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# Light focusing through strongly scattering media by binary amplitude modulation[*]

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Based on the angular spectrum method and the circular Gaussian distribution (CGD) model of scattering media, we numerically simulate light focusing through strongly scattering media. A high contrast focus in the target area is produced by using feedback optimization algorithm with binary amplitude modulation. It is possible to form the focusing with one focus or multiple foci at arbitrary areas. The influence of the number of square segments of spatial light modulation on the enhancement factor of intensity is discussed. Simulation results are found to be in good agreement with theoretical analysis for light refocusing.

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When light passes through the inhomogeneous random materials, such as paper, paint and human tissue, light will be multiply scattered. Light propagating in such materials is diffuse, and the materials are opaque[1,2]. Recently, focusing light through opaque strongly scattering media has been demonstrated by modulating the phase of the wavefront of the incident light[3]. Under this modulation, the amplitude of each segment stays the same, but the phase is varied. The resulting waves can overcome the scattering effects of the sample and create a focus through the medium in the output plane.

Many research groups have demonstrated some methods for wavefront modulation using different algorithms, including stepwise sequential algorithm[4], parallel algorithm[5], genetic algorithm[6], and so on. All of these algorithms can achieve light focusing through scattering media, but different algorithms have different times for realizing the focusing through the opaque materials. It seems that focusing light through scattering media has tremendous potential applications in various fields, such as biomedical imaging[7,8], optical trapping[9] and communication[10,11].

In this paper, a simulation method based on angular spectrum and circular Gaussian distribution (CGD) model is presented. The angular spectrum method is a technique for modeling the propagation of a wave field traveling in different directions. Scattering in the sample is described by the unknown transmission matrix (TM), in which the elements are statistically independent and obey a circular Gaussian distribution. For practical purposes, an additional energy optimization is used to generate the workable TM.

Fig.1 shows the schematic diagram of light refocusing by binary amplitude modulation. The speckle pattern is an intensity pattern produced by the mutual interference of a set of wavefronts[12,13]. It is shown in Fig.1(a) that the incident plane wave transmits through the sample and forms a random speckle pattern. The working surface of the spatial light modulation (SLM) is spatially divided into a variable number ($N$) of equal squared segments. By monitoring the intensity in the target focus, the transmittances of all segments are successively set with the binary amplitude modulation algorithm. For optimal result, some segments are turned on, which means that the transmittance is set to be 1, if they interfere constructively. And the rest of the segments are turned off because of deconstructive interference. However, here, we do not modulate the phase of the segments. After modulation, a single spot is formed from the shaped wavefront as shown in Fig.1(b). Because of the randomness of the scattering medium, the interference among output channels is random. Nearly half of the segments are turned on in the modulated wavefront.

Scattering in the sample is described by the transmission matrix elements of $t_{mn}$ with Gaussian statistics. This matrix denotes the relationship between the fields of the input light and the transmitted light. The transmitted electric field can be expressed as[14]

$$E_m = \sum_{n=1}^{N} t_{mn} E_n \ , \tag{1}$$

where $E_m$ and $E_n$ are the $m$th output channel and the $n$th

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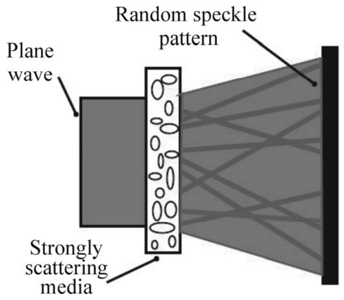
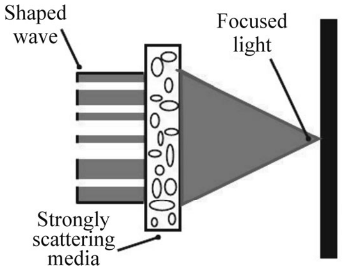
input channel of the electric field, respectively.



(a) Random speckle pattern formed from a plane wave



(b) A single spot formed from the shaped wavefront by binary amplitude modulation

**Fig.1 Schematic diagram of the light transmission through the scattering media**

The ideal enhancement factor $\eta$ is defined as the ratio of the spot intensity after modulation $I_{\mathrm{m}}$ to the average intensity before modulation, which can be calculated as[15]

$$\eta \approx 1+\frac{1}{\pi}\left(\frac{N}{2}-1\right) . \tag{2}$$

It is shown from Eq.(2) that the ideal enhancement factor for the ideally stable and noise free system increases linearly with the increasing number of segments $N$. This indicates that as the more segments are divided, the more input channels are independently controlled, the angular resolution is increased. For $N$>>1, we have $\eta \approx N/2\pi$.

Now we perform the simulation according to the flow chart illustrated in Fig.2. The primary parameters for the simulation are as follows. The wavelength of the incident wave is 632.8 nm, the focal length of lens is 300 mm, the distance between SLM and lens is 100 mm, the distance between lens and sample is 250 mm, and the distance between sample and CCD is 50 mm.

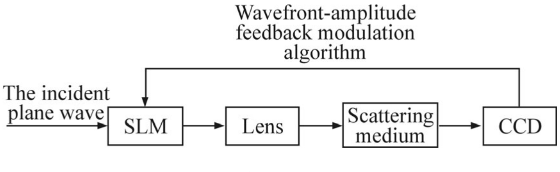


**Fig.2 Flow chart of the simulation process**

When light passes through the opaque strongly scattering materials, light will propagate randomly at any direction due to the multiple scattering. The angular spectrum method can be used to describe the non-paraxial transmission[16-18]. We apply the angular spectrum method to describe the light propagation between optical devices, which can be expressed as

$$\boldsymbol{E}\left(x,y\right)=F^{-1}\left\{F[\boldsymbol{E}_0(x_0,y_0)]H\left(f_x,f_y\right)\right\} , \tag{3}$$

where $\boldsymbol{E}_0(x_0, y_0)$ and $\boldsymbol{E}(x, y)$ represent the optical fields of the source plane and the observed plane, respectively. $H(f_x,f_y)=\exp\left[\mathrm{j}kd\sqrt{1-(\lambda f_x)^2-(\lambda f_y)^2}\right]$ is the angular spectrum propagator. $F$ and $F^{-1}$ represent Fourier transform and inverse Fourier transform, respectively. $f_x$ and $f_y$ are the frequency domain coordinates. $k$ is the wave vector, and $d$ denotes the distance between two optical devices. Eq.(3) can be used to calculate the input field of SLM ($\boldsymbol{E}_{\mathrm{SLM\_in}}$), the input fields of lens ($\boldsymbol{E}_{\mathrm{lens\_in}}$) and scattering medium ($\boldsymbol{E}_{\mathrm{medium\_in}}$), and the output field of the system ($\boldsymbol{E}_{\mathrm{out}}$).

The output field of SLM is given by

$$\boldsymbol{E}_{\mathrm{SLM\_out}}=b_n\cdot\boldsymbol{E}_{\mathrm{SLM\_in}}, \tag{4}$$

where $b_n$ is the state of segment $n$, which is set to be 0 or 1.

And the output field of the lens can be obtained by:

$$\boldsymbol{E}_{\mathrm{lens\_out}}=\boldsymbol{E}_{\mathrm{lens\_in}}\cdot t(x,\ y), \tag{5}$$

where $t(x,\ y)$ is the complex amplitude transmittance function of the lens, which is given by $t(x,y)=P(x,y)\exp(-\mathrm{i}k\frac{x^2+y^2}{2f})$. $P(x,\ y)$ is the pupil function, and $f$ is the focal length of lens.

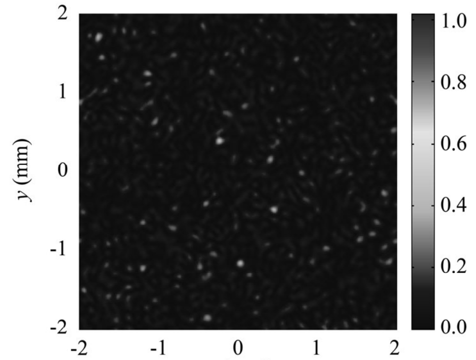
The elements in the transmission matrix of scattering medium are statistically independent and obey a circular Gaussian distribution[14,19]. We should perform the singular value decomposition (SVD) on the transmission matrix, because a further energy optimization should be considered[20,21]. And we obtain the transmission matrix $\boldsymbol{T}$ which can be used in the simulation. The output field of the scattering medium can be achieved as

$$\boldsymbol{E}_{\mathrm{medium\_out}}=\boldsymbol{E}_{\mathrm{medium\_in}}\cdot\boldsymbol{T}. \tag{6}$$

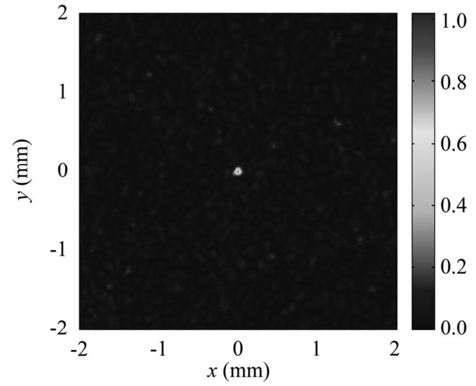
According to the above equations, the output field of the system $\boldsymbol{E}_{\mathrm{out}}$ is available. A feedback optimization algorithm with binary amplitude modulation is employed to modulate the incident wavefront. After modulation, the transmitted light interferes constructively, and forms a bright focus at any target position.

Fig.3 shows the simulation results with $N$=256 segments. Before optimization, when the non-modulated incident light transmits through the scattering sample, all segments are turned on, and a speckle pattern is formed as shown in Fig.3(a). The feedback optimization algorithm with binary amplitude modulation is employed to modulate the transmittance of the SLM. After several iterations, the transmitted light converges to the target area and forms a bright focus as shown in Fig.3(b). Fig.3(a) and (b) are presented on the same logarithmic color scale. The enhancement factor is plotted against the number of controlled segments $N$ for optimization, which is shown in Fig.3(c). It is found that the enhancement factor $\eta$ is about 41.670 5 when $N$=256. Fig.3(d) shows the amplitude pattern on the SLM, which is used to obtain the focusing spot shown in Fig.3(b). In this case, there are 130 segments on the amplitude pattern turned off. This demonstrates that the simulation method can be used effectively to simulate the light focusing through scattering media.

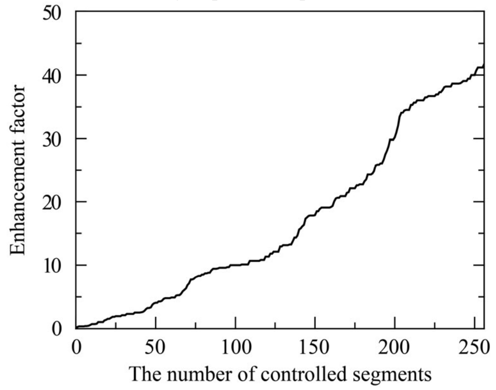
The enhancement factors obtained from theoretical calculation based on binary amplitude modulation and simulations plotted against the segment number of the SLM are shown in Fig.4. As shown in Fig.4, in the simulation, the wavefront is divided as 64, 256, 1 024 and 4 096 segments, respectively, and each data point is an average of 12 data points obtained from measurements. It can be seen from Fig.4 that the enhancement factor increases with the increase of segment number $N$, since the number of independently controlled input channels increases. The results show that the used simulation method can achieve the maximum possible optimization of $\eta\approx N/2\pi$.



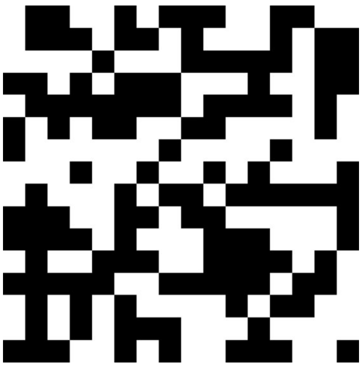
(a) Random speckle pattern



(b) A single spot after optimization



(c) Relation between the enhancement factor $\eta$ and the number of controlled segments $N$



(d) Amplitude pattern on the SLM used to form (b)

**Fig.3 Simulation results with binary wavefront optimization**

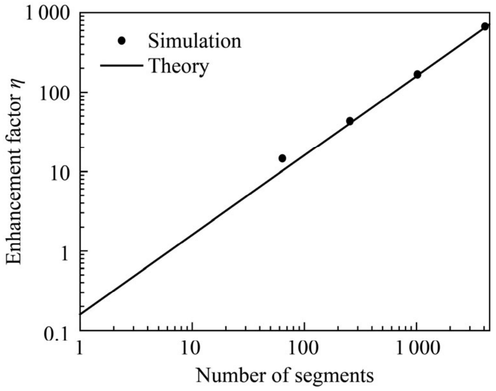
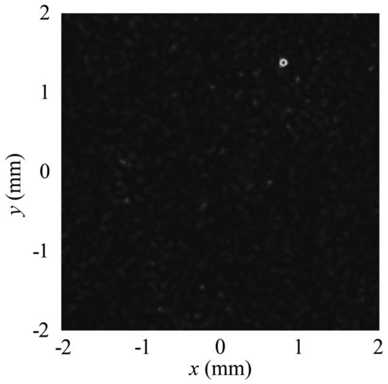
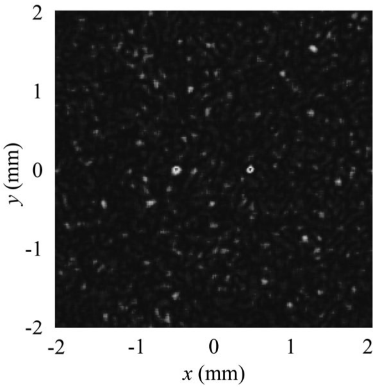


**Fig.4 Intensity enhancement factors from theoretical calculation and simulation at the target position versus the number of segments on the SLM**

We can realize the incident light transmitting through the sample, and produce a focus at arbitrary area, as shown in Fig.5(a). By adjusting the target function used as feedback, it is possible to optimize multiple foci simultaneously as shown in Fig.5(b).



(a) Single spot focusing



(b) Multi-spot focusing

**Fig.5 Interference patterns at the defined target after optimization**

In conclusion, we introduce a simulation method for focusing light through strongly scattering media with binary wavefront modulation. By combining the angular spectrum method and the available transmission matrix, a speckle pattern can be obtained. And a high contrast focus in the target area is produced by using the feedback optimization algorithm. The intensity enhancement factor increases linearly with the increase of the number of segments. And the simulation results are in good agreement with theoretical analysis.

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