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Direct generation of 2D arrays of random numbers for high-fidelity optical ghost diffraction and information transmission through scattering media

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ABSTRACT

In this paper, we propose a new approach for high-fidelity optical ghost diffraction and information transmission through scattering media in free space using a series of 2D arrays of random numbers as information carriers. A series of 2D arrays of random numbers are directly generated to encode the ghosts, i.e., original signals or images. The generated 2D arrays of random numbers are sequentially embedded into amplitude-only spatial light modulator (SLM), and are illuminated to propagate through scattering media in free space. Experimental results show feasibility and effectiveness of the proposed method, and different types of ghosts (e.g., analog signals and grayscale images) can be encoded and retrieved with high fidelity. In addition, comparisons using different algorithm parameters and different experimental parameters (e.g., different diffraction distances and wavelengths) are conducted to analyze and illustrate performance of the proposed method. It is found that the proposed method possesses high robustness against scattering media, and can realize high-fidelity ghost diffraction and optical information transmission. The proposed high-fidelity optical ghost diffraction could open up an avenue for many applications, e.g., free-space optical transmission through scattering media. @ 2022.

1. Introduction

Optical information transmission through scattering media is always considered as a significant challenge, since optical field could be severely destroyed in scattering environment. A number of methods [1–4] have been developed to realize information transmission through scattering media. A typical method is based on wavefront shaping [3], in which phase or amplitude modulation is usually conducted to control light to focus at a certain point of the output plane. Manipulation of interference among different optical channels is also applied to establish effective information channels [4], and amplitude or phase information of light through scattering media is further used as a feedback to optimize optical field. However, conventional methods could be complex and time-consuming due to the optimization and precise stability requirements. In addition, high-fidelity and high-robustness free-space optical data transmission through scattering media has not been fully realized.

To solve key scientific problems in conventional free-space optical transmission through scattering media, ghost diffraction can be explored to provide a promising solution. Ghost diffraction originated from quantum [5,6], in which the entangled state of two photons generated from spontaneous parametric down-conversion was used to realize the imaging. Later, ghost diffraction was further proved to be feasible with classical thermal light [7,8]. Ghost diffraction can be applied in different areas [9–19], e.g., three-dimensional reconstruction [9,10], phase object recovery [11,12], Terahertz [13,14], and X-ray imaging [18,19]. In ghost diffraction process with only one single-pixel bucket detector, a number of 2D patterns [20–23] need to be generated and sequentially embedded into a spatial light modulator (SLM). Then, these 2D patterns are illuminated to propagate at object wave path, and light intensity is collected by using a single-pixel bucket detector. The object information can be recovered by using correlation algorithms [20–23] with the 2D patterns and the collected intensity. It is required that a large number of patterns are usually applied to enhance quality of the recovered object image and mitigate environmental and detection noise. However, in ghost diffraction, the 2D patterns embedded into SLM usually contain no meaningful information about the data or object, and cannot be directly employed as information carriers for optical data transmission. Moreover, a non-correlation relationship usually exists among the 2D patterns, and there is also no determined relationship between the 2D patterns and the recorded intensity. Therefore, high-fidelity data transmission through scattering media is not feasible in traditional ghost diffraction, when the 2D patterns are directly used and coherent light source is applied. It is highly desirable to explore an easy-to-implement and feasible way to apply ghost diffraction and optical modulation method to enable high-fidelity ghost diffraction and optical information transmis-

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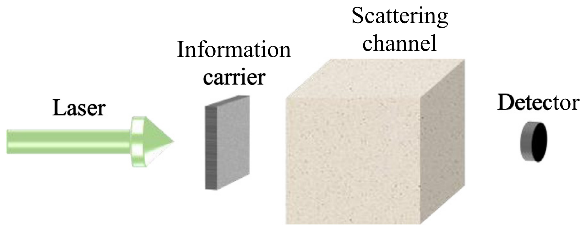

Fig. 1. A schematic for optical transmission.

sion through scattering media in free space. It is also desirable that 2D arrays of random numbers can be generated and directly used as information carriers to conduct ghost transmission through scattering media in free space with high fidelity and high robustness.

In this paper, we propose optical ghost diffraction using a series of 2D arrays of random numbers and coherent light source to realize optical field modulation and optical information transmission in free space through scattering media, which can provide an easy-to-implement way with high fidelity and high robustness. Instead of a direct realization of signal transmission with a laser, various types of ghosts, e.g., analog signals and grayscale images, are first encoded into 2D arrays of random numbers as information carriers. The generated 2D arrays of random numbers are sequentially embedded into SLM, and are sequentially illuminated to propagate through scattering media in free space. A single-pixel bucket detector is used at the receiving end to collect the intensity. Original signals or images can be retrieved at the receiving end using a simple retrieval operation. The main contributions of this work are described as follows: (1) To the best of our knowledge, it is the first time to realize free-space optical signal transmission through scattering media using a series of 2D arrays of random numbers as information carriers. (2) An entirely new method is proposed to design a series of 2D arrays of random numbers to realize high-fidelity and high-robustness free-space optical information transmission through scattering media. (3) Optical experiments are conducted to analyze the effect of different parameters and different environments on free-space optical information transmission by utilizing the proposed method. (4) Light intensity is collected by using a single-pixel bucket detector so that the collimation and alignment problem of free-space optical transmission channel can be solved at the receiving end. Optical experimental results and observation could shed light on free-space optical information transmission through scattering media.

2. Principle

An optical model is shown in Fig. 1. Data to be transmitted is encoded into 2D information carriers, and 2D information carriers are sequentially embedded into the SLM. A laser is modulated by the 2D information carriers, and the modulated light propagates through scattering channel which consists of diffusers (i.e., ground glass) and reflective media (i.e., A4 paper). Light intensities are collected by using a single-pixel bucket detector at the receiving end, and are utilized to retrieve the signal.

In the proposed method, the signal or image is first encoded into 2D arrays of random numbers. The proposed generation process of 2D arrays of random numbers is described as follows:

(1) Enlarge each original signal pixel (S) by using a magnification factor (M): $A = M \times S$;

(2) Arbitrarily generate a random matrix P with real and non-negative values (i.e., from 0 to 1);

(3) Calculate a difference y between the enlarged value A obtained in step (1) and the sum of the generated matrix P: $y = A - \mathrm{sum}(\mathrm{P})$;

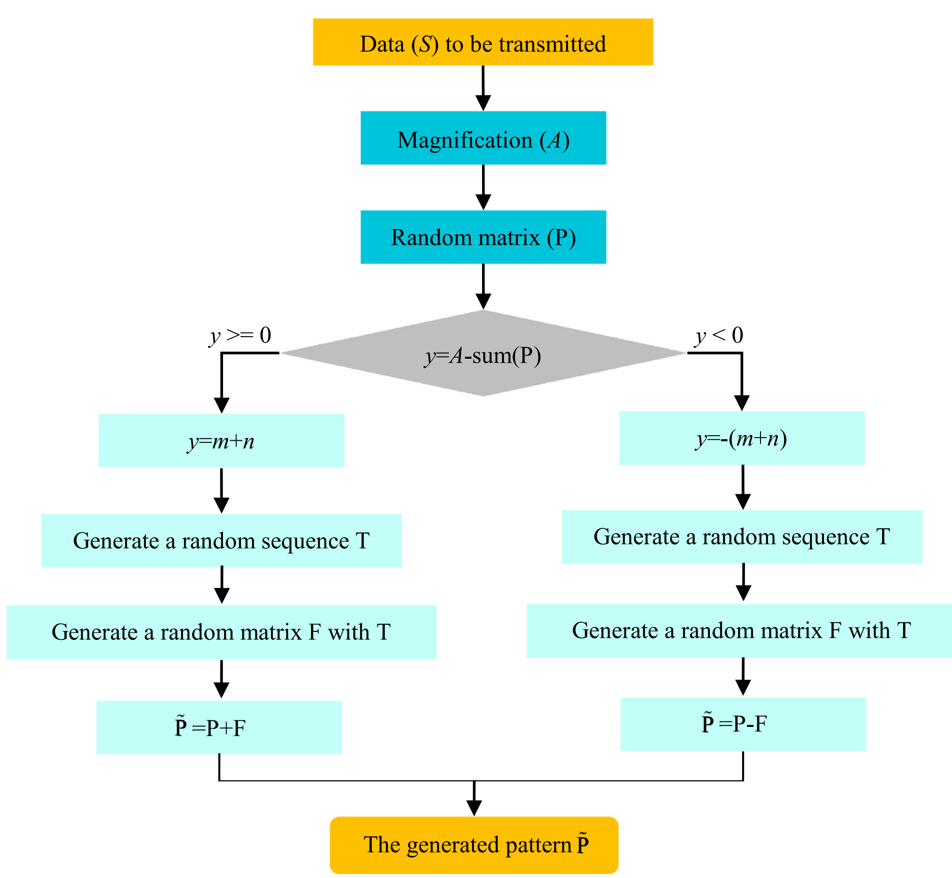

Fig. 2. A flowchart of the proposed pattern generation algorithm.

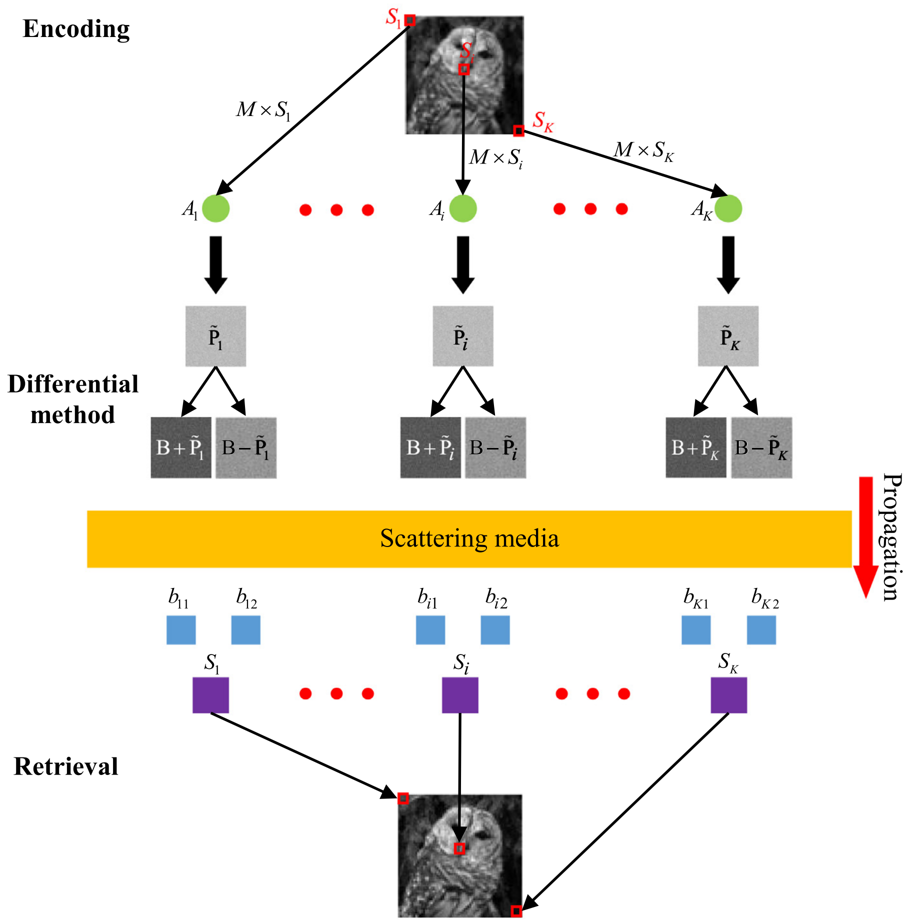

Fig. 3. A flowchart of the proposed optical information encoding and retrieval process.

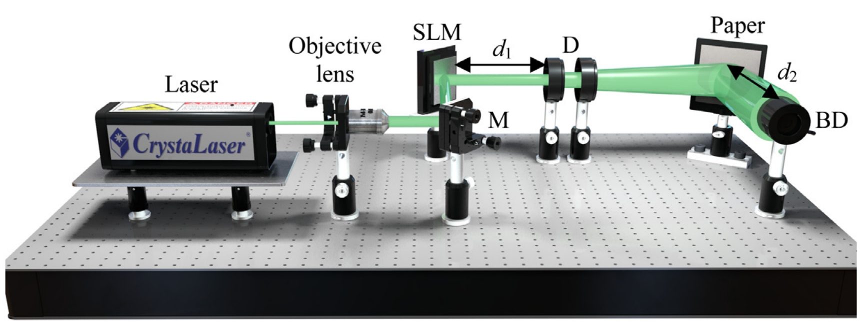

Fig. 4. A schematic experimental setup for the proposed free-space optical ghost diffraction and information transmission through scattering media: M, Mirror; SLM, Amplitude-only spatial light modulator; D, Diffusers; BD, Single-pixel bucket detector. d_1 denotes axial distance between the SLM and the first diffuser, and d_2 denotes axial distance between the A4 paper and single-pixel bucket detector. Two cascaded diffusers and a reflective A4 paper are used as a typical example in this study.

(4) Generate another matrix F with real and non-negative values, sum of whose pixel values is equivalent to absolute value of y obtained in step (3): $\mathrm{sum}(\mathrm{F}) = |y|$, where $|\ |$ denotes an absolute operation;

(5) When the difference y obtained in step (3) is negative, a 2D array corresponding to the enlarged data in step (1) is generated by calculating the difference between the matrix P and the matrix F. When the difference y obtained in step (3) is positive, a 2D array corresponding to the enlarged data in step (1) is generated by the addition of matrix P and matrix F:

$$\tilde{\mathrm{P}} = \begin{cases} \mathrm{P}+\mathrm{F}, & y >= 0 \\ \mathrm{P}-\mathrm{F}, & y < 0 \end{cases}. \quad (1)$$

To analyze the selection of different parameters in the proposed method aforementioned, original signal, i.e., acting as ghost, is normalized to be within a range from 0 to 1. (i) Since the generated 2D arrays of random numbers are sequentially embedded into the SLM, the large size of 2D arrays, e.g., 256 × 256 or 512 × 512 pixels, is required in order to provide sufficient light intensity in the experiments. (ii) Although the magnification factor used in the proposed method can be arbitrarily selected, it needs to satisfy that the enlarged value obtained in step (1) is comparable to the total pixel number of its correspondingly generated 2D array. (iii) The matrix F is generated in a random process. The difference y is first calculated by using a subtraction operation between the enlarged value obtained in step (1) and the sum of random matrix P, whose absolute value consists of an integer value denoted as m and a decimal (fractional part) denoted as n. Then, the steps for the generation of matrix F are as follows: A random sequence T with a length of $2 \times m$ is first generated, of which the upper half are random numbers between 0 and 1 and the lower half are obtained by calculating the difference between 1 and each value of the upper half. Then, an all-zero matrix with the same size of the matrix P is generated, and pixels with the number of $2 \times m + 1$ are randomly selected from this all-zero matrix. Finally, the decimal (fractional part) n and all values of the random sequence T are arbitrarily assigned to those randomly-selected

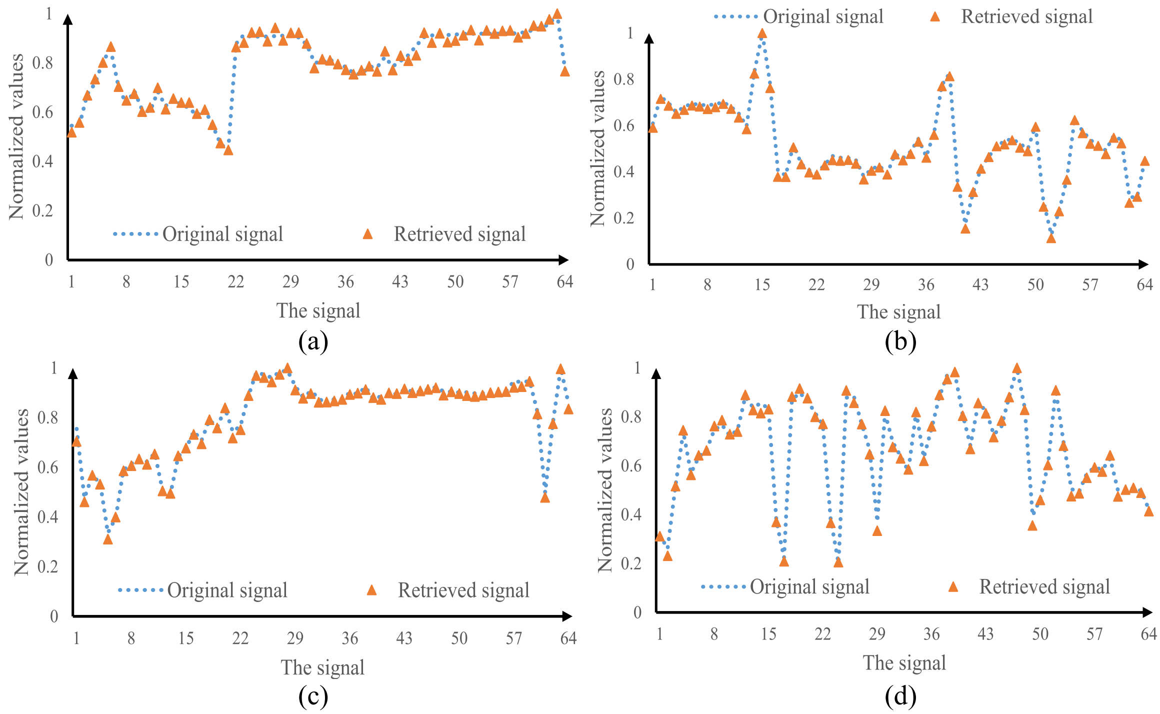

Fig. 5. The signals retrieved at the receiving end in different environments: the signal obtained (a) when no scattering medium is in wave propagation path in Fig. 4, (b) when only the reflective A4 paper is placed in wave propagation path in Fig. 4, (c) when one diffuser and the reflective paper are placed in wave propagation path in Fig. 4, and (d) when two cascaded diffusers and the reflective paper are placed in wave propagation path in Fig. 4. PSNR values of the retrieved signals in (a-d) are 35.62 dB, 38.20 dB, 38.02 dB and 36.35 dB, respectively. MSE values of the retrieved signals in (a–d) are 2.74×10^{-4}, 1.52×10^{-4}, 1.58×10^{-4} and 2.31×10^{-4}, respectively.

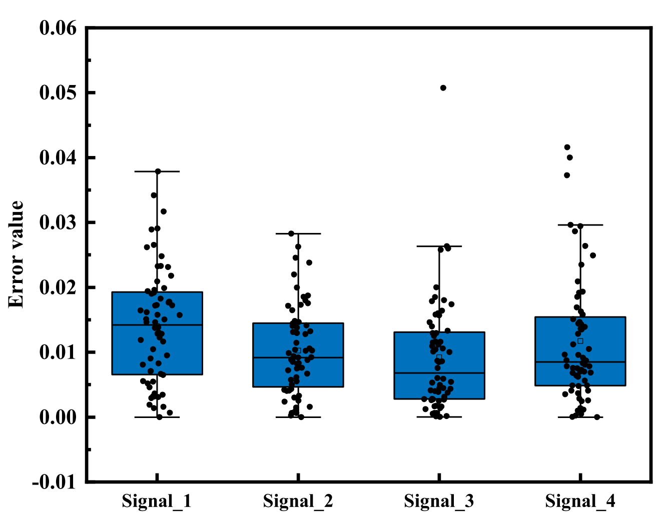

Fig. 6. Error distributions obtained between original signals and the retrieved signals in Fig. 5(a)–(d).

pixel positions with the number of $2 \times m + 1$ in order to generate the matrix F.

A flow chart of the proposed pattern generation process is shown in Fig. 2, and important and relevant parameters have been described. The following objective can be achieved: the sum of the generated 2D array of random numbers is equivalent to the enlarged value obtained in step (1), and each signal pixel to be transmitted is individually encoded into a 2D array of random numbers.

The whole encoding and retrieval process is shown in Fig. 3. For an original signal (as ghost, i.e., S_i, $i = 1,2,3,\ldots,K$) with K pixels to be transmitted, the proposed whole process is as follows: Each signal pixel is first encoded into a 2D array of random numbers ($\tilde{P}_i$, $i = 1,2,3,\ldots,K$) using the proposed algorithm aforementioned. To fully mitigate environmental and detection noise, a differential method is further developed to convert each generated 2D array of random numbers into two 2D arrays of random numbers (i.e., $\mathrm{B} + \tilde{P}_i$ and $\mathrm{B} - \tilde{P}_i$) with a real and positive constant B to remove negative values. Then, for each pixel of the signal to be transmitted, the two generated 2D arrays of random numbers are sequentially embedded into an amplitude-only SLM in Fig. 4, and two intensity points (b_{i1}, b_{i2}) can be sequentially collected by a single-pixel bucket detector. In information retrieval process, a simple subtraction operation with these two collected intensity values (b_{i1}, b_{i2}) is carried out to retrieve each signal pixel value (S_i), which has a close relationship with its corresponding pixel value in original signal, i.e., with a scaling factor. According to the principles of wave propagation through scattering media [24,25], intensity $\mathrm{I_{out}}$ collected by single-pixel bucket detector can be described by $\mathrm{I_{out}} \approx t|\mathrm{E}_n|^2$,where t denotes a scaling factor and E_n ($n = 1, 2, 3,\ldots$) denotes each element of wavefront information. The scaling factors can be considered to be the same in this study, and are obtained in optical experiments. Original signal can be retrieved with high fidelity by using scaling factors and collected light intensities. The proposed method is able to realize high-fidelity optical ghost diffraction and information transmission through scattering media in free space, when a single-pixel bucket detector is used at the receiving end.

3. Experimental results and discussion

An experimental setup in Fig. 4 is conducted to show feasibility and effectiveness of the proposed method. A diode pumped green laser (CrystaLaser, CL532–025-S) with power of 25.0 mW and wavelength of 532.0 nm is expanded with an objective lens. The collimated light source illuminates amplitude-only SLM (Holoeye, LC-R720) with pixel

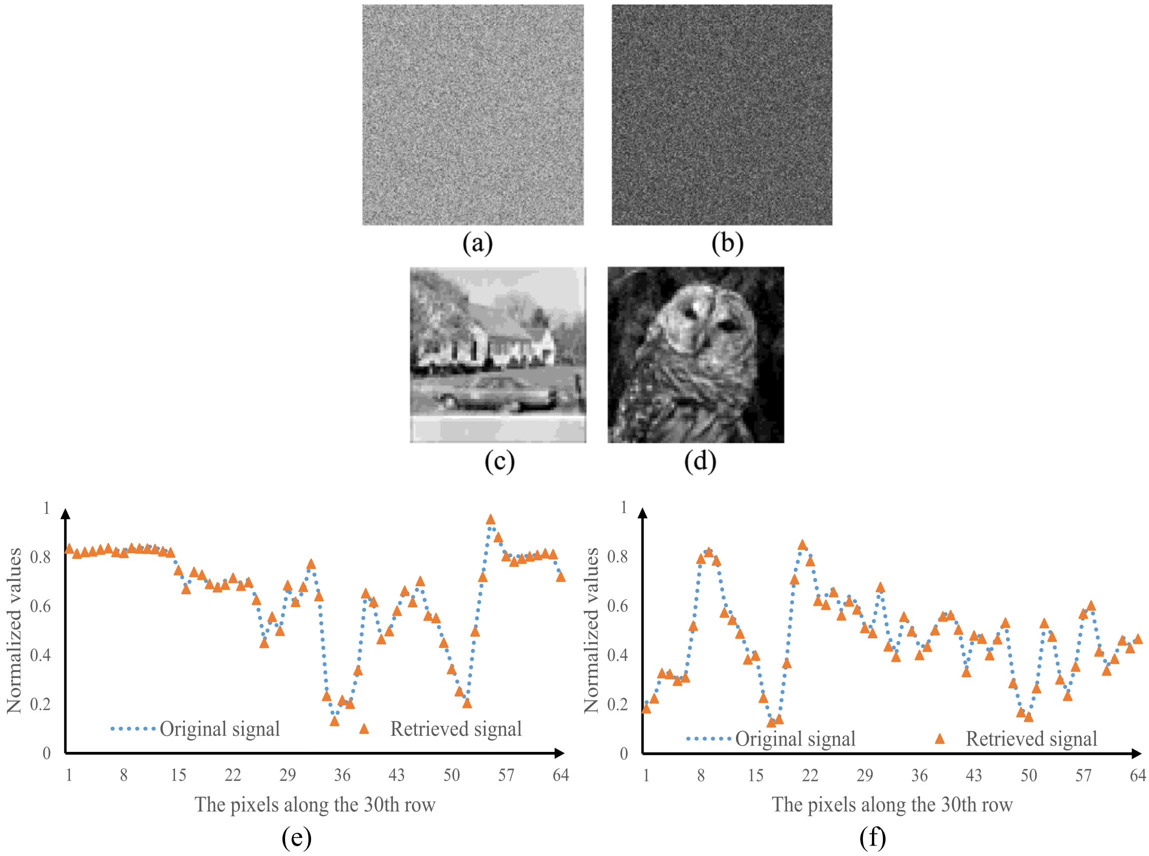

Fig. 7. Experimental results retrieved at the receiving end: (a) and (b) the typically generated 2D arrays of random numbers containing ghost information, (c) and (d) the retrieved ghosts (64 × 64 pixels) using the proposed method, (e) a typical comparison between the 30th row of the retrieved ghost in (c) and those original values, and (f) a typical comparison between the 30th row of the retrieved ghost in (d) and those original values. PSNR values of (c) and (d) are 37.94 dB and 37.26 dB, respectively. MSE values of (c) and (d) are 1.61×10^{-4} and 1.88×10^{-4}, respectively.

size of 20.0 μm. The generated 2D arrays of random numbers with size of 512 × 512 pixels are sequentially embedded into the SLM, and then are illuminated to propagate through scattering media in free space. Here, two cascaded diffusers (Thorlabs, DG10–1500) and one reflective ordinary A4 paper are used as a typical example. After wave propagation, light intensity at the receiving end is collected by using a single-pixel bucket detector (Newport, 918D-UV-OD3R). Axial distance between the two diffusers is 25.0 mm. Axial distance between the SLM and the first diffuser is denoted as d_1 with a default value of 12.5 cm. Axial distance between the second diffuser and the A4 paper is 11.0 cm, and axial distance between the A4 paper and single-pixel bucket detector is denoted as d_2 with a default value of 2.5 cm.

When the series of generated 2D arrays of random numbers is sequentially embedded into the SLM and the modulated wave propagates through scattering media in free space, a series of intensity values are sequentially collected by using the single-pixel bucket detector at the receiving end. Here, four different 1D analog signals are used as the ghosts to be individually encoded and optically transmitted through scattering media in free space to verify the proposed method. The optical experimental results are shown in Fig. 5(a)–(d), where the dotted points represent original signals and triangle points represent the retrieved signals. As can be seen in Fig. 5(a)–(d), the encoded ghosts are retrieved at the receiving end with high fidelity in different transmission environments. Peak signal-to-noise ratio (PSNR) and mean squared error (MSE) [26–32] are calculated to quantitatively evaluate experimental results, given in Fig. 5. The high PSNR values and low MSE values demonstrate that high-fidelity ghost diffraction and optical information transmission through scattering media in free space are experimentally realized by using the proposed method.

To further show the difference between the retrieved signals and original signals in Fig. 5(a)–(d), a box chart is shown in Fig. 6. As shown in Fig. 6, all the normalized errors between the retrieved signals and original signals are within a very small range, meaning that original signals are retrieved with high fidelity.

2D grayscale images are also used as ghosts to be encoded into a series of 2D arrays of random numbers, and optical information transmission through scattering media in free space are conducted using the experimental setup in Fig. 4. Here, two grayscale images with 64 × 64 pixels are selected as original signals (i.e., ghosts). Each grayscale image contains 4096 pixels to be sequentially encoded into 2D arrays of random numbers by using the proposed method, and then these generated 2D arrays of random numbers are sequentially embedded into SLM and are illuminated to propagate through scattering media in free space. Here, two typical 2D arrays of random numbers are shown in Fig. 7(a) and (b). As described in Section 2, each generated 2D array of random numbers is further transformed into two 2D arrays of random numbers (i.e., $\mathrm{B} + \tilde{P}_i$ and $\mathrm{B} - \tilde{P}_i$) with a real and positive constant B to remove negative values. Fig. 7(a) shows a typical image of $\mathrm{B} + \tilde{P}_i$,and Fig. 7(b) shows a typical image of $\mathrm{B} - \tilde{P}_i$. In this experiment, a refreshing rate of the SLM is set as 1.25 Hz as a typical example to illustrate the proposed method, and there are totally 8192 patterns sequentially embedded into the SLM for each 2D grayscale image with 64 × 64 pixels. The time to acquire 2D information by using single-pixel bucket detector is 6553.6 s. A proof-of-principle optical experiment is conducted in this study, and

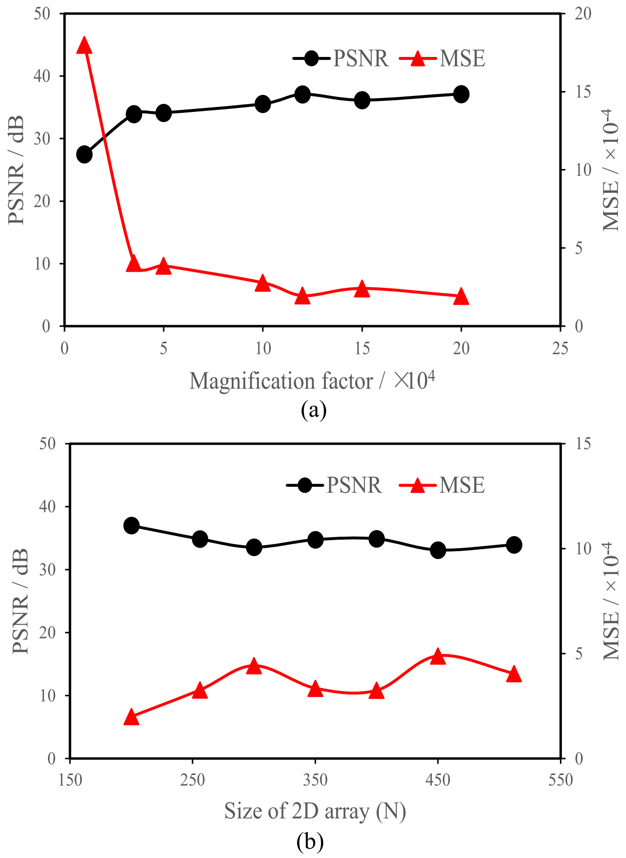

Fig. 8. (a) PSNR and MSE values of the signals retrieved at the receiving end when different magnification factors are used in the proposed method, and (b) PSNR and MSE values of the signals retrieved at the receiving end when 2D arrays with different sizes are used.

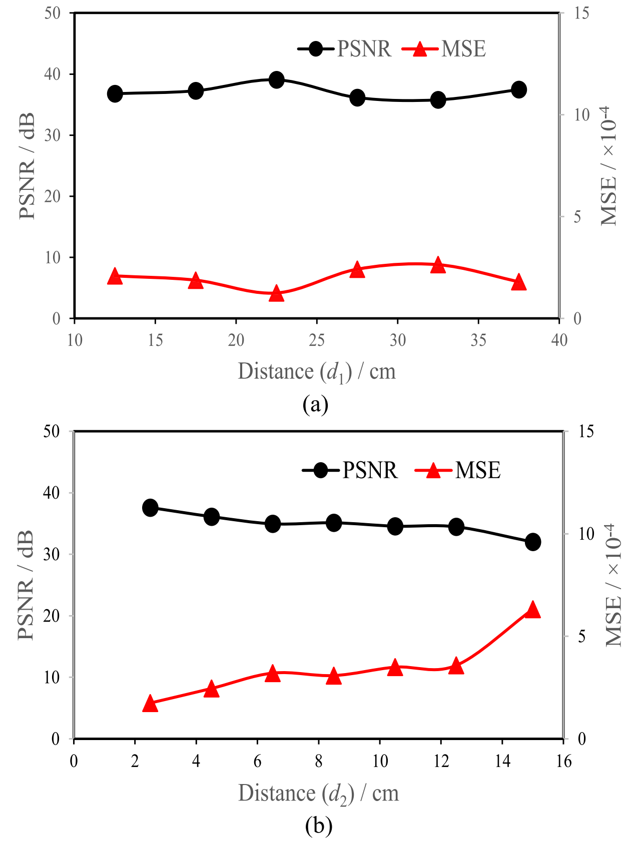

Fig. 9. (a) PSNR and MSE values of the signals retrieved at the receiving end using different propagation distances d_1, and (b) PSNR and MSE values of the signals retrieved at the receiving end using different propagation distances d_2.

the refreshing rate can be further increased by using digital micromirror devices (DMD).

A series of intensity values are correspondingly collected by the single-pixel bucket detector, and these intensity values are further used to retrieve image data. Optical experimental results are shown in Fig. 7(c) and (d) and the PSNR and MSE values are given in Fig. 7, which demonstrates that high-fidelity optical transmission of 2D images can also be realized by using the proposed method when there is a scattering medium in the optical path.

To further illustrate quality of the images (ghosts) retrieved at the receiving end, cross-sectional comparisons between original signals and the retrieved ghosts are conducted and shown in Fig. 7(e) and (f). A typical comparison between the pixels along the 30th row of the retrieved ghost in Fig. 7(c) and those original values is shown in Fig. 7(e). A typical comparison between the pixels along 30th row of the retrieved ghost in Fig. 7(d) and those original values is shown in Fig. 7(f). It is demonstrated again that high-fidelity signals are retrieved at the receiving end. As discussed in Section 2, scaling factor can be calculated to denote the relationship between intensity values collected by a single-pixel bucket detector and original information. 4096 scaling factors can be calculated for each grayscale image in optical experiment. The scaling factors in Fig. 7(c) and (d) are within a small range, i.e., 2.06×10^{-11}~2.24×10^{-11} and 2.00×10^{-11}~2.25×10^{-11}, respectively. This verifies the validity of the proposed method. It is experimentally demonstrated that high-fidelity 2D image (as ghost) transmission through scattering media in free space can be realized by encoding pixel values into a series of 2D arrays of random numbers.

To better evaluate performance of the proposed method with different parameters, two important parameters, i.e., the magnification factor and size of 2D arrays, are further analyzed for a comparison using the experimental setup in Fig. 4.

Different magnification factors are selected to generate 2D arrays of random numbers as information carriers, and these 2D arrays of random numbers are further used for free-space ghost transmission through scattering media. In this case, size of the generated 2D arrays of random numbers is fixed as 512 × 512 pixels. The experimental results using different magnification factors ranging from 1.0×10^4 to 2.0×10^5 are shown in Fig. 8(a). As can be seen in Fig. 8(a), high PSNR values and low MSE values are always obtained when the magnification factor is larger than 3.5×10^4. It is also experimentally found that when the magnification factor is low, influence of environmental and detection noise is large. Experimental results using different sizes (N × N pixels) of the generated 2D arrays of random numbers are shown in Fig. 8(b). The experimental setup in Fig. 4 is applied. In this case, the magnification factor is fixed as 35,000. It is demonstrated in Fig. 8(b) that high PSNR values and low MSE values are always obtained when N is larger than 200. In this study, the laser with a fixed power is used in the experiments, and insufficient light reflected by the SLM would be collected by the single-pixel bucket detector when the size of 2D arrays is small (e.g., 64 × 64 or 128 × 128 pixels). The magnification factor in this experiment should be larger than 3.5×10^4. In terms of the range of size (N × N pixels) of 2D arrays of random numbers, N should be larger than 200.

Different propagation distances are further employed to evaluate the proposed method, and experimental results are shown in Fig. 9(a) and (b). Here, d_1 denotes axial distance between the SLM and the first diffuser, and d_2 denotes axial distance between the A4 paper and single-pixel bucket detector in Fig. 4. In Fig. 9(a), the distance d_2 is fixed as 2.5 cm, and the propagation distance d_1 ranges from 12.5 to 37.5 cm.

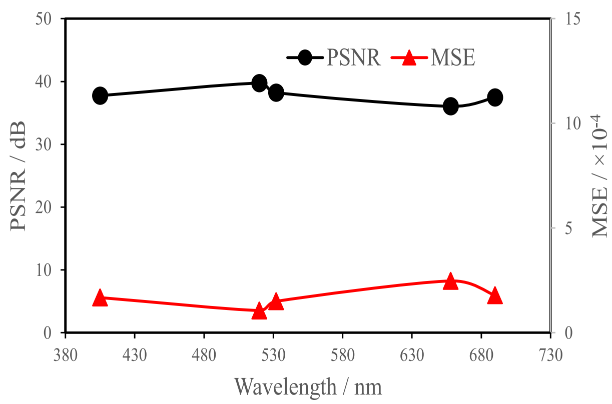

Fig. 10. PSNR and MSE values of signals retrieved at the receiving end when the laser with different wavelengths is used.

It is shown in Fig. 9(a) that high PSNR values and low MSE values are always obtained, and high-fidelity data transmission through scattering media in free space is realized. In Fig. 9(b), the distance d_1 is fixed as 12.5 cm, and the propagation distance d_2 ranges from 2.5 to 15.0 cm. It is also illustrated in Fig. 9(b) that high PSNR values and low MSE values are always obtained, and high-fidelity data transmission through scattering media in free space is realized. When the propagation distance d_2 is approaching to or larger than 15.0 cm, the scattered light intensity collected by single-pixel bucket detector is weaker and quality of the retrieved ghosts decreases as shown in Fig. 9(b). In terms of d_1, the distances of 12.5 cm to 37.5 cm can be used in this experiment, when d_2 is fixed as 2.5 cm. In terms of d_2, the distances smaller than 12.0 cm can be used, when d_1 is fixed as 12.5 cm.

The laser with different wavelengths is also used to conduct the proposed free-space ghost diffraction and optical information transmission through scattering media. Here, the laser with five different wavelengths (i.e., 405.0, 520.0, 532.0, 658.0 and 690.0 nm) is individually used in the experiments. Experimental results of optical diffraction through scattering media using the generated 2D arrays of random numbers are shown in Fig. 10. It can be seen in Fig. 10 that PSNR and MSE values of the retrieved data remain stable, and high-fidelity free-space optical ghost diffraction and information transmission through scattering media are always realized when different wavelengths are used. Therefore, multiple transmission channels are potentially feasible.

In this study, two cascaded diffusers and one A4 paper are utilized as scattering media and reflective media, which provide typically optical experimental results in scattering environment. It is believed that the proposed method can also work well through other scattering media, and in our future study we will further evaluate performance of the proposed method in different scattering environments. Compared with wavefront shaping [3], the proposed method does not require a time-consuming optical alignment and calibration process. Compared with other optical methods that use linear intensity modulation [4] to realize information transmission, the proposed method can realize high-fidelity free-space analog signal transmission and retrieval through scattering media.

4. Conclusion

We have proposed a new method to directly generate a series of 2D arrays of random numbers to encode the ghost (e.g., signals or images) in order to realize high-fidelity free-space optical information transmission through scattering media. Optical experimental results demonstrate that high-fidelity free-space optical information transmission through scattering media is realized. The proposed ghost diffraction could open up an avenue for many applications, e.g., high-fidelity free-space optical information transmission through scattering media.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Yonggui Cao: Data curation, Methodology, Writing – original draft, Validation, Writing – review & editing. **Yin Xiao:** Methodology, Writing – review & editing. **Zilan Pan:** Writing – review & editing. **Lina Zhou:** Writing – review & editing. **Wen Chen:** Conceptualization, Methodology, Writing – review & editing, Supervision, Project administration.

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