Optics and Lasers in Engineering 150 (2022) 106880

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

journal homepage: www.elsevier.com/locate/optlaseng

Analog ghost hidden in 2D random binary patterns for free-space optical data transmission

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A R T I C L E I N F O

Keywords:
Optical transmission in free space
High-fidelity analog-signal retrieval
Scattering media
2D random binary patterns

A B S T R A C T

We propose high-fidelity analog ghost diffraction and transmission through scattering media in free space using a series of 2D randomly-distributed binary patterns. The proposed method utilizes ghost diffraction to enable high-fidelity free-space optical transmission through scattering media. Any type of ghosts, e.g., analog signal, can be encoded into a series of 2D randomly-distributed binary patterns to serve as information carriers. After the generated 2D randomly-distributed binary patterns are sequentially embedded into spatial light modulator and are illuminated to propagate through scattering media in free space, a single-pixel detector is used to collect light intensity at the receiving end and high-fidelity signals can be retrieved without any complex post-processing algorithm. The proposed method possesses high robustness for high-fidelity free-space optical transmission through scattering media, and different wavelengths and different propagation distances can be flexibly used for free-space optical transmission. The method could open up an avenue towards many applications, e.g., free-space optical data transmission and communication.

1. Introduction

Ghost diffraction originates from quantum optics in which entangled photon pairs generated from the process of spontaneous parametric down-conversation are used for correlation imaging [1,2]. Subsequently, ghost diffraction concept is further investigated from theories and experiments to be used in classical domain [3,4]. Ghost diffraction methods usually apply correlation algorithms to extract spatially resolved objects [5,6]. The ghost diffraction has been widely developed over the past decades [7–14], and has been successfully applied in many areas, e.g., three-dimensional ghost imaging [15], electron ghost imaging [16], ghost diffraction with atoms [17] and ghost cytometry [18].

In ghost diffraction, it is always necessary to use a number of 2D patterns [7–14] to enhance quality of the retrieved ghost, and noise existing in the retrieved ghost could not be fully suppressed. It is still a great challenge to utilize 2D random patterns to realize high-fidelity ghost retrieval [7–14]. In addition, it is more feasible to apply 2D binary patterns for data storage and wave propagation when spatial light modulator (SLM) or digital micro-mirror device is employed. However, when 2D random binary patterns are used, quality of the retrieved ghost is usually degraded. It has been well recognized that it is highly desirable to explore an effective strategy to enable high-quality ghost retrieval using 2D random binary patterns. Furthermore, ghost diffraction concept using 2D random binary patterns has not been investigated for free-space optical data transmission, since it is difficult to design 2D randomly-distributed binary patterns as information carriers. It is significant and meaningful to further study ghost diffraction through scattering media using 2D random binary patterns in order to realize high-fidelity and high-robustness free-space optical data transmission.

In this paper, we propose high-fidelity free-space analog ghost diffraction and transmission through scattering media using a series of 2D randomly-distributed binary patterns. Different from conventional ghost diffraction methods which are used for imaging the objects, the proposed method utilizes ghost diffraction to enable high-fidelity analog-signal transmission through scattering media in free space. The proposed method can encode any type of ghosts (e.g., analog signal) into a series of 2D randomly-distributed binary patterns to serve as information carriers. The 2D randomly-distributed binary patterns generated by using the proposed method are sequentially embedded into a SLM and are illuminated to propagate through scattering media in free space. A single-pixel detector is used to collect light intensity at the receiving end, and high-fidelity signals can be retrieved without any complex post-processing algorithm. The proposed method possesses high robustness for high-fidelity optical data transmission through scattering media in free space, and different wavelengths and different propagation distances can be flexibly used for free-space optical data transmission. The method could open up an avenue towards many applications, e.g., free-space optical data transmission and communication.

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https://doi.org/10.1016/j.optlaseng.2021.106880
Received 7 August 2021; Received in revised form 6 October 2021; Accepted 8 November 2021
Available online 20 November 2021

2. Principle

The proposed method treats a ghost (e.g., analog signal to be transmitted) as independent pixel values which are sequentially encoded into a series of 2D randomly-distributed binary patterns. The analog signal can be sampled into discrete values, and the sampled values are further encoded into 2D randomly-distributed binary patterns. The proposed generation procedure of 2D randomly-distributed binary patterns is as follows: (i) generate an initialized 2D random pattern R with real values; (ii) apply Fourier transform to the pattern R and get its Fourier spectrum FS; (iii) replace zero-frequency component of Fourier spectrum FS by a pixel value of data information to get an updated Fourier spectrum FS'; (iv) apply inverse Fourier transform to Fourier spectrum FS' to generate an updated 2D random pattern R'; (v) apply a binarization operation to the updated 2D random pattern R' to generate a 2D randomly-distributed binary pattern H. The above steps (i)-(v) are repeated for all pixel values of data information to be transmitted.

The Fourier transform can be expressed by

$$FS(\xi,\eta)=\int\int R(x,y)e^{-2\pi j(x\xi+y\eta)}dxdy, \tag{1}$$

where $j=\sqrt{-1}$, (x,y) denotes the coordinate in spatial domain, and (ξ,η) denotes the coordinate in Fourier domain. In Eq. (1), the Fourier spectrum FS can be divided into two parts, i.e., zero-frequency component z and all other Fourier spectrum coefficients.

When the zero-frequency component in Fourier spectrum FS is replaced by a pixel value of data information to be transmitted, the new Fourier spectrum FS' can be expressed as

$$FS'(\xi,\eta)=z'\odot\delta(\xi,\eta)+FS(\xi,\eta)\odot[1-\delta(\xi,\eta)], \tag{2}$$

where z' denotes a pixel value of data information to be transmitted, $\odot$ denotes element-wise product, and $\delta(\xi,\eta)$ denotes an impulse function with the central entry being one and other entries being zero. When inverse Fourier transform is further applied to Eq. (2), an updated 2D random pattern $R'(x,y)$ can be described by

$$R'(x,y)=\frac{z'-z}{MN}T(x,y)+R(x,y), \tag{3}$$

where M and N denote dimensional sizes, and T(x,y) denotes a 2D matrix with all elements of 1.

A relationship between the generated pattern and the data can be described by

$$z'=\int\int R'(x,y)e^{-2\pi j(x\xi+y\eta)}dxdy\Big|_{\xi=0,\eta=0}. \tag{4}$$

The single-pixel detection process can be described based on Eq. (4), which enables the proposed method to realize signal retrieval in scattering environment.

The generated 2D random amplitude-only pattern R'(x, y) is further binarized in order to enhance system speed, when the SLM or digital micro-mirror device is used. Here, when the elements in R'(x,y) are larger than 0, they are set as 1. Otherwise, the elements are set as −1. A binary pattern BR'(x, y) is correspondingly generated which contains only −1 and 1, and the sum of all elements in BR'(x, y) is denoted as α. The value α is not equivalent to the encoded pixel value z' of data information. The difference, e.g., α-z', can be directly used to further adjust some elements in BR'(x,y), and several elements with values of 1 or −1 in BR'(x, y) can be arbitrarily selected to be respectively set as −1 or 1 in order to generate a 2D randomly-distributed binary pattern H(x,y). To facilitate the usage of optical device (i.e., the SLM), H(x,y) is divided into two different patterns, i.e., H_1 and H_2, which contain elements of 0 and 1. The procedure for generating random amplitude-only patterns and binary patterns is shown in Figs. 1(a) and (b).

It is worth noting that the proposed method maps a single value into a 2D randomly-distributed binary pattern to realize arbitrary amplitude modulation of light source. This process is different from conventional communication procedures in which the desired value is first quantified as a series of 1D binary values (i.e., 0 and 1) and then these 1D binary values are sent to the receiving end successively to realize signal transmission. Compared with the method using a series of 1D binary values, the proposed method can effectively enhance the channel capacity since analog data can be transmitted directly in free space without quantization process. In addition, compared with conventional 1D amplitude modulation method by using arbitrary waveform generator, the proposed method can reduce the cost dramatically without expensive waveform generation device to realize signal transmission in practice. Furthermore, compared with commonly-used encoding techniques, the proposed method shows obvious advantage in the reduction of algorithm complexity.

Light scattering [19–22] is a major obstacle for information delivery in free space, and could lead to information loss. After propagating through scattering media, the waveform is scrambled into disordered interference patterns [23,24]. Therefore, it is difficult to realize high-fidelity and high-robustness optical data transmission in free space through scattering media. In this study, optical experiments in a scattering environment are conducted by using the proposed method to realize high-fidelity free-space data transmission.

3. Experimental results and discussion

A schematic experimental setup is shown in Fig. 2 to demonstrate feasibility and effectiveness of the proposed method. He-Ne laser with power of 17.0 mW and wavelength of 633.0 nm is expanded by using an objective lens and collimated by a lens with a focal length of 100.0 mm. The collimated light source illuminates the SLM (Holoeye, LC-R720) with pixel size of 20 μm, and 256 × 256 random binary patterns $H_1(x, y)$ and $H_2(x, y)$ generated by using the proposed method are sequentially embedded and are illuminated to propagate through scattering media. Here, three diffusers (Thorlabs, DG10–1500) are cascaded as a typical example. The axial distance between the first diffuser and the second diffuser is 25.0 mm, and the axial distance between the second diffuser and the third diffuser is 10.0 mm. The axial distance between the SLM and the first diffuser is 100.0 mm, and the axial distance between the third diffuser and single-pixel detector is 35.0 mm. A single-pixel (bucket) detector (Newport, 918D-UV-OD3R) is used to collect the light intensity at the receiving end.

In the proposed method, after wave propagation through scattering media, intensity I_{out} at the detection plane can be described by

$$I_{out}\approx k|E_n|^2, \tag{5}$$

where k denotes a scaling factor, and E_n (n = 1,2,3…) denotes each element of wavefront information. It is found that the proposed method is able to realize high-fidelity ghost diffraction and transmission through scattering media in free space, when a single-pixel (bucket) detector is used at the receiving end.

When the series of generated 2D randomly-distributed binary patterns is sequentially embedded into the SLM and is illuminated to propagate through scattering media in free space, a series of intensity points can be recorded by the single-pixel (bucket) detector at the receiving end. Then, two successive intensity values, e.g., B_1 and B_2, are used to retrieve one pixel value of the transmitted signal, i.e., B_1-B_2. The intensity values B_1 and B_2 can be expressed by

$$B_1=k\int\int H_1(x,y)e^{-2\pi j(x\xi+y\eta)}dxdy\Big|_{\xi=0,\eta=0}, \tag{6}$$

$$B_2=k\int\int H_2(x,y)e^{-2\pi j(x\xi+y\eta)}dxdy\Big|_{\xi=0,\eta=0}. \tag{7}$$

Then, the following expression can be further obtained.

$$B_1-B_2=k\int\int\left[H_1(x,y)-H_2(x,y)\right]e^{-2\pi j(x\xi+y\eta)}dxdy\Big|_{\xi=0,\eta=0}=kz'. \tag{8}$$

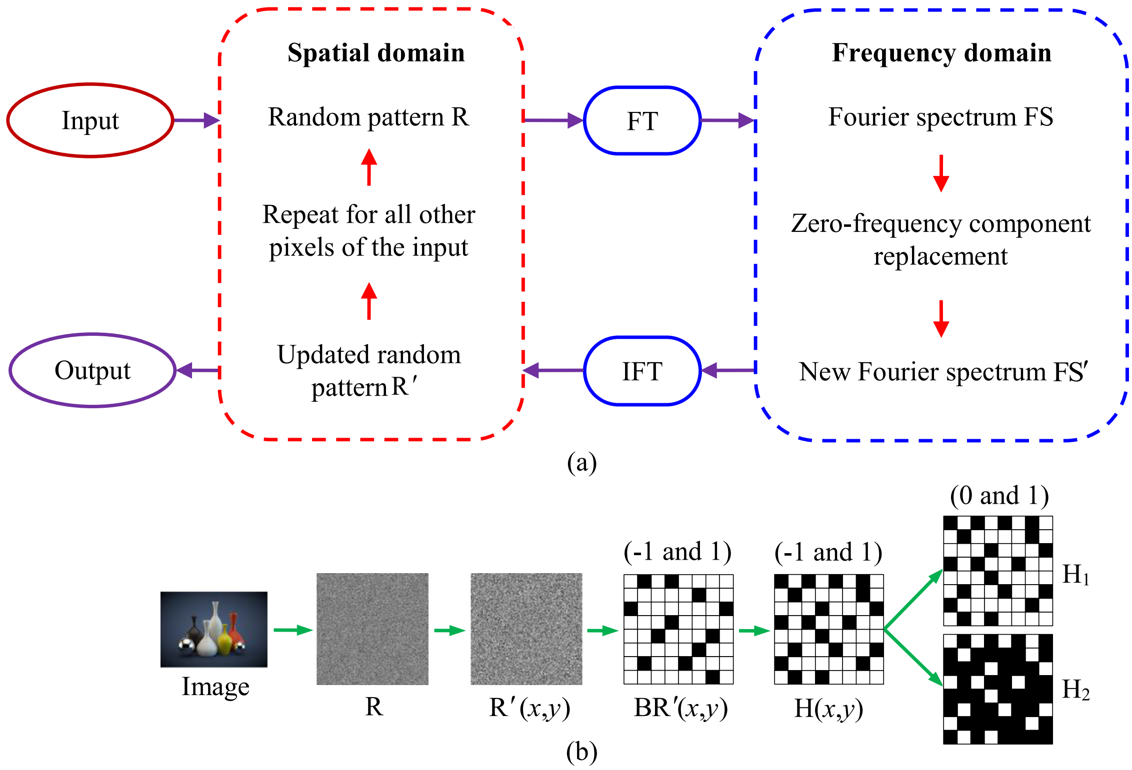

Fig. 1. (a) A flowchart for generating an updated random amplitude-only pattern and (b) a schematic process for generating binary patterns H_1 and H_2. In (a), FT denotes Fourier transform, and IFT denotes inverse Fourier transform.

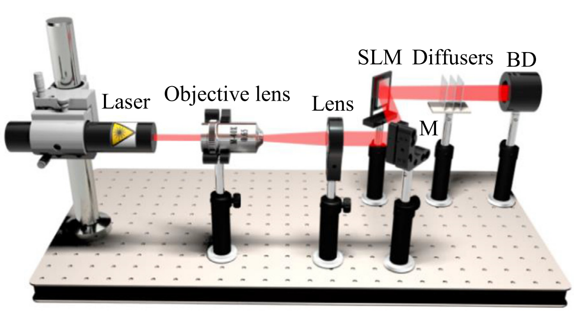

Fig. 2. A schematic experimental setup for the proposed free-space analog-signal transmission through scattering media (i.e., three cascaded diffusers as a typical example); M: Mirror; BD: Single-pixel (bucket) detector.

In Eq. (8), the retrieved value is proportional to the encoded pixel value, and then a normalization operation can be further applied in practice.

Two typically experimental results are shown in Figs. 3(a) and (b). Two different 1D analog signals are used here and encoded as typical examples to show the proposed method for free-space optical transmission through scattering media. As can be seen in Figs. 3(a) and (b), ghost encoded into 2D random binary patterns has been fully realized, and high-fidelity data transmission through scattering media has been achieved. Peak signal-to-noise ratio (PSNR) and mean squared error (MSE) are calculated to quantitatively evaluate the experimentally retrieved signals. The PSNR values for Figs. 3(a) and (b) are 37.18 dB and 34.65 dB, respectively. The MSE values for Figs. 3(a) and (b) are 1.91×10^{-4} and 3.43×10^{-4}, respectively. The high PSNR values and low MSE values demonstrate that high-fidelity transmission through scattering media in free space has been realized by using the proposed method with a series of 2D randomly-distributed binary patterns.

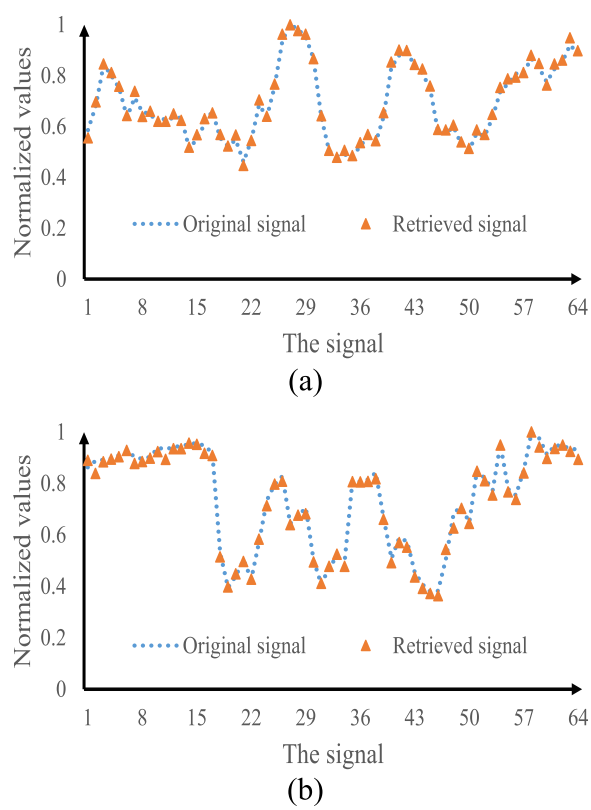

Fig. 3. (a) and (b) Comparisons between analog signals experimentally retrieved at the receiving end and original signals (i.e., ghosts).

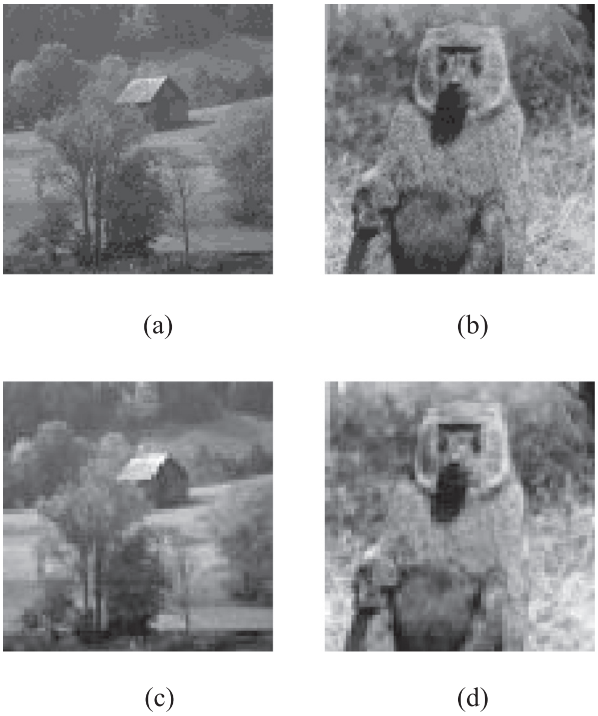

Fig. 4. (a) and (b) Original images (64 × 64 pixels), (c) and (d) two experimentally retrieved images (64 × 64 pixels) obtained at the receiving end using the proposed method. The PSNR values for (c) and (d) are 40.94 dB and 37.01 dB, respectively. The MSE values for (c) and (d) are 8.06×10^{-5} and 2.00×10^{-4}, respectively.

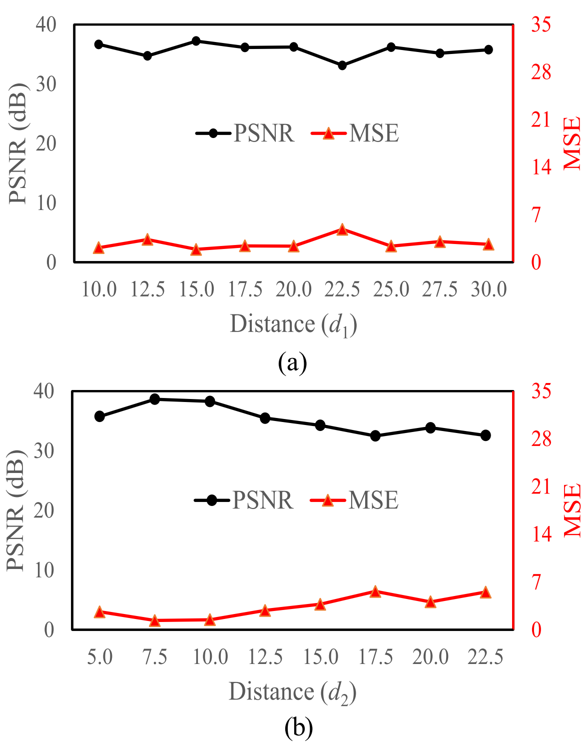

Fig. 5. (a) PSNR values and MSE values (magnitude of the coefficients: 10^{-4}) of the signals retrieved at the receiving end when different propagation distances d_1 (unit: cm) are used, and (b) PSNR values and MSE values (magnitude of the coefficients: 10^{-4}) of the signals retrieved at the receiving end when different propagation distances d_2 (unit: cm) are used.

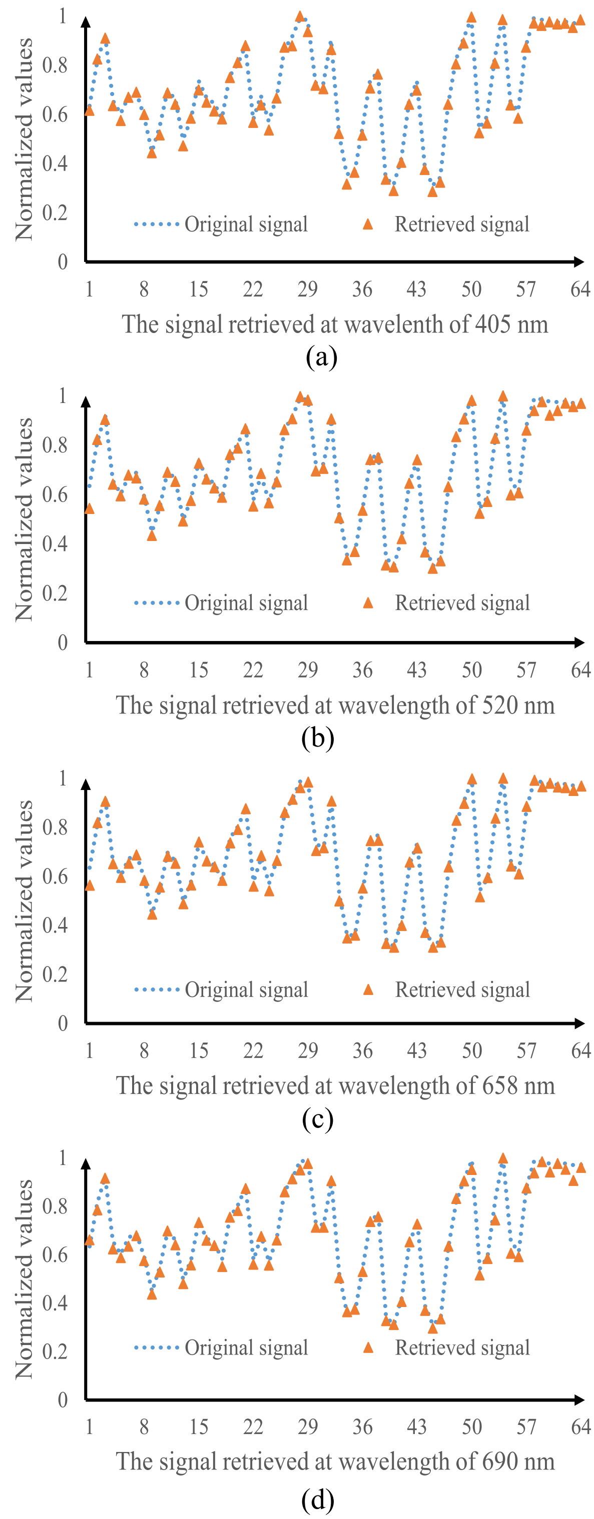

Fig. 6. (a)-(d) Comparisons between the experimentally retrieved analog signals and original signals (i.e., ghosts) when the light source with different wavelengths (i.e., 405.0 nm, 520.0 nm, 658.0 nm and 690.0 nm) is respectively used. PSNR values for the retrieved analog ghosts in (a)-(d) are 33.71 dB, 33.60 dB, 36.06 dB and 32.82 dB, respectively. MSE values for the retrieved analog signals in (a)-(d) are 4.25×10^{-4}, 4.36×10^{-4}, 2.48×10^{-4} and 5.22×10^{-4}, respectively.

To further illustrate the proposed high-fidelity free-space ghost diffraction and transmission, 2D images are used as ghosts to be encoded in 2D random binary patterns which are transmitted through scattering media in free space. Here, two grayscale images with 64 × 64 pixels in Figs. 4(a) and (b) are encoded and transmitted through three cascaded diffusers in free space. The grayscale images are first encoded into a series of 2D randomly-distributed binary patterns, and then the generated 2D randomly-distributed binary patterns serve as information carriers. When the series of 2D randomly-distributed binary patterns is sequentially embedded into the SLM and is illuminated to propagate through scattering media in free space as shown in Fig. 2, a series of intensity points are recorded by the single-pixel (bucket) detector and the experimentally retrieved images obtained at the receiving end are shown in Figs. 4(c) and (d). The PSNR values and MSE values for the retrieved data are calculated and given in Fig. 4. The experimental results in Figs. 4(c) and (d) demonstrate that high-fidelity optical transmission is also realized by using the proposed method, when 2D analog signals are encoded in 2D random binary patterns to be transmitted through scattering media in free space.

Since only pure Fourier transform is used for data encoding in the proposed method, different wavelengths and different propagation distances can be flexibly used for free-space optical transmission through scattering media. Here, different propagation distances are further used for free-space transmission to illustrate performance of the proposed method. The experimental results are shown in Figs. 5(a) and (b). d_1 denotes the axial distance between the SLM and the first diffuser, and d_2 denotes the axial distance between the third diffuser and single-pixel detector. In Fig. 5(a), the propagation distance d_2 is fixed as 5.0 cm, and the propagation distance d_1 is from 10.0 cm to 30.0 cm. In Fig. 5(b), the propagation distance d_1 is fixed as 30.0 cm, and the propagation distance d_2 is from 5.0 cm to 22.5 cm. It is demonstrated in Figs. 5(a) and (b) that the PSNR and MSE values are stable, and different propagation distances can be flexibly used for the developed high-fidelity optical transmission through scattering media in free space.

The light source with different wavelengths is also used for free-space optical transmission through scattering media to analyze performance of the proposed method. The experimentally retrieved signals obtained at the receiving end are shown in Figs. 6(a)–(d). The wavelengths used in Figs. 6(a)–(d) are 405.0 nm, 520.0 nm, 658.0 nm and 690.0 nm, respectively. The PSNR values and MSE values for the retrieved signals are calculated and given in Fig. 6. It is demonstrated in Figs. 6(a)–(d) that the light source with different wavelengths can be flexibly used for the developed high-fidelity analog ghost diffraction and transmission through scattering media in free space, which can provide a potential for data transmission with multiple-wavelength channels.

4. Conclusion

We have proposed high-fidelity free-space analog ghost diffraction and transmission through scattering media using a series of 2D randomly-distributed binary patterns. It is experimentally demonstrated that the proposed method is able to realize high-fidelity optical transmission through scattering media using a series of 2D randomly-distributed binary patterns with single-pixel detection. The proposed method possesses high robustness for high-fidelity free-space data transmission through scattering media, and different wavelengths and different propagation distances can be flexibly used for free-space optical transmission. The proposed method overcomes significant challenges existing in ghost diffraction and transmission, and an avenue towards many applications could be opened up.

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

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

Acknowledgments

This work was supported by Hong Kong Research Grants Council under Grant C5011-19G and The Hong Kong Polytechnic University under Grants 1-W167 and 1-W19E.

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