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High-Fidelity Optical Transmission around the Corner

Yin Xiao and Wen Chen

Abstract—**It is a great challenge to use visible and coherent light source to realize high-fidelity optical transmission in free space around the corner where blockade, reflection and scattering occur, and quality of the information retrieved at the receiving end is significantly affected. In this Letter, we propose a novel method to solve the problems encountered in data transmission in free space around the corner when visible and coherent light source is applied. The proposed method is highly robust to coherent light diffraction, multiple scattering effect and environmental noise, which can make it promising for practical applications. A number of optical experiments have been conducted to successfully transmit different types of signals (e.g., analog) in free space around the corner to achieve high fidelity. The proposed method could lead to a development in many relevant applications, e.g., optical transmission in free space, information propagation in free space, telecommunication, and optical security.**

Index Terms—**Optical transmission in free space, Transmission around the corner, High-fidelity analog-signal retrieval, Scattering media, Analog-signal transmission in free space.**

I. INTRODUCTION

DATA transmission plays an important role in modern society, especially in the field of communication [1]. Optical wave serving as information carrier is one important means for transmitting signals [2]–[6]. Different from wave propagation in optical fiber, optical wave propagating in free space is usually encountered by some media that scatter and absorb the propagating wave, therefore it is difficult to give an exact description about the propagation of light through scattering media [7]–[10]. Light scattering is a major obstacle for information delivery in free space, and leads to an irretrievable loss of information. After propagating through strongly scattering media, the desired waveform is scrambled into disordered interference patterns [11]. In this case, statistical optics and transport theory are developed for exacting information from the noise-like patterns [12], [13]. However, these methods are hardly to retrieve original data in a high-fidelity way even using complex mathematical tools. Recently, wavefront shaping methods have also been proposed to control wave modes in free space [14]–[16]. However, they are still inadequate for practical applications due to the need of speckle corrections or optimization procedures. Therefore, it is significant and meaningful to explore new methods which are able to deliver the desired data through scattering media in a high-fidelity way without complex operation procedures. Till now, no studies have been focused on optical transmission using random amplitude patterns to achieve high-fidelity transmission in free space. Although random patterns are easily generated in practice [17], [18], they are rarely considered as a candidate of optical information carriers due to a severe lack of controllability. In addition, in the optical realm, visible lights with a large spectrum range are seldom used for information propagation in free space due to their short wavelengths, and coherent lights used for the long transmission distance always accompany inevitable speckle noise. Hence, it is a great challenge to use visible and coherent light source to realize high-fidelity optical transmission in free space around the corner where blockade, reflection and scattering occur, and quality of the information retrieved at the receiving end is significantly affected.

In this Letter, we report for the first time a novel method to realize high-fidelity optical transmission in free space around the corner by using a visible and coherent light source. In the proposed method, a signal, e.g., analog, is considered as a series of independent pixel values, and each pixel is converted into a two-dimension (2D) random amplitude-only pattern. Then a series of 2D random amplitude-only patterns corresponding to the signal are generated. Subsequently, the generated amplitude-only patterns are embedded into a spatial light modulator (SLM) and are successively illuminated to propagate in free space to serve as optical information carriers. The generated amplitude-only patterns are illuminated and then propagate in free space, suffering from scattering and reflection around the corner. The propagating wave is even blocked partly when it propagates around the corner. At the receiving end, light intensity is collected by a single-pixel detector. The potential benefits of applying single-pixel detector include its low cost and high capability under the conditions of non-visible wavelength band (e.g., X-ray [19], [20] and Terahertz light [21], [22]) and different environments. After light intensities are recorded, high-fidelity transmission is achieved without the use of post-processing algorithms. The proposed method is highly robust to coherent light diffraction, multiple scattering effect and environmental noise, which can make it promising for

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practical applications. In particular, it is important to note that there are two extraordinary features of the proposed method. The first one is that when the patterns (i.e., information carrier) are blocked partly by opaque medium (e.g., walls) and simultaneously reflected by scattering media, the intensity data collected at the receiving end is still effective for retrieving the high-fidelity signals. The second one is that under a condition where the generated amplitude-only patterns are illuminated and then propagate through a diffuser before reaching the corner, high-fidelity optical transmission is still achieved by using the proposed method. The 1D irregular analog signals are tested and transmitted in optical experiments to demonstrate feasibility and effectiveness of the proposed method. The proposed principle and experimental demonstration offer an opportunity for the studies of optical transmission in free space around the corner, and provide a powerfully optical means for high-fidelity transmission in different wave propagation environments, e.g., free space and strongly scattering environment. The proposed method could lead to a further development on optical transmission in free space, information propagation in free space, telecommunication, and optical security.

II. PRINCIPLE

A schematic optical experimental setup for the proposed method is illustrated in Fig. 1, where the generated amplitude-only patterns are sequentially illuminated and then propagate in free space towards the corner. The wave scattered and reflected around the corner is correspondingly collected by a single-pixel detector.

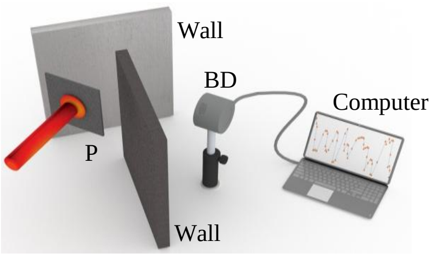


Fig. 1. Schematic optical experimental setup for the proposed high-fidelity optical transmission in free space around the corner: BD, single-pixel bucket detector; P, the generated pattern.

For a two-dimensional matrix, after Fourier transform (FT), its energy concentrates on the central point of Fourier spectrum, i.e., zero-frequency component. Inverse Fourier transform (IFT) can disperse this energy (i.e., pixel at the central point) to be a two-dimensional matrix in spatial domain. As a result, when zero-frequency component is replaced by the desired pixel information, IFT operation can encode this pixel information to be a two-dimensional amplitude-only pattern. The random amplitude-only patterns (i.e., optical information carriers) can be generated according to the following procedure: (i) an initialized random amplitude pattern *AP*; (ii) carry out FT(*AP*) to generate spectrum *T*; (iii) zero frequency of Fourier spectrum *T* is replaced by one pixel of the signal to generate a new spectrum *TT*; (iv) finally carry out IFT(*TT*) to get an updated amplitude-only pattern *P* as optical information carrier. After the aforementioned procedure is applied to the whole signal, a series of 2D random amplitude-only patterns corresponding to the signal are obtained. In single-pixel detection process, the pattern *P* can be described by

$$\begin{aligned} B &= \iint P(x,y)\, e^{-2\pi j(x\xi+y\eta)}\,\mathrm{dxdy}\Big|_{\xi=0,\eta=0} \\ &= \iint P(x,y)\,\mathrm{dxdy} \end{aligned}, \qquad (1)$$

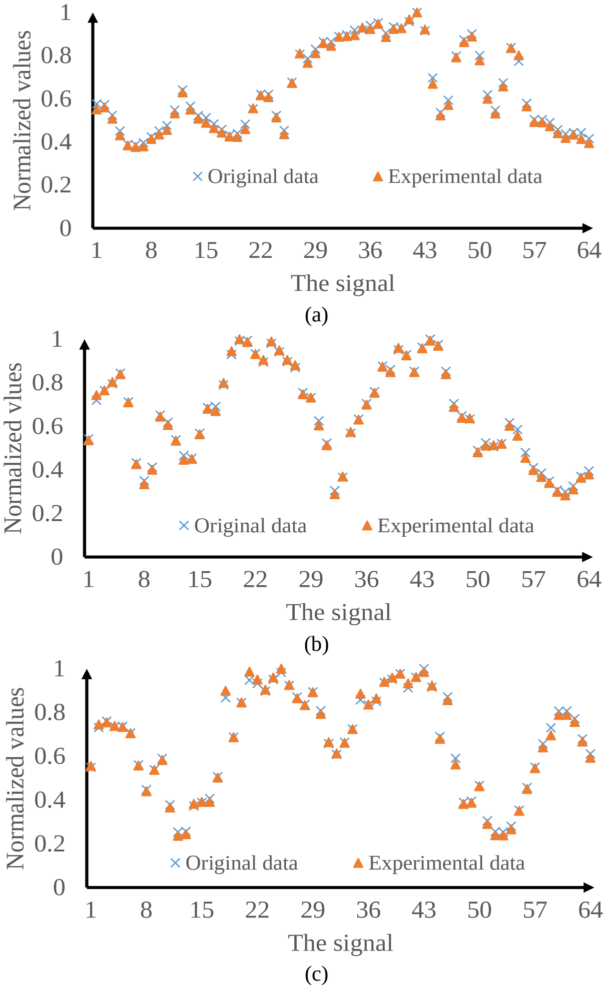
where $P(x,y)$ denotes the generated pattern, $j=\sqrt{-1}$, (x,y) and (ξ,η) denote the coordinates respectively in spatial and frequency domains, and B denotes zero-frequency component. When optical transmission around the corner is studied, Eq. (1) corresponds to a single-pixel detection process. It is found that when wave propagation around the corner is considered, the generated random amplitude-only patterns *P* serving as optical information carriers possess ultra-high robustness against scattering, reflection and blockade. In the proposed method, size of the generated patterns *P* can be flexibly adjusted in practice, when the devices like the SLM are used for optical transmission.

According to the proposed principles, after the signal is encoded into a series of 2D random amplitude-only patterns, the most straightforward way for transmitting the signal is to sequentially illuminate these patterns embedded in the SLM. However, two practical factors need to be considered and further addressed, i.e., negative values existing in the generated patterns and the noise arising from environment and detection. Since negative values are impossible to be displayed directly by the SLM in practice, for each generated amplitude-only pattern *P* we separate it into two different patterns, i.e., $a+P$ and $a–P$, where a is a constant. This strategy can make the generated patterns particularly suitable to be used for transmitting the signals in an optical way and can simultaneously offer a significant advantage of suppressing the effect of environment and detection noise. For patterns $a+P$ and $a–P$, two corresponding intensity values (i.e., B_1 and B_2) can be respectively collected at the receiving end by using a single-pixel detector. These two intensity values can be applied for directly retrieving a pixel value of the analog signal, i.e., $B_1–B_2$.

III. EXPERIMENTAL RESULTS AND DISCUSSION

A number of optical experiments have been carried out to demonstrate feasibility and effectiveness of the proposed method. In the optical experimental setup schematically shown in Fig. 1, a laser beam with wavelength of 633.0 nm is expanded by a pinhole and collimated by a lens with focal length of 100.0 mm. In practice, various light sources can be applicable. The collimated light illuminates a SLM (Holoeye, LC-R720) with pixel size of 20.0 μm which sequentially displays the series of the generated amplitude-only patterns. The refresh rate of SLM is set as 1.25 Hz as a proof-of-principle experiment in this study. A single-pixel detector (Newport, 918D-UVOD3R) is used to collect the propagating wave scattered and reflected around the corner.

First of all, three different 1D irregular analog signals, i.e., any value within a range from 0 to 255, are transmitted by using the proposed method. In this case, the generated random amplitude-only patterns have the size of 512×512 pixels and have a side length of 12.0 mm around the corner. The axial distance between the SLM and the corner is 25.0 cm, and the corner separation size is 13.0 mm. Figures 2(a)–2(c) show three different signals with 64 pixels retrieved at the receiving end. As seen in Figs. 2(a)–2(c), the experimental data nearly overlap with original analog data, and these analog signals are successfully transmitted in a high-fidelity way even after the propagating waves suffer from scattering and reflection around the corner. For the comparisons, original analog data and experimental data have been normalized to be within a range from 0 to 1. To quantitatively evaluate quality of the data retrieved at the receiving end, peak signal-to-noise ratio (PSNR) and mean squared error (MSE) values are calculated, and the high PSNR values and low MSE values for the retrieved data shown in Figs. 2(a)–2(c) demonstrate that high-fidelity optical transmission around the corner is observed and realized.

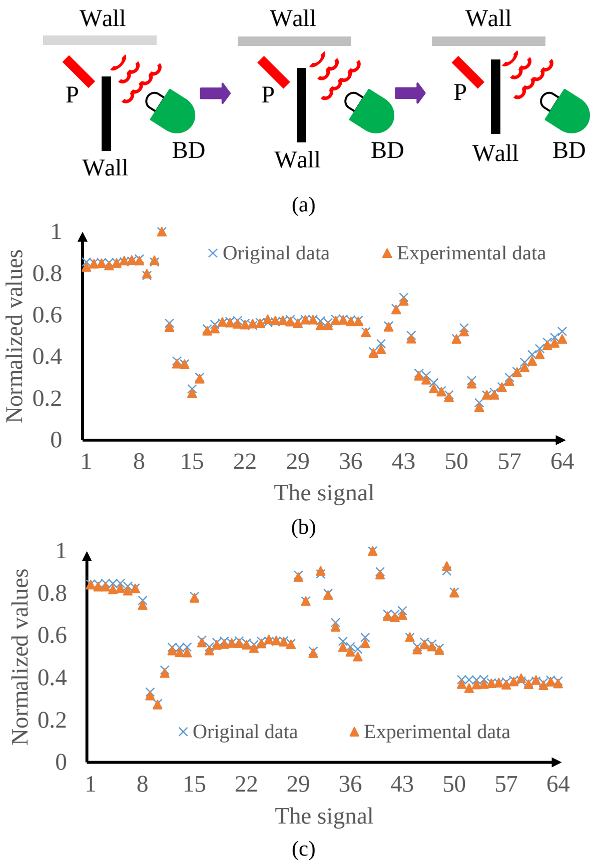


(a)

(b)

(c)

Fig. 2. (a)–(c) Comparisons between original analog data and experimental data retrieved at the receiving end when different 1D irregular analog signals are transmitted. PSNR values of the retrieved data shown in (a)–(c) are 36.11 dB, 38.93 dB, and 37.39 dB, respectively. MSE values of the retrieved data shown in (a)–(c) are 2.45×10^{-4}, 1.28×10^{-4}, and 1.82×10^{-4}, respectively.



(a)

(b)

(c)

Fig. 3. (a) The gradual change of corner separation size, (b) a comparison between original analog data and the experimentally retrieved data when corner separation size is 10.0 mm, and (c) a comparison between original analog data and the experimentally retrieved data when the corner separation size is 6.0 mm.

It is necessary to further explore the effect when the propagating waves are partly blocked by the walls as shown in Fig. 3(a). It is a common sense that the blockade of information carrier can lead to an inevitable information loss. Here, it is observed that there is an obvious superiority in the proposed method for information propagation in free space around the corner. In optical experiments, the pattern is of 512×512 pixels and has a side length of about 12.0 mm around the corner. When the corner separation size is big (e.g., 13.0 mm), the optical wave can fully propagate around the corner and suffers from scattering and reflection. As the corner separation size decreases, the propagating wave is blocked gradually, as shown in Fig. 3(a). When different corner separation sizes are applied, it is also observed that the proposed method can show high robustness against the blockade. To clearly illustrate this point, the typical results for 1D analog signals transmitted around the corner with different corner separation sizes are respectively shown in Figs. 3(b) and 3(c), when the corner separation size is 10.0 mm and 6.0 mm, respectively. The PSNR values of the retrieved data shown in Figs. 3(b) and 3(c) are 36.88 dB and 36.07 dB, respectively. The MSE values of the retrieved data shown in Figs. 3(b) and 3(c) are 2.05×10^{-4} and 2.47×10^{-4}, respectively. As shown in Figs. 3(b) and 3(c), although the propagating waves are blocked partly, information delivery is not blocked in this case since it is still successful to retrieve the data in a high-fidelity way. Ultra-high robustness against the blockade in complex environment has been achieved in the proposed method. Here, the principle is described as follows: When each pixel value is encoded to be a two-dimensional pattern, each point on the pattern serves as a light source after the illumination according to Huygens-Fresnel principle. As a result, at wave propagation path, each point in free space could contain information of the encoded pixel.

Feasibility and effectiveness of the proposed method are further verified when the propagating waves are scattered by a diffuser before reaching the corner. A schematic optical experimental setup is shown in Fig. 4(a), where the propagating wave is first disturbed by a diffuser (Thorlabs, DG10-1500) and then the scattered wave propagates towards the corner. A typical experimental result is shown in Fig. 4(b), which demonstrates that high-fidelity transmission is also achieved. The PSNR value and MSE value are 36.32 dB and 2.33×10^{-4}, respectively. This is the other remarkable feature of the proposed method. Optical experiments through thick scattering media (e.g., three cascaded diffusers) in free space and through normal diffuse reflections have also been conducted, and it is found in our experimental results that high-fidelity data transmission can always be realized.

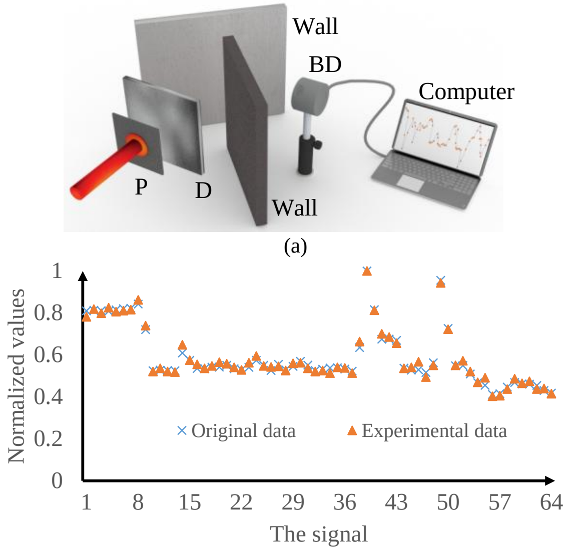


Fig. 4. (a) A schematic optical experimental setup for the proposed high-fidelity optical transmission in free space when a diffuser is also placed (D: diffuser), and (b) a typical experimental result for 1D irregular analog signal transmission.

IV. CONCLUSION

We have realized the high-fidelity optical transmission around the corner. Optical experiments illustrate that various types of signals, e.g., analog signals, can be transmitted in free space around the corner in a high-fidelity way by using the proposed method. It is demonstrated that the generated random amplitude-only patterns can effectively serve as optical information carriers, and the proposed method is effective and possesses ultra-high robustness against scattering, reflection and blockade. The proposed method could open up a new avenue towards optical transmission in free space, information propagation in free space, telecommunication, and optical security. Although proof-of-concept experiments are conducted with a short distance here, the proposed method can be tested by using different transmission distances in the future work.

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