorial vortex filter, the polarization state of the light field needs to be considered and a space-variant birefringent optical element (Q-plate) or a spatially variable half-waveplate (s-wave plate) is usually used in the Fourier plane to emphasize specific characteristics of the input object [14,15,17–19]. There are also some other methods to achieve anisotropic edge enhancement by breaking down the symmetry of the filtering process with scalar spatial filters, such as a fractional spiral phase filter (SPF) [20], by shifting of the SPF [21], an anisotropic vortex phase mask [22–24].

Recently, a nonlinear vortex filter is proposed to achieve a visible edge enhancement under invisible illumination based on the second harmonic generation (SHG) effect in nonlinear optics [25]. This work opens a way to optically implement nonlinear spatial filter and has received
much attention. More recently, a nonlinear optical vortex coronagraph based on sum-frequency generation is proposed to change the observation wavelength [26], which gives a new perspective for the application of the nonlinear spatial filter. But with this scalar nonlinear spatial filter, all phase or intensity edges of a sample are highlighted simultaneously, independent of their local directions. The vectorial nonlinear spatial filter which can highlight the specific direction is still lacking. On the other hand, vector light field modulation in nonlinear optics has attracted much attention recently. In 2019, Yang et al. realized nonlinear frequency conversion of cylindrical vector beams by using a Sagnac loop [27]. In the same year, Wu et al. provided a theoretical toolkit to analyze the type-II SHG, which was applicable to the scalar and the vector cases [28]. Zhang et al. conducted the SHG with the full Poincare beams and observed the hidden topological structures transferred from the input polarization state to the output observable intensity patterns [29]. They further realized frequency conversion from vector fields to vector fields based on the vectorial nonlinear optical process [30].

Based on the vectorial light field modulation technique in SHG, here, we propose a vectorial nonlinear vortex filter to complement the scalar one. Compared with the scalar nonlinear vortex filter which uniformly highlights the edges of the object, the vectorial one can implement a selective edge enhancement. Here, we use a Q-plate instead of the spiral phase plate in Ref. [25] to produce orthogonal polarization vortex, then we imprint the Fourier spectrum of the object and the orthogonal polarization vortex onto two cascaded nonlinear crystals to produce the enhanced edges of the object. By rotating the angle of the polarizer in object arm, one can select the direction of the edges or contours of the object in visible region. Our work not only extends the nonlinear spatial filter research area but also offers an interesting way to see and emphasize the different directions of edges or contours of phase and intensity objects under invisible illumination.

2. Theoretical analysis

Let’s first summarize the traditional vectorial vortex filter in linear optics: as shown in Fig. 1(a), a 4-f imaging system with a filter on its Fourier plane. The input object \( g(r, \phi) \) is illuminated by the incident light \( L_{in} = [\cos \alpha, \sin \alpha]^T \), generally, with a visible wavelength of \( \lambda_{vis} \), which is a planar wave with linear polarization oriented at the angle of \( \alpha \) after passing through the polarizer \( P_1 \). The Jones vector of the object light field is expressed as \( E_{in}(r, \phi, \lambda_{vis}) = g(r, \phi)[\cos \alpha, \sin \alpha]^T \). Then, the Fourier spectrum, \( \tilde{E}_{in}(\rho, \phi, \lambda_{vis}) = F[E_{in}(r, \phi, \lambda_{vis})] \), is obtained after the object light field passing through the lens \( L_1 \), \( F \) denotes the Fourier transform. A Q-plate with initial orientation \( \theta = 0 \) for \( q = 1/2 \) is placed in the Fourier plane. Since the Q-plate is a polarization sensitive element [31], the light field after passing through the Q-plate is usually denoted by \( T(r, \phi) = L_{in} \cdot t(\rho, \theta) \), where \( t(\rho, \theta) \) is the transmission matrix of the Q-plate [14,15,18] and usually denoted by:

\[
t(\rho, \theta) = \begin{bmatrix}
\cos 2q\theta & \sin 2q\theta \\
\sin 2q\theta & -\cos 2q\theta
\end{bmatrix},
\]

Then the final light field in the back-focal plane of the 4f system is:

\[
E_{out}(r, \phi) = F[\tilde{E}_{in} \cdot T(r, \phi)] = E_{in} \otimes h(r, \phi),
\]

where \( \otimes \) represents the convolution, and \( h(r, \phi) \) represents the point spread function (PSF) of the optical system with Q-plate as the Fourier filter, which can be calculated in polar coordinates by:

\[
h(r, \phi) = -\frac{2\pi A}{\lambda f} \left[\frac{\cos (\phi - \alpha)}{\sin (\phi - \alpha)}\right] \int_0^R J_1 \left(\frac{2\pi}{\lambda f} r \rho \right) \rho d\rho,
\]
where $A$ is a constant factor, $f$ is the focal length of lens $L_2$, $R$ is the radius of the Q-plate and $J_1(\cdot)$ is the first-order Bessel-function [15]. The PSF above is a vector representation with Jones matrix, which has a similar distribution as the cylindrical vector beam with an inhomogeneous spatial polarization change. So, the component who contributes to the filtering process in the PSF depends on the polarization of the incident light. According to Eq. (2)–(3) and the convolution theorem, each point of the image is multiplied by the PSF. Thus, at the certain orientation, the unit region of constant distribution is canceled after summing all image points in the certain area, while the edge regions with different phases or intensities are highlighted.

**Fig. 1.** Schematic illustration of edge enhancement. (a) Vectorial vortex filter in linear optics. (b) Vectorial vortex filter in nonlinear optics.

Our proposed vectorial nonlinear vortex filter is illustrated in Fig. 1(b). A Q-plate and two nonlinear crystals are united as the nonlinear filter. Here, the two nonlinear crystals act as a tool to convert the infrared domain to visible one based on the SHG effect. The object is illuminated by an invisible light $\lambda_{\text{invis}}$, and Fourier transformed by the lens $L_1$. The crystals are just placed on the right focal plane of $L_1$. The Q-plate is re-imaged onto the crystal plane and then interacts with the object’s Fourier spectrum in the crystals. Considering the paraxial approximation, the SHG light fields of the crystals can be described by:

\[
\frac{d\tilde{E}_\text{H}^V(\rho, \varphi, \lambda_{\text{vis}})}{dz} = \frac{i2\pi d_{\text{eff}}}{\lambda_{\text{vis}} n_{\text{vis}} c} \times \tilde{E}_\text{H}^V(\rho, \varphi, \lambda_{\text{invis}}) \times T^V(r, \phi, \lambda_{\text{invis}})
\]

\[
\frac{d\tilde{E}_\text{H}^H(\rho, \varphi, \lambda_{\text{vis}})}{dz} = \frac{i2\pi d_{\text{eff}}}{\lambda_{\text{vis}} n_{\text{vis}} c} \times \tilde{E}_\text{H}^H(\rho, \varphi, \lambda_{\text{invis}}) \times T^H(r, \phi, \lambda_{\text{invis}}),
\]
where $\tilde{E}_{in}^{H}$, $\tilde{E}_{in}^{V}$, $T^{H}$, $T^{V}$ denote the horizontal and vertical component of the object arm light field $\tilde{E}_{in}(\rho, \varphi, \lambda_{\text{vis}})$ and the Q-plate arm light field $T(r, \phi, \lambda_{\text{vis}})$ in the crystals, respectively. $n_{\text{vis}}$ represents the refractive index for visible light, $d_{\text{eff}}$ represents the effective nonlinear coefficient, and $z$ represents the propagation distance. From Eq. (4), one can clearly see that it actually implements two nonlinear vortex filtering with orthogonal polarization states. With small-signal approximation, we can obtain the filtered image on the right focal plane of $L_2$ as:

$$E_{\text{out}}^{H}(r, \phi, \lambda_{\text{vis}}) \propto E_{\text{in}}^{V}(r, \phi, \lambda_{\text{vis}}) \otimes F[T^{V}(r, \phi, \lambda_{\text{vis}})]$$

$$E_{\text{out}}^{V}(r, \phi, \lambda_{\text{vis}}) \propto E_{\text{in}}^{H}(r, \phi, \lambda_{\text{vis}}) \otimes F[T^{H}(r, \phi, \lambda_{\text{vis}})].$$

(5)

The constant coefficient in Eq. (5) can be ignored. The horizontal and vertical components of the right-hand side of the Eq. (5) are similar to the Eq. (2) which can also be divided into two parts. Then, based on the Eq. (3), one can predict a visible selective edge enhancement whose orientation depends on the polarization of the incident invisible light. Compared with Fig. 1(a), the polarizer $P_2$ before the CCD is omitted because the phase matching conditions for performing the SHG of the two crystals actually play the role of the polarizer.

It is noted that, from the Eq. (4) and (5), one can see that the intensity ($E_{\text{out}}^{2} = E_{\text{out}}^{H2} + E_{\text{out}}^{V2}$) of the output filtered object is proportional with the product of the intensity in object arm ($E_{\text{in}}^{2}(r, \phi, \lambda_{\text{vis}})$) and the spatial filter arm ($T^2(r, \phi, \lambda_{\text{vis}})$), which can be denoted as:

$$E_{\text{out}}^{2} \propto \eta E_{\text{in}}^{2} \cdot \beta T^2,$$

if the light field of the object arm is very weak ($\eta = 0.001$), while the spatial filter one is strong ($\beta = 1000$), it is still possible to obtain a distinct filtered object since one can always modulate the intensity to keep $\eta \beta = C$, where $C$ is the appropriate intensity relation between the two input light fields. This striking feature might be used in biological imaging, since the light field reflected from the sample is always weak.

3. **Experimental setup**

The sketch of the experimental setup of our proposed vectorial nonlinear vortex filter is displayed in Fig. 2. The invisible source comes from a vertically linearly polarized 1064 nm laser. A half-wave plate (HWP) with its fast axis orienting at 22.5°, is used to produce the diagonal polarization state and the light is then separated into two paths by a 50:50 non-polarizing beam splitter (BS). The reflected light beam is incident on a computer-controlled spatial light modulator (SLM). The SLM is a reflective device consisting of an array of pixels (792 × 600) with an effective area of 16 mm ×12 mm and a pixel pitch of 20 µm. Each pixel imprints individually the incoming light with a phase modulation (0 ∼ 2π) according to the 8-bit grayscale (0 ∼ 255). And the whole SLM acts as a reconfigurable diffractive element, allowing an interactive manipulation with a response time comparable to the video displays. Here, we use the SLM to display arbitrary phase or intensity objects via designing suitable holographic gratings. The desired object is then obtained by a 4f system with an iris in the Fourier plane to filter out the first-order diffraction of the light field. The lens ($L_2$) is used to obtain the Fourier spectrum of the object on the plane of the crystals. Here, the two nonlinear crystals are the BBO crystals, whose fast axes are configured elaborately to be perpendicular to each other. The transmitted light beam from the BS passes through a Q-plate. The Q-plate is re-imaged onto the crystals by an imaging lens ($L_1$) with 2f ∼ 2f configuration. The two beams are recombined by another BS. One needs to carefully modulate the coincide angle of the two beams to satisfy the type-I phase matching conditions of the two orthogonally placed BBO crystals. It is noted that here we use non-collinear phase matching to obtain the desired output light field. Since there are two light beams incident in the crystals, one comes from the object arm $H_0$ and the other one is the filter arm $H_F$, and according
to the principle of SHG, the output light fields after the crystals are consisted of three parts which is proportional to $H_O \cdot H_O, H_F \cdot H_F, H_O \cdot H_F$, respectively. The first two cases, which are also called as self-doubling frequency effect, have been studied in polarization singularity [32] and vortex beams [33]. Based on Eq. (5), we only consider the third part of $H_O \cdot H_F$. Thus, by slightly modulating the coincide angle of the two beams, one can separate the three parts of the light field slightly and then filter out the desired light field. A short pass filter is used to block the 1064nm light fields. The SHG light fields with visible 532nm green light are recorded by a CCD camera placed on the right focal plane of $L_3$. The filtered object with selective edge enhancement is then obtained by the CCD. It is noted that one striking feature of the proposed setup is that it can realize the visible filtered results under invisible illumination, which has a fundamental difference from the traditional linear optical spatial filtering system [14,15,17–19].

4. Results

To clearly demonstrate our theory, firstly, a simple disk intensity object is displayed on the SLM, as shown in Fig. 3(a). For an easy comparison, the Q-plate is removed firstly to obtain the up-conversion object image, as shown in Fig. 3(b). Then the Q-plate is carefully inserted at the certain position of the experimental setup. By adjusting the fast axis of the HWP at 1064nm to orientate at arbitrary angle $\theta$, one can get a series of notched ring at 532nm, which the gaps of the circles orientate to different directions. The simulation results are shown in Figs. 3(a1)-(a4). One can clearly see that the uniform circed edge enhancement is broken, and a gap in each ring is shown and rotates with the $\theta$, as predicted by the Eq. (3). Here, we use the general horizontal, diagonal, vertical and anti-diagonal polarization state as the experimental test, which is corresponding to the $\theta = 0^\circ, 22.5^\circ, 45^\circ, 67.5^\circ$ respectively. Our experimental results are illustrated in Figs. 3(b1)-(b4). A clearly gap in each ring is well observed and the rotation direction of the gap is roughly with $0^\circ, 45^\circ, 90^\circ, 135^\circ$ (here, we define the vertical gap direction is $0^\circ$), which just coincides with the input polarization state. Note that the sharpness of the edges in our experimental results is determined by the sharpness of the edge of the object and the imperfection of the lens imaging systems. For a quantitative comparison of the quality of the filtered image, we choose the center of the gap of the ring edge (red dotted line) and its orthogonal direction (yellow dotted line) to calculate the contrast of the intensity. The results can be seen in the third row of Figs. 3(c1)-(c4) corresponding to the experimental results of Figs. 3(b1)-(b4).
The blue curve and red curve correspond to the pixel-value (normalized) of yellow and red dotted line in each graph of the second row. The double peak of the red curve in each graph is clearly shown that the original disk object has been edge enhanced and the gentle rolls of the blue curve illustrate that the uniform edge enhancement has been broken. To quantitative analysis the selective edge-enhancement effect, we further introduce the contrast of the selective edge enhancement as

\[ V = \frac{\bar{I}_{\text{red}} - \bar{I}_{\text{blue}}}{\bar{I}_{\text{red}} + \bar{I}_{\text{blue}}} \]

where \( \bar{I}_{\text{red}} \) is the peak mean intensity of the notched ring and denoted by the red dotted line, while \( \bar{I}_{\text{blue}} \) is the gap mean intensity of the notched ring and denoted by the blue dotted curve. Then we have the contrast of all of the obtained experimental results with 91.5%, 90.33%, 89.16%, 87.29% for Figs. 3(c1)-(c4), respectively. It is noted that the background of the experimental results has been subtracted. The background is obtained by the same setup but without illumination light beam into the CCD camera. The good visibility of the edge enhanced image in different directions clearly demonstrates that we have successfully realized a visible selective edge enhancement under invisible illumination with the proposed vectorial nonlinear vortex filter.

Fig. 3. Simulation and experimental results of the filtered image of a disk object. The upper row shows the simulation of the selective edge-enhancement with the polarization direction of the incident light is 0°, 45°, 90°, 135°. The second row shows the selective edge enhancement experimental results with the vectorial nonlinear vortex filter. The last row shows the pixel-value (or intensity curves) of the dotted line in second row, the red curve corresponds to the red dotted line, while the blue curve corresponds to the yellow dotted line.

For practical application, a real sample usually contains both intensity and phase information, so we further exploit a complex-amplitude object whose intensity is uniform but the phase has a jump of 0 and \( \pi \) between the inner and outer circles, as shown in the insert figure of Fig. 2. It is noted that there is also have an intensity edge between the object and the background. So, there are both intensity and phase edges for the object, as can be seen from the simulation results in Fig. 4(a). One can predict that a double-notched-ring would be observed based on our theory. The simulation results are illustrated in Figs. 4(a1)-(a4). In a similar way, we first obtain the up-conversion object image as shown in Fig. 4(b), whose intensity profile shows an additional
dark line along the edge of $\pi$ phase jump compared with Fig. 3(b). Then we have the visible selective edge enhancement results of the complex-amplitude object as shown in Figs. 4(b1)-(b4). A clearly double-notched-ring is observed in each graph of Fig. 4. The rotation behavior of the gap in each ring also depends on the $\theta$, as predicted by the Eq. (3). The quantitative comparison between the gap and its orthogonal direction is illustrated in the third row of Figs. 4(c1)-(c4) corresponding to the experimental results of (b1)-(b4). We also calculate the contrast of the selective edge enhancement $V$ for Figs. 4(c1)-(c4), which are 88.88%, 88.45%, 87.44%, 95.22%, respectively. It is noted that the reason why the intensity of the inner edge is brighter than the outer one is that the inner one comes from the phase jump, $e^{i0} - e^{i\pi} = 2$, while the outer one comes from intensity change as $1 - 0 = 1$. Despite of the difference of the intensity, the featured results with four peaks have shown the robustness of the proposed vectorial nonlinear vortex filter even can be worked with a real complex object.

Fig. 4. Simulation and experimental results of the filtered image of a complex-amplitude object. The upper row shows the simulation of the selective edge-enhancement with the polarization direction of the incident light is $0^\circ$, $45^\circ$, $90^\circ$, $135^\circ$. The second row shows the selective edge enhancement experimental results with the vectorial nonlinear vortex filter. The last row shows the pixel-value (or intensity curves) of the dotted line in second row, the red curve corresponds to the red dotted line, while the blue curve corresponds to the yellow dotted line.

As we mentioned in theoretical part, Eq. (4) predicts an interesting phenomenon under the nonlinear optics. So we further measured the intensity ratio defined as $\nu = \eta/\beta$, where $\eta$, $\beta$ denote the intensity of the object arm and filter arm before entering the BBO crystals. Under the same input 1064nm laser power, we find that by adding a series of neutral filters in object arm to reduce its intensity, the filtered image can be still visualized even with $\nu = 0.01$. The striking feature of which the intensity of the object arm is much weaker than the filter arm may have special applications in biological imaging or microscopy with light-sensitive specimens, where a low-frequency photon is essential as a high-frequency photon might have detrimental effects.
5. Conclusion

In conclusion, we have proposed a vectorial nonlinear vortex filter theoretically and experimentally to realize the visible selective edge enhancement under invisible illumination. The experimental selective edge detection results of the intensity and phase object obtained by controlling the polarization state of the illumination invisible light field, clearly show the validity of the theory and method. We also have quantitatively calculated the contrast of the vectorial nonlinear spatial filter for visible selective edge enhancement. The proposed vectorial nonlinear vortex filter may also be extended to the biological edge detection or microscopy research area. The striking feature of which the intensity of the sample arm is much weaker than the filter arm offers a practical application that the super-weak light signals reflected from the sample, especially in biological imaging [34] or microscopy with light-sensitive specimens [35], might also be highlighted. By adopting a more effective scheme to enable strong photon-photon interaction, our method may provide a meaningful technique for infrared spatial filtering at the few-photon level [36]. Moreover, this easy-to-implement filtering technique might also be integrated into the microscope to provide additional functions and can be readily extended to other nonlinear optical processes [37], such as different frequency generation, four-wave mixing and so on, to meet different demands.

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Disclosures

The authors declare no conflicts of interest

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