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Modulating Phase via Rotation for Optical Encoding Based on Correlated Photon Imaging

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***Abstract*—Correlated photon imaging using a novel phase modulation strategy is proposed for optical encoding. Only few pixels guided by modulation pattern (i.e., some superposed arbitrarily-positioned circumferences) are selected from the pre-generated random phase-only mask, and positions of selected pixels are rotated for the generation of a new phase-only mask. Since great space savings, i.e., larger than 60.0%, are achieved for the storage or transmission, the designed optical encoding system is sufficiently efficient. Modulation patterns are generated via superposition of different arbitrarily-positioned circumferences, which guarantees system security. It is illustrated that the phase modulation strategy is simple and flexible to enable real application of the proposed optical encoding system. The proposed method can provide a promising alternative for exploring applications of correlated photon imaging.**

***Index Terms*—Optical encoding, correlated photon imaging, phase modulation, pixel rotation.**

I. INTRODUCTION

IN recent years, correlated photon imaging, known as ghost imaging [1]–[4], has been widely studied and applied, such as sensing and tomography. The sample can be decoded via the correlation between photocurrents obtained from the separated detectors illuminated by two highly correlated beams [1],[2],[5]. Since the sample can be obtained at reference beam arm where the sample is not located, this counterintuitive phenomenon has driven many researchers to conduct the studies for the explanation of correlated photon imaging principles. Although it was first interpreted with entangled photons generated in spontaneous parametric down-conversion [6],[7], it was later illustrated that key characteristics obtained with entangled photons can also be realized by applying classical pseudo-thermal light source [8],[9].

It is well known that in correlated photon imaging, a series of random phase-only masks are usually used during the encoding, and a series of reference intensity patterns (at reference beam arm) and photons (at object beam arm) can be obtained respectively by CCD camera and single-pixel bucket detector (without spatial resolution). In practice, computational approach [1],[10] can be applied to calculate the series of reference intensity patterns at reference beam arm, and recordings at reference beam arm using CCD camera are not compulsory. Due to complexity of its parameters, correlated photon imaging has been explored and applied to optical security field [11]–[17]. However, huge storage or transmission burdens [12]–[14], such as a series of phase-only masks or reference intensity patterns, can be considered as one of the most serious concerns in the correlated photon imaging systems. On the other hand, when system parameters are simple (such as using only one-dimensional vector [11]), it might not be highly efficient to guarantee system security. Hence, it is desirable that efficient storage or transmission of system parameters can be realized simultaneously with guaranteed security. It is also useful that a novel phase modulation strategy can be developed and applied without scrambling algorithm [17] in the correlated photon imaging system, since scrambling operation may request additional spaces, such as memories for the selected pixel positions.

In this letter, correlated photon imaging using a novel phase modulation strategy is proposed for optical encoding. Only few pixels guided by modulation pattern (i.e., some superposed arbitrarily-positioned circumferences) are selected from a pre-generated random phase-only mask, and positions of selected pixels are rotated for the generation of a new phase-only mask. Since great space savings are achieved for the storage or transmission, the designed optical data encoding system is efficient. The modulation patterns are generated via superposition of different arbitrarily-positioned circumferences, which can guarantee system security. It will also be numerically illustrated that the developed phase modulation strategy is simple and flexible to enable applications of the proposed optical encoding system.

II. SYSTEM PRINCIPLES

Figure 1 shows a schematic setup for illustrating the proposed method. One pre-generated phase-only mask $M(x,y)$, randomly distributed in the range of $[0,2\pi]$, is first employed to generate a series of random phase-only masks $[M_1(x,y)\,......\,M_N(x,y)]$. Figure 2 shows a schematic for illustrating the process to generate the phase-only masks $[M_1(x,y)......M_N(x,y)]$, which is described as follows: (1) Some circumferences with different diameters are generated and arbitrarily positioned to form a modulation pattern, such as $P_1(x,y)$. Subsequently, all pixels in each circumference are selected, hence the pixels in the pre-generated random phase-only mask $M(x,y)$ can be correspondingly chosen. As shown in Fig. 2, positions of selected pixels are rotated to their

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neighboring positions, and here rotation steps are set as 3 for each selected pixel along the clockwise direction. When positions of corresponding pixels in the pre-generated random phase-only mask $M(x,y)$ are processed according to each circumference in the modulation pattern, a new phase-only mask, i.e., $M_1(x,y)$, is generated. (2) Similarly to those described in step (1), other random phase-only masks $[M_2(x,y)......M_N(x,y)]$ are obtained by using their corresponding patterns $[P_2(x,y)......P_N(x,y)]$ via modulation of the same pre-generated phase-only mask $M(x,y)$. Since different circumferences are arbitrarily positioned in each modulation pattern, it is guaranteed that corresponding pixels in pre-generated phase-only mask $M(x,y)$ are randomly selected for the modulations.

Figure 3 shows flow chart for schematically illustrating encoding process of the proposed optical system, and one input, denoted as $O(\xi,\eta)$, is placed just before single-pixel bucket detector (without spatial resolution) as plaintext. When the series of generated phase-only masks $[M_1(x,y)......M_N(x,y)]$ is sequentially embedded into spatial light modulator (SLM), a series of intensity points $\{B_i\}$ $[i=1......N]$, acting as ciphertexts, can be obtained by single-pixel bucket detector.

For the decoding, only some information, i.e., one pre-generated random phase-only mask $M(x,y)$, modulation patterns and setup parameters, should be stored or transmitted. The decoding process can be described as follows: (1) Authorized receiver applies the correct modulation patterns to modulate random phase-only mask $M(x,y)$ for generating a series of phase-only masks $[M_1(x,y)......M_N(x,y)]$; (2) Using the series of generated phase-only masks $[M_1(x,y)......M_N(x,y)]$, a series of reference intensity patterns $[I_1(\xi,\eta)......I_N(\xi,\eta)]$ can be calculated at reference beam arm based on free-space wave propagation [18], i.e., $I_i(\xi,\eta)=|M_i(x,y)*h(x,y,d)|^2$, where h denotes point pulse function [18], d denotes axial distance and $*$ denotes convolution; (3) When the ciphertexts $\{B_i\}$ $[i=1,2,...N]$ are available, the input can be decoded by using correlation function $[\langle BI(\xi,\eta)\rangle-\langle B\rangle\langle I(\xi,\eta)\rangle]$, where $\langle\cdot\rangle$ denotes ensemble average. The correlation function [14],[17] can be further described by $\frac{1}{N}\sum_{i=1}^{N}\left(B_i-\langle\{B_i\}\rangle\right)\left[I_i(\xi,\eta)-\langle\{I_i(\xi,\eta)\}\rangle\right]$. Here, peak signal-to-noise ratio (PSNR) and mean square error (MSE) are calculated to evaluate quality of decoded data.

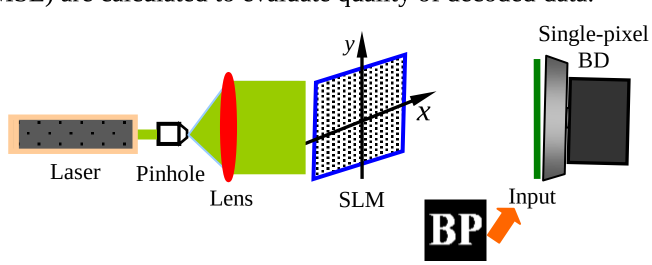


Fig. 1. Schematic setup [16],[17]: SLM, spatial light modulator; BD, bucket detector. For the sake of brevity the reference arm is not illustrated here since computational correlated photon imaging [1],[10],[17] is applicable.

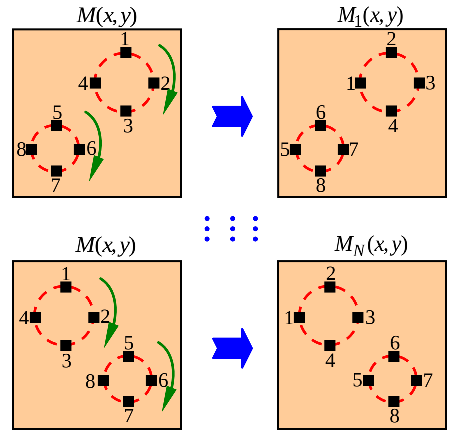


Fig. 2. A schematic for illustrating the modulation of positions of few pixels in one pre-generated random phase-only mask $M(x,y)$ for generating each new phase-only mask [i.e., $M_1(x,y)......M_N(x,y)$]. In this schematic illustration, two different circumferences are used to form a modulation pattern, and positions of all pixels in each circumference are correspondingly rotated. Non-selected pixels are still maintained, and their positions are not modified.

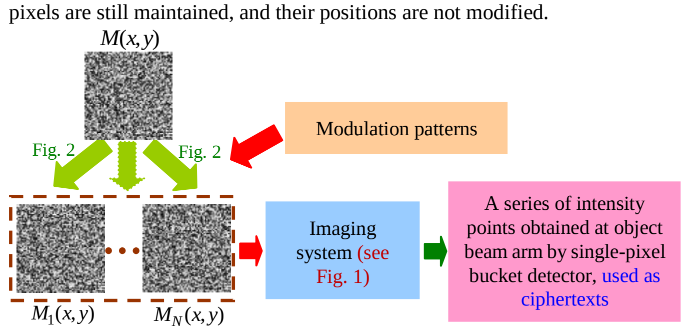
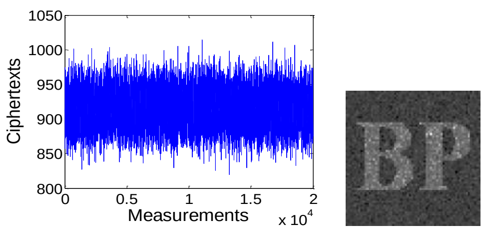


Fig. 3. Flow chart for schematically illustrating optical encoding process. Here, N is equivalent to 20000. Although simplified decryption using less measurements could be feasible, decryption quality will be affected. Therefore, security-key distribution approach should be efficiently designed.

III. RESULTS AND DISCUSSION

The correlated photon imaging setup shown in Fig. 1 is computationally applied to show feasibility and effectiveness of the proposed method. The collimated plane wave, with a waist of 740 μm and wavelength of 630.0 nm, is generated to illuminate the phase-only SLM. When the series of phase-only masks is generated by the proposed method and sequentially embedded into phase-only SLM (pixel pitch of 18 μm and pixel number of 64×64), a series of intensity points, acting as ciphertexts, are recorded by single-pixel bucket detector (without spatial resolution). In this study, the method is more suitable for encoding binary data rather than grayscale image. If multiple wavelengths are used, it is straightforward to apply the proposed method for color-image encoding. In the setup, axial distance d between phase-only SLM and detector (at reference or object beam arm) is 11.0 cm. 500 different circumferences are arbitrarily positioned to form each modulation pattern. It should be emphasized that it is straightforward to apply other geometries to form the modulation patterns, such as lines.

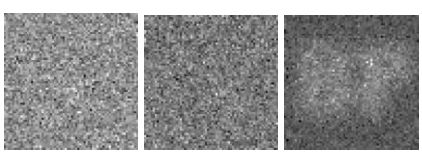
Using modulation patterns and the proposed phase modulation strategy, a series of phase-only masks $[M_1(x,y)......M_N(x,y)]$ can be generated, which are sequentially embedded into phase-only SLM during the encoding. Hence, the ciphertexts can be correspondingly obtained by using single-pixel bucket detector (without spatial resolution), and Fig. 4(a) shows the ciphertexts obtained in the proposed optical encoding system. The number of measurements is 20000, i.e., N=20000. It is illustrated that only noisy distribution can be obtained after the encoding. Figure 4(b) shows the decoded input data, when all keys are correctly applied during the decoding. The PSNR for Fig. 4(b) is 9.69 dB. It can be seen in Fig. 4(b) that high-quality input can be decoded, when system keys are available. Since correlated photon imaging is applied for optical encoding, the main objective is to decode the complete information (i.e., plaintext) when correct keys are available, rather than to pursue the higher-resolution reconstruction as those in conventional imaging systems [1],[2]. Although correlations among the generated phase-only masks are higher than those directly using a series of differently random phase-only masks, the decoded data as shown in Fig. 4(b) are fully visible or acceptable for clear observation of the input.



(a) (b)

Fig. 4. (a) Ciphertexts obtained in the developed optical encoding system, and (b) decoded data obtained when all keys are correctly applied during the decoding. The MSE value for (b) is 0.107.

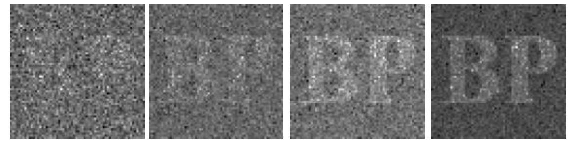
The performance of system keys is further analyzed. Figure 5(a) shows the decoded data, when only the pre-generated phase-only mask $M(x,y)$ is wrongly applied for the decoding, such as by unauthorized receivers. The PSNR for Fig. 5(a) is 5.95 dB. Figure 5(b) shows the decoded data, when only modulation patterns are wrongly used during the decoding. The PSNR for Fig. 5(b) is 5.95 dB. Figure 5(c) shows the decoded data, when wavelength contains an error of 10.0 nm and axial distance d contains an error of 0.5 cm during the decoding. The PSNR for Fig. 5(c) is 7.22 dB.



(a) (b) (c)

Fig. 5. Decoded data obtained when (a) only phase-only mask $M(x,y)$ is wrongly used, (b) only modulation patterns are wrongly used, (c) wavelength contains error of 10.0 nm and distance d contains error of 0.5 cm. The MSE values for (a)–(c) are 0.254, 0.254 and 0.189, respectively.

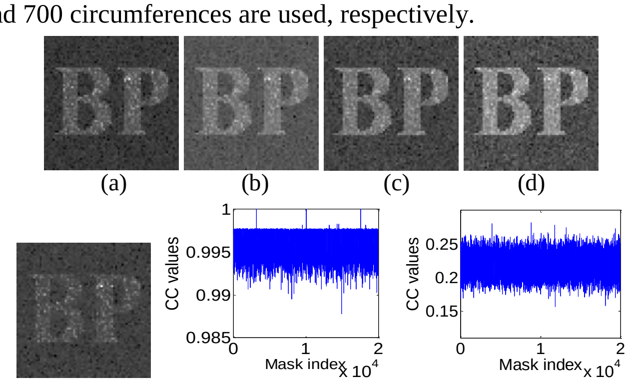
To further evaluate security of the proposed optical encoding system, the decoding is conducted under different percentages of eavesdropping when unauthorized receiver has got partial information related to principal keys, i.e., pre-generated random phase-only mask $M(x,y)$ and modulation patterns. Figures 6(a)–6(d) show the decoded data, when 35.0%, 45.0%, 55.0% and 65.0% of principal keys are eavesdropped to decode the input, respectively. The PSNRs for Figs. 6(a)–6(d) are 6.17 dB, 6.64 dB, 7.39 dB and 8.37 dB, respectively. As seen in Figs. 6(a)–6(d), to slightly observe the input data more than 35.0% keys should be eavesdropped. It is illustrated that the proposed optical system possesses high security.



(a) (b) (c) (d)

Fig. 6. The decoded data obtained when (a) 35.0%, (b) 45.0%, (c) 55.0% and (d) 65.0% of principal keys are eavesdropped for the decoding. The MSE values for (a)–(d) are 0.241, 0.216, 0.182 and 0.145, respectively.

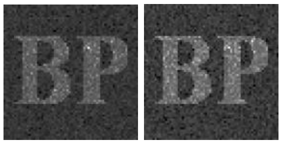
In the proposed optical encoding system, the number of circumferences in each modulation pattern can be flexibly designed and applied, which can enhance system security. Figures 7(a)–7(d) show the decoded data using correct keys, when 300, 400, 600 and 700 circumferences are used to form each modulation pattern, respectively. The PSNRs for Figs. 7(a)–7(d) are 9.12 dB, 9.39 dB, 9.85 dB and 10.08 dB, respectively. When fewer circumferences are applied in each modulation pattern, the less pixels in the pre-generated phase-only mask $M(x,y)$ will be modulated and there is higher correlation among the generated phase-only masks. Hence, the decoded data will be of lower quality, i.e., see Figs. 7(a) and 7(b). On the contrast, the higher quality is achieved [see Figs. 7(c) and 7(d)], when more circumferences are used and arbitrarily positioned to form each modulation pattern during the encoding. To clearly illustrate the minimum case, Fig. 7(e) shows the decoded data, when only 1 circumference is used. The PSNR and MSE for Fig. 7(e) are 6.50 dB and 0.224, respectively. For a comparison, Figs. 7(f) and 7(g) show correlations among the generated phase-only masks, when 1 and 700 circumferences are used, respectively.



(e) (f) (g)

Fig. 7. The decoded data obtained when (a) 300, (b) 400, (c) 600 and (d) 700 circumferences are used. The MSE values for (a)–(d) are 0.122, 0.115, 0.103 and 0.098, respectively. (e) Decoded data obtained when only 1 circumference is used. Correlations among the generated phase-only masks obtained when (f) 1 or (g) 700 circumferences are used. In this case, the first generated phase-only mask is used as a base for the calculation. CC denotes correlation coefficient. Average CC values for (f) and (g) are 0.996 and 0.22, respectively.

Rotation steps can also be flexibly applied for modifying positions of selected pixels in each arbitrarily-positioned circumference. Figure 8(a) shows the decoded input, when keys are correctly applied during the decoding. In this case, position of each selected pixel is rotated in the circumference with two steps, and other settings are the same as those used for Fig. 4(b). The PSNR for Fig. 8(a) is 9.66 dB. Figure 8(b) shows another decoded input, when keys are correctly applied during the decoding. In this case, position of each selected pixel is rotated in the circumference with four steps, and other settings are the same as those used for Fig. 4(b). The PSNR for Fig. 8(b) is 9.73 dB. It can be seen in Figs. 8(a) and 8(b) that different rotation steps can be flexibly applied for modulating positions of the pixels in the circumferences during the encoding.



(a) (b)

Fig. 8. The decoded input using correct keys obtained when (a) 2 rotation steps or (b) 4 rotation steps are employed in the proposed phase modulation method. The MSE values for (a) and (b) are 0.108 and 0.106, respectively.

Advantages of the proposed method and some comparisons are discussed as follows:

(1) In conventional methods [12],[14] each random phase-only mask (with 64×64 pixels) is independently generated and applied, and in the proposed optical system one modulation pattern (i.e., 500 different circumferences) can be represented by 1500 digits for modulating the pre-generated phase-only mask $M(x,y)$ to generate a random phase-only mask $[M_1(x,y) \ldots\ldots M_N(x,y)]$. Hence, for each generated phase-only mask approximately 63.38% spaces are saved for the storage or transmission, and for the total measurements (such as 20000) the great space savings can be correspondingly achieved. Although the simple method, i.e., using only an one-dimensional vector [11], can be applied as keys and generator of phase-only masks to achieve space savings, it is concerned that key complexity is low. In the proposed method, the circumferences are arbitrarily positioned and superposed to form each modulation pattern, and it can be guaranteed that positions of the selected pixels are random. The higher security, based on a random phase-only mask and modulation patterns, can be correspondingly guaranteed in the developed optical encoding system compared with previous works [11],[12], since higher percentage of eavesdropping should be applied as illustrated in Figs. 6(a)–6(d). There is a better trade-off between space savings and system security (or key complexity) in the proposed method. Phase modulation via rotation is proposed in this study to resolve the existing concern, and it is expected that the work in this manuscript can inspire researchers to study other methods.

(2) A contribution of this study or a major difference from previous work [17] is that simple phase modulation via pixel rotations with multiple arbitrarily-superposed circumferences is studied for the secured imaging without additional scrambling algorithms, and flexible rotation steps can be designed [see Figs. 8(a) and 8(b)]. The requested memories related to scrambling algorithms [17] are saved.

(3) High flexibility has also been achieved in the proposed optical encoding system, since the number of circumferences can be flexibly used to form each modulation pattern as illustrated in Figs. 7(a)–7(d).

(4) Although correlations among the generated phase-only masks are higher than those directly using a series of random phase-only masks in previously optical encoding infrastructures [12], the decoded data as shown in Fig. 4(b) are sufficiently clear for the observation of the input which satisfies the requirement of optical encoding schemes [19]–[21].

IV. CONCLUSIONS

Correlated photon imaging using a novel phase modulation strategy has been proposed for optical encoding. Only few pixels guided by modulation pattern are selected from the pre-generated random phase-only mask, and positions of selected pixels are rotated for the generation of a new phase-only mask during the encoding and decoding. Since great space savings are achieved for the storage or transmission, the developed optical data encoding system is efficient. It has been illustrated that modulation patterns can be arbitrarily generated in correlated photon imaging system, hence high security is guaranteed. Compared with previous works, there is a better trade-off between space savings and system security in the proposed optical encoding system. It has also been demonstrated that the developed phase modulation strategy is simple and flexible to enable its application to optical security.

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