Spectral-to-spatial mapping for channel-definable information transmission in multimode fiber

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Abstract: The concept of spectral coding to control light is proposed for arbitrary spatial focusing through multimode fiber, where, utilizing the randomness of speckle pattern, transmission channel is established for encrypting information.

1. Introduction

Scattering is a common optical phenomenon, which declines the performance of optical systems and even disturbs the propagation process of light severely. However, the added characteristics of scattering, can also bring improvement to optical systems, such as optical super-resolution imaging [1]. Among the scattering media, multimode optical fiber (MMF), a weak scattering medium, has the advantages of low transmission loss, compact structure, adaptability to fiber communication systems, and abundant degrees of modal freedom, which is widely employed in the field of information transmission and imaging [2-9].

Random distribution of modes hampers MMFs to transmit information directly. One precondition for the effective utilization of multi-modes is that the distribution of the random modes could be modulated. Wavefront shaping [2] and measuring the transmission matrix [3] are popular modulation methods, which can control modes distribution at the distal end of a MMF. In some scenarios, a speckle pattern from MMF can also carry valid information. For example, deep learning is employed to recover information by training the fingerprints of speckle patterns [4], or speckle patterns can act as the structured illumination in ghost imaging for high resolution [5,6].

MMFs have shown their enormous prospects for information transmission. Recently, an information channel is established in the scattering medium through spatially selective lighting, which provides a new perspective for information transmission in disordered media [7]. For other examples, the random characteristic of modes distribution in MMF has been applied for encrypted communication [8].

In all, MMF has gained increasingly attention in the field of optical information, and current methods of modulation in MMF mainly resort to spatial light modulators, which is a spatial-to-spatial method of light control. In this paper, a spectral coding method is proposed to modulate the output of MMF, where a channel is established in the form of light focusing (optical spot) at the distal end of MMF. Different from the former studies, we control the output intensity of light in MMFs through spectral shaping. The proposed method controls light transmission in MMF (e.g., single-spot and multi-spot focusing) through more intuitive, feasible, and linear modulation with all-fiber structure and fiber-access devices. Benefiting from the use of wavelength degree of freedom, a scenario of channel-definable information transmission (i.e., selective-spot encrypted information transmission) is proposed, which is of great significance for light control and applications in weakly scattering media.

2. Principle and results

When the interval of two input wavelengths exceeds the spectral decorrelation bandwidth (or spectral correlation function) of a MMF, completely incoherent speckle patterns would be formed [9]. Resorting to this wavelength sensitivity of the spatial speckle, our method for mode modulation involves two steps. The first step is to obtain the mapping between input wavelengths and output speckle patterns, wherein a tunable laser with a scanning wavelength is injected to the MMF to get a series of speckle patterns corresponding to specific wavelengths. Each speckle pattern brightening at a target output spot will be recoded with its wavelength information (i.e., the positive wavelength and speckle pattern). The second step is to focusing the output light through spectral shaping, wherein the recorded wavelengths, i.e., the positive wavelength, will be lunched by a tunable laser for focusing, namely, mode modulation through spectral coding.

In order to get a further understanding of mode modulation via coding spectra, we give a mathematical model of spectral transmission matrix,

$$P = M \bullet S \tag{1}$$

where P is the one-dimensional column vector of the output speckle pattern, S is the column vector of spectra, and M is the two-dimensional transmission matrix connecting the input wavelength and the output speckle. For a specific input wavelength, λ_i , the wavelength vector $S_i = [\lambda_1, \lambda_2, ..., \lambda_i, ..., \lambda_n]^T$ is set to a Dirac function, where T denotes matrix transpose. Our first step of light modulation is to determine the spectral transmission matrix M . That is only one wavelength in S is set to be 1 (λ_i=1), while the rest of the wavelengths are 0, to get a corresponding speckle P_i ($i \leq n$). After measuring all the wavelengths, the transmission matrix is $M = [P_1, P_1, ..., P_n]$. Once the spectral transmission matrix is obtained, spectra shaping in the second step can be write as

$$P = \sum_{i=target} P_i = M \bullet \sum_{i=target} S_i = M \bullet S \qquad (2)$$

which can focus light at a specific output spot by summing the wavelength components that contribute to the brightening of the spot, generating a specific information channel of light transmission.

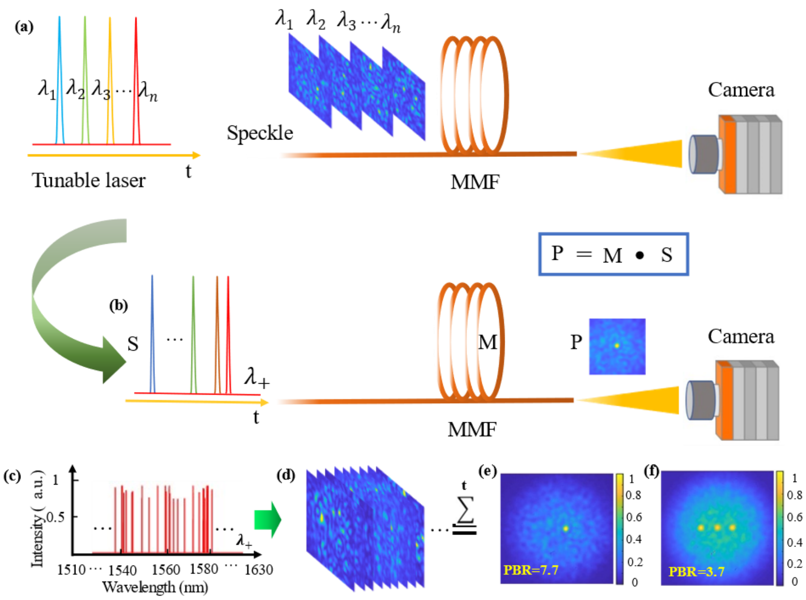

Fig. 1. Experimental setup and establishment of channel(s). Two steps were implemented to established the channel(s) (namely optical focusing). (a) The first step: obtaining the mapping between input wavelengths and output speckle patterns. (b) The second step: focusing the output light through spectral coding. (c) Part of the selected positive wavelengths. (d) Part of the selected positive speckle sequences. (e) Focus arose from the temporal superposition of speckle patterns in (d) which were excited by the positive wavelengths in (c). (f) Three focal spots were realized.

The experimental setup is shown schematically in Figs. 1(a) and (b). Fig 1(a) corresponds to the first step, wherein output of a tunable laser with wavelength range from 1510 nm to1630 nm and spectral resolution of 0.02 nm was coupled to a coiled MMF (105/125um core/cladding diameter, step index, 60 m long and 0.04nm decorrelation bandwidth) by a single mode fiber. An infrared camera was placed at the distal end of the MMF to capture the speckle patterns. Fig. 1(b) corresponds to the second step. The tunable laser was used to form a desired spectrum temporally according the target spot of light focusing, i.e., according to S in Eq. (2). In Figs. 1(d) and (e), a bright focusing spot arose by temporally integrating the 33 positive speckle patterns, which were excited by the positive wavelengths partially shown in Fig. 1(c).

The peak-to-background ratio (PBR) defined as the ratio between the intensity of the target spot and the mean intensity of the background, is used to characterize the quality of focusing, i.e., light modulation. The PBR of the pattern in Fig. 1(e) equals 7.7, which would be further enhanced by increasing the positive wavelengths in a wider wavelength range. Multi-spot focusing is also realized by spectral coding, i.e., Fig. 1(f) shows a three-spot focusing pattern, which can function as definable multi channels.

Actually, position-definable information transmission channel(s) can be established by light focusing at the arbitrary target spot(s) via coding the spectra through various methods. Taking the time-integral method as an example, the successive parts propose and demonstrate a scenario of encrypted information transmission.

The speckle will distribute randomly when excited by varied wavelengths. Combining the randomness of speckle pattern and the definable feature of channel, we propose an encrypted transmission scheme. Similar as the method in Fig. 1, we select the positive wavelengths that contribute to light focusing at the target spot, defining a transmission channel between the input port and the target output spot/mode. The positive wavelengths are denoted as λ_+ and the left wavelengths within the light source are denoted as λ_- . Figs. 2(a) and 2(b) shows the procedure of information coding. An image matrix is coded into a binary digital array through line vectorization and set the bright pixels to 1 and the dark pixels to 0. These binary digitals were encoded on the input wavelength successively in time domain. In one time slot, N different wavelengths of λ_+ (λ_-) were chosen randomly and fed into the MMF when there is a digital one (zero), generating a bright (dark) spot at the target output mode.

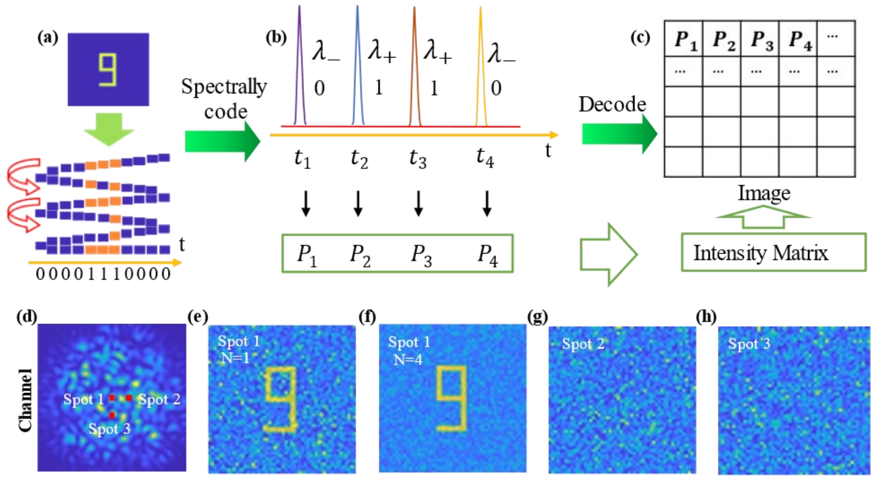

Fig. 2. Encrypted transmission by spectral coding. (a) An original image and its binary signal in time domain. (b) The signal is encoded temporally and modulated on the input wavelengths. (c) Schematic of image recovery from the received signal. (d) The channel (marked as "spot 1") and two neighbor spots (marked as "spot 2" and "spot 3"). (e) and (f) Decoded signal received at the channel, spot 1, $N = 1$ and $N = 4$ respectively. (g) and (h) Decoded signals received at two monitoring spots, spot 2 and spot 3.

At the receiving end, the temporally-varied intensity signal received at the target spot (output mode) reflect the binary digitals, which can be used to recover the image, as shown in Fig. 2(c). Intensity signals received at other output spots vary randomly, and cannot be used to recover the image. In Fig. 4(d), spot 1 denotes the target output mode, namely the established channel, spots 2 and 3 denote the neighbor modes. The decoded image based on output at spots 1-3 are given in Figs. 2(e)-2(h), respectively, indicating that only the output at the target spot can be used to recover the image. Larger number of wavelengths, N, in one time slot brings higher reconstruction quality, where Figs. 2(e) (N=1) and (f) (N=4) are presented. In all, this provides a channel-definable way of encrypted information transmission. The random mode distribution of MMF ensure high security of the information channel formed through spectral transmission matrix. Besides, the transmission matrix can be renewed easily by adding perturbation to the MMF, which is a demanded characteristic of information encryption.

3. Conclusion

In conclusion, we have proposed and realized a way of light focusing as well as defining of transmission channels in MMFs through spectral coding based on implementation of spectral transmission matrix. The route of time-integral focusing by superposition of wavelength-dependent speckle patterns are proposed. Moreover, a scenario of secure information transmission is implemented, which provide an enormous potential in encrypted information transmission through an optical fiber. The spectral coding method of light focusing and information transmission expands the mode modulation method from spatial-to-spatial method to spectral-to-spatial method, and the spectral degrees of freedom also benefit for light control and information coding through full-fiber structure or fiber-access devices.

4. References

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