Logical Image Reconstruction by Monitoring a Seeded Potential in Variable Detection Planes

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ABSTRACT Optical image computing, such as spatial differentiation, logical transform, and addition-subtraction operation, is of great importance to signal enhancement, transform, and extraction, but such nonlinear methods are restrained in incoherent or scattering imaging. Here, the logical white-light image reconstruction, as an optical image computing method for incoherent and scattered images, is proposed by monitoring a seeded potential in variable detection planes. The weak white-light signals collectively seed a potential at the expense of scattering noise based on seeded modulation instability in a photorefractive crystal. Then the logical image operation is achieved by sensitively probing the seeded potential and recording the intensity distribution of the probe beam in different detection planes. The proposed method has a strong ability of ballistic signal recording, reproduction, and reversal. The numerical and experimental results show a new physical phenomena in which the indirect interaction between light waves through a seeded potential is presented in different forms. The nonlinear method is proved to effectively operate pure images, the images scattered by a rotating diffuser, and the images scattered by fogs whether under back lighting or under front lighting. Our work suggests an alternative method for all-optical image processing, recovery, and computing.

INDEX TERMS Seeded modulation instability, variable detection plane, logical image reconstruction.

I. INTRODUCTION

Optical image computing is of great importance to signal enhancement, transform, and extraction [1]–[5]. These technologies have broad applications in parallel information processing, ranging from atmospheric imaging to underwater imaging to biological imaging. However, when used in incoherent and scattering imaging, these nonlinear methods are restrained due to statistical dephasing of temporally and spatially incoherent light [6]. The light from flames, bulbs, and sun is temporally and spatially incoherent in natural or artificial illumination environments. The absorption and scattering further decays the energy and coherence of light when imaging through turbid media, such as fogs, muddy water, and tissues [7]–[9]. Obviously, optical image computing methods for incoherent and scattered images are more universal to improve the quality of low-contrast images in practical applications. The implement of the technologies depends on both optical image operation and recovery. Some progresses about optical image recovery have been made in the past few years. Dylov et al. developed and exploited a nonlinear method called stochastic resonance (SR) to recover the weak underlying images overwhelmed by strong background or scattering noise with laser illumination [10]–[12]. The weak signals excite an instability and reinforce themselves at the expense of noise under self-focusing nonlinearity in a photorefractive crystal. The work raises an interesting point of optical image recovery and then is extended to pulse noisy image recovery and underwater object detection [13]–[15]. The nonlinear method presents more detailed information by exploiting the presence and interaction of many photons [16]. Feng et al. explored the feasibility of achieving the SR based on nematic liquid crystals (NLC) because NLC with the molecular reorientation effect has a strong nonlinear optical response [17], [18]. Recently, we reported the white-light image recovery via seeded modulation instability [19]. The white-light signals of entire temporal spectrum collectively seed a potential and contribute to the resonance. Despite significant progress,
optical image operation for incoherent and scattered images has never been reported. Logical image transform is a fundamental mathematical operation in optical information processing. In the case of logical image transform, we suggest an optical image computing method for incoherent and scattered images. This type of exploration may open up an interesting direction of optical image computing in incoherent and scattering imaging.

Here, we theoretically and experimentally demonstrate the logical white-light image reconstruction by monitoring a seeded potential in variable detection planes. The self-focusing nonlinearity allows the weak-light signals to induce a gradient potential by coupling with scattering noise. Then the growth of intensity perturbation gradually turns into the decay of intensity perturbation when sensitively probing the seeded potential and reasonably moving the position of the detection plane from front to back. The growth and decay of intensity perturbation is treated as the positively and inversely logical image reconstruction, respectively. Through the systematical and in-depth study, we find that the logical image operation with the ability of ballistic signal recording, reproduction, and reversal is effective to process pure images, the images scattered by a rotating diffuser, and the images scattered by fogs whether under back lighting or under front lighting. In brief, our contributions are as below. Firstly, we suggested an optical image computing method for incoherent and scattered images. Secondly, the proposed method can effectively recover both noise-hidden bright objects and noise-hidden dark objects under different illumination and scattering conditions, not only just noise-hidden bright objects. Thirdly, the experimental results showed that the method is able to achieve the enhancement and reconstruction of the images scattered by fogs.

II. EXPERIMENTAL SETUP

The experimental set-up is shown in Fig. 1. The logical image operation is studied in three different conditions: no scattering, being scattered by a rotating diffuser, and being scattered by fogs. Each condition is divided into two types: back lighting and front lighting. (1) No scattering: For back lighting, the white light emitted from LED$_1$ (0.5 W) is selected as the illumination beam. The extraordinarily polarized visible light passes through a resolution chart to generate a binary image, and then the object (0.2 mW/cm$^2$) is imaged onto an ordinary color camera. The recorded intensity distribution of the probe beam is dependent on the relative position of the seeded potential and the detection plane (the object plane of the second lens). The relative position is changed by moving the crystal or the camera. Positively logical image transform is achieved when the detection plane (located in Position 2 shown in Fig. 1) is in front of the seeded potential. The light exiting the crystal is imaged onto an ordinary camera. Either a rotating diffuser or a plastic box (the inset marked in red) filled with fogs are placed to scatter the signals.

FIGURE 1. Experimental set-up. A white-light beam (emitted from either LED$_1$ or LED$_2$) passes through a resolution chart, and then is imaged onto an SBN:61 photorefractive crystal. The beam evolves nonlinearly through the crystal and seeds a gradient potential based on seeded modulation instability under self-focusing nonlinearity. The white-light beam emitted from LED$_2$ is used to asynchronously probe the seeded potential. The light exiting the crystal is imaged onto an ordinary camera. Either a rotating diffuser or a plastic box (the inset marked in red) filled with fogs are placed to scatter the signals. VPF: visible pass filter. PBS: polarization beam splitter. BS: beam splitter.
potential is created, the implement procedures of logical image operation are same in different illumination and scattering conditions. Except this, the differences are as follows. For front lighting, the white light emitted from LED 2 (0.5 W) is selected as the illumination beam. The binary image (0.2 mW/cm²) is formed by the reflected light. This situation is more representative in actual imaging. (2) Being scattered by a rotating diffuser: a rotating diffuser is placed between the object and the first lens to scatter the signal beam. For back lighting, the signal beam passes through the diffuser once. For front lighting, the signal beam passes through the diffuser twice. The illumination beam becomes more incoherent in this case.

The ballistic signals are overwhelmed by scattering noise when being scattered. (3) Being scattered by fogs: instead of the rotating diffuser, a 6.5 cm plastic box (see the inset in Fig. 1) filled with fogs is placed in front of the object for scattering the signal beam. The fogs enter the box from the hole at the top and exit from the two lateral holes. The fog drops with the diameter of ~5 µm are generated by an ultrasonic humidifier. The small particles lead to a large angle scattering according to Mie scattering theory. The scattering noise covers the whole area of the image and overwhelms the weak signals. In this situation, achieving the logical image reconstruction is challenging.

III. METHODS

Several different approaches have been proposed to describe the propagation of monochromatic spatially incoherent beams in a self-focusing medium [21]–[26]. The diffusive light is considered to be temporally and spatially incoherent. Here, for including temporally and spatially incoherent properties, we use an extended radiation transfer approach:

\[ \frac{\partial f^0}{\partial z} + \beta \mathbf{k} \cdot \frac{\partial f^0}{\partial \mathbf{r}} + \frac{\partial (\Delta n)}{\partial \mathbf{r}} \cdot \frac{\partial f^0}{\partial \mathbf{k}} = 0 \]  

(1)

where \( z \) is the propagation direction, \( f^0(\mathbf{r}, \mathbf{k}, z) \) is the time-averaged phase-space (Wigner) distribution for the light of each frequency, \( \omega \) is the frequency of light, \( \beta = \lambda/2\pi n_0 \) is the diffraction coefficient for the light of wavelength \( \lambda \), \( n_0 \) is the base index of refraction, and \( \Delta n \) is the nonlinear index change induced by the time-averaged total light intensity \( I = \int \int f^0 d\omega d\mathbf{k} \). \( \mathbf{r}(r_x, r_y) \) and \( \mathbf{k}(k_x, k_y) \) represent the position and momentum vectors perpendicular to the direction of propagation, respectively. The diffusive light generated by a rotating diffuser is considered to have an angular spectrum of the Gaussian type \( f^0(k_x, k_y) = \frac{I_0}{(2\pi \Delta k^2)^{3/2}} \exp[-(k_x^2 + k_y^2)/(2\Delta k^2)] \), where \( \Delta k = 2\pi/l_c \) represents the spectral spread for a noisy image with the coherent length \( l_c \). The wave mixing of statistical light under self-focusing nonlinearity can be treated as an optical quasi-particle interaction according to the photonic beam-plasma instability [27], [28]. By analogy, such an interaction is a resonance, requiring mode matching between the statistical light and the signals. Equation (1) implies the conservation of the number of optical quasi-particles. For the quasi-particle system, the phase-space distribution is rewritten as

\[ f^{\omega} = \sum_{i=1}^{N} f_i^{\omega}(\mathbf{r}, \mathbf{k}, z) \]

(2)

The motion of each quasi-particle in a nonlinear medium is described by

\[ F = \frac{\partial (\Delta n)}{\partial \mathbf{r}} \]

(3)

\[ dk = \frac{F}{m} \cdot \frac{dz}{k_0} \]

(4)

\[ dr = k \cdot \frac{dz}{k_0} \]

(5)

where \( F \) represents the gradient-driven force, \( m = \lambda/2\pi n_0 \) is the mass of each quasi-particle, \( k_0 \) is the average wave number. The nonlinear coupling is analyzed by statistically recording the response of positions and momentum of quasi-particles to the refractive index change. In addition, when the light passes through a lens, the position and direction of each quasi-particle is updated by

\[ r_2 = r_1 \]

(6)

\[ r' = k_1 \frac{l}{\sqrt{k_0^2 - k_1^2 - k_2^2}} \]

(7)

\[ k_2 = \frac{r - r_1}{|r - r_1|} k_0 \]

(8)

where \( (r_1, k_1) \) and \( (r_2, k_2) \) are the phase-space distribution of each quasi-particle before and after passing through a lens with the focus length of \( l \), respectively.

The simulation process is described as following. The light beam is considered to be formed by plenty of quasi-particles. A lot of quasi-particles are generated and used to represent the signal beam and the probe beam, respectively. Each quasi-particle has its own position and momentum. The statistical intensity distribution and angular spectrum of quasi-particles is consistent with that of the represented signal or probe beam. In simulation, the intensity distribution of quasi-particles is calculated through the particle-in-cell method. The signal beam propagates through the first lens, and then enters the nonlinear crystal. The nonlinear beam propagation in the crystal is analyzed by iteratively solving the quasi-particle motion equations (Eqs. (3)-(5)) and updating the positions and momentum of quasi-particles.

The quasi-particles exit from the crystal after 100 iterations across 10 mm. In every iteration, the nonlinear index change induced by the signal beam is recorded. Then the probe beam formed by quasi-particles enters the nonlinear crystal. The propagation of the probe beam is dependent on the nonlinear index change induced by the signal beam. Finally, the probe beam propagates through the second lens, and then reach the camera. The simulation process is consistent with the process of light propagation in experiment. As a result, we obtain the results of logical image reconstruction by calculating the intensity distribution of the probe beam in different detection planes.
As shown in Fig. 2, we study the recorded intensity distribution of the probe beam versus the relative position of the potential and the detection plane with back lighting based on the numerical model. The white signals collectively induce a gradient potential in the crystal under self-focusing nonlinearity. After the potential is created, the probe beam is used to sensitively probe the potential. The intensity distribution of the recorded probe beam is dependent on the relative position of the detection plane and the seeded potential. As shown in Figs. 2(a)-2(f), bright strips gradually turn into dark strips when the relative position is adjusted from 0 mm (Position 1 shown in Fig. 1) to −10 mm (Position 2 shown in Fig. 1). The image-intensity-reversal process is clearly shown. The cross-sections of strips are shown in Figs. 2(g)-2(l). The image quality is evaluated by calculating the visibility of the signal area highlighted by the blue rectangle in Fig. 2. The visibility is defined by $\text{visibility} = \frac{(I_{\text{max}} - I_{\text{min}})}{(I_{\text{max}} - I_{\text{min}})}$. Fig. 2(m) shows the visibility of the recorded probe beam versus relative positions. The visibility first decreases, then increases. The seeded potential concentrates the local statistical light when the detection plane is in front of the potential, which results in the growth of intensity perturbation on the top of a uniform background. The potential disperses the local statistical light when the detection plane is behind the potential, which results in the decay of intensity perturbation on the bottom of a uniform background. It is seen that the recorded outputs have a high visibility when the relative positions are 0 mm or −10 mm. The nonlinear output consisting of bright strips can be regarded as the result of positively logical image transform. The nonlinear output consisting of dark strips can be regarded as the result of inversely logical image transform.

IV. EXPERIMENTAL RESULTS

Based on the experimental setup shown in Fig. 1, the logical image reconstruction is demonstrated in this section. The results of positively and inversely logical image reconstruction are obtained by asynchronously probing the seeded gradient potential and recording the intensity distribution of the probe beam in different detection planes. The recorded intensity distribution of the probe beam is regarded as the result of the positively logical image reconstruction when the detection plane is in front of the potential. The recorded intensity distribution of the probe beam is regarded as the result of the inversely logical image reconstruction when the detection plane is behind the potential. The detail results and discussion are as follows.

A. LOGICAL IMAGE TRANSFORM AND LOGICAL IMAGE RECONSTRUCTION

Firstly, we experimentally validate the logical image transform with back lighting. Figs. 3(a) and 3(d) show that the object ($\text{visibility} = 1$) consisting of bright strips is clear with no scattering. The pure white-light image collectively seeds a steep gradient potential in the crystal under self-focusing nonlinearity with the applied voltage of 1000 V. The refractive index distribution of the potential is consistent with the intensity distribution of the signals, which leads to the energy redistribution of the probe beam when the probe beam enters...
the crystal. The potential concentrates the local statistic light when the detection plane is in front of the potential, which leads to the generation of bright strips. The potential disperses the local statistical light when the detection plane is behind the potential, which leads to the generation of dark strips. The indirect interaction between the signal beam and the probe beam through a seeded potential is presented in different forms, which is regarded as positively logical image transform and inversely logical image transform, respectively. The positive transform is shown in Figs. 3(b) and 3(e) ($ visibility = 0.7$). The inverse transform is shown in Figs. 3(c) and 3(f) ($ visibility = 0.69$). It is seen that the results of logical image transform are all in a high contrast. The numerical and experiment results are consistent and indicate the effectiveness of the logical image transform. Furthermore, we find that the intensity of the regions between strips is not consistent with that of background both in Figs. 3(e) and 3(f). The reason for this is that the gradient potential leads to the energy redistribution of the probe beam. The regions between strips are darker than background in Fig. 3(e). The regions between strips are brighter than background in Fig. 3(f). The phenomena improves the brightness difference between the strips and their adjacent areas and enhances the visibility of the strips. This property can be considered as an advantage of the nonlinear method. However, it is noticeably that the nonuniform intensity distribution of the background may cause the difficulty of further optical information extraction [29], [30].

Then we demonstrate the logical image reconstruction with back lighting. A rotating diffuser is placed between the object and the first lens. The diffuser is located in the position where the image is almost overwhelmed by scattering noise. The remaining component of the ballistic light is defined to evaluate the scattering strength, which is given by $ballistic\_component = (E_{Total} - E_{Noise})/E_{Total}$. $E_{Total}$ and $E_{Noise}$ represent the total light energy and the noise energy, respectively. $E_{Noise}$ is obtained by multiplying the average intensity of noise by the area of noise. The average intensity of noise is estimated by calculating the average intensity of the noise area which contains no signal. As shown in Figs. 3(g) and 3(j), the images ($ visibility = 0.15$, $ballistic\_component = 5.3\%$) is in a low contrast with being scattered. The coherent length of the diffusive light is $110 \mu m$. It is difficult for the scattered images to induce a steep enough gradient potential. Seeded modulation instability and varying the positions of detection planes is the key to achieving the logical image reconstruction. For concreteness, weak white-light signals excite an instability and seed a potential in the crystal based on seeded modulation instability under self-focusing nonlinearity with the applied voltage of 1000 V. In turn, the potential enhances the signals by concentrating the scattering noise [11]. The process is continuously repeated in the response time and the potential is continuously reinforced under the force of the positive feedback. Once a steep enough gradient potential is created, the logical image reconstruction is achieved by sensitively probing the seeded potential and reasonably recording the intensity distribution of the probe beam in different detection planes. The positively logical image reconstruction ($ visibility = 0.52$) is shown in Figs. 3(h) and 3(k). It is seen that the underlying signals become visible. The inversely logical image reconstruction ($ visibility = 0.54$) is shown in Figs. 3(i) and 3(l). It is seen...
that the image is formed by dark strips and the signal reversal occurs. The reconstructed images have better visibility than the scattered images, which reveals the effectiveness of logical image reconstruction. The logical image operation has a strong ability of recording, reproducing, and reversing weak white-light signals. Moreover, the edges of the reconstructed images are rough. This is because chaotic scattering noise disturbs the generation of the potential and decreases the quality of the reconstructed images. Note that the lower the visibility of the image is and the stronger the scattering noise is, the worse the reconstruction effect is.

Next we study the logical image transform and the logical image reconstruction with front lighting. Figs. 4(a) and 4(d) show that the images ($visibility = 1$) consist of dark strips and are clear with no scattering. The dark strips seed a negative gradient potential under self-focusing nonlinearity with the applied voltage of 1000 V. The positive transform ($visibility = 0.59$) is shown in Figs. 4(b) and 4(e). The inverse transform ($visibility = 0.61$) is shown in Figs. 4(c) and 4(f).

It is seen that the logical image transform is effective. Figs. 4(g) and 4(j) show that the images ($visibility = 0.13$, $ballistic\_component = 4.2\%$) are blurred with being scattered by a rotating diffuser. The coherent length is 110 $\mu m$. The positively logical image reconstruction ($visibility = 0.4$) is shown in Figs. 4(h) and 4(k). The inversely logical image reconstruction ($visibility = 0.39$) is shown in Figs. 4(i) and 4(l). The image visibility is obviously improved after the nonlinear reconstruction. We compare the results of positively and inversely logical image reconstruction and find that the reconstructed images formed by bright strips have a higher visibility.

In summary, the logical image reconstruction is effective to recover both the noise-hidden bright objects and the noise-hidden dark objects whether with back lighting or with front lighting. Compared with the image-intensity-reversal technique described in Ref. 3, the proposed method effectively achieves the logical transform of incoherent scattered images and are not confined to coherent pure images. In addition, the intensity of the signals is fixed and very weak signals are able to trigger the logical image operation in the whole process. However, the proposed method is not real-time. Even so, suggesting an optical image computing method for incoherent and scattered images is still meaningful and promising.

**B. LOGICAL RECONSTRUCTION OF THE IMAGES SCATTERED BY FOGS**

The signals are mainly scattered by suspended particles when imaging through turbid media in actual imaging. In order to prove the generality of logical image reconstruction, the rotat- ing diffuser is replaced by a plastic box filled with fogs. Figs. 5(a) and 5(d) show the pure images with no scattering under back lighting and front lighting, respectively. Figs. 5(b) ($visibility = 0.1$, $ballistic\_component = 2.4\%$, scattering coefficient $\sim 0.37 \ cm^{-1}$) and 5(e) ($visibility = 0.11$, $ballistic\_component = 2.7\%$, scattering coefficient $\sim 0.3 \ cm^{-1}$) show the corresponding images scattered by fogs. Highly scattering seriously decreases image brightness and contrast. Fog drops with the diameter of $\sim 5 \ \mu m$ cause a large angle scattering according to Mie scattering theory [31]. The scattering noise is extremely incoherent and severely out of phase. Multiple scattering destroys the direct transmission of most
ballistic photons. The applied voltage is set as 1500V. The positively logical image reconstruction (visibility = 0.4) is shown in Fig. 5(c) with back lighting. The inversely logical image reconstruction (visibility = 0.37) is shown in Fig. 5(f) with front lighting. It is seen that the nonlinear method can both enhance and recover the weak images overwhelmed by big angle scattering noise. Note that the very weak ballistic signals exhibit a weak seeded modulation instability. The creation of the potential is very slow by coupling with extremely incoherent scattering noise under self-focusing nonlinearity.

In summary, the reconstructed image has a resolution of 28.3 lp/mm. For the images scattered by a rotating diffuser, the resolution is increased by about 0.7 times according to Rayleigh criterion after the nonlinear reconstruction. For the images scattered by fogs, the resolution is increased by more than 0.7 times after the nonlinear reconstruction. Even if the underlying signals are very weak and the scattering noise is extremely incoherent, the signals can still trigger seeded modulation instability in nonlinear conditions. The nonlinear method has a strong ability of recording, reproducing, and reversing weak signals.

V. CONCLUSION

We demonstrate the logical white-light image reconstruction by monitoring seeded modulation instability in variable detection planes. Highly scattering destroys the direct transmission of most ballistic photons, but a small number of photons carry the image information and penetrate through turbid media. The self-focusing nonlinearity allows the nonlinear crystal to record the weak ballistic signals by seeding a gradient potential based on seeded modulation instability. Then the logical image operation is achieved by asynchronously probing the seeded potential and recording the intensity distribution of the probe beam in different detection planes. The numerical and experimental results show that the nonlinear technology has a strong ability of recording, reproducing, and reversing weak signals. The technology is studied and proved to be effective in three different conditions: nothing scattered, being scattered by a rotating diffuser, and being scattered by fogs. Each condition is further divided into two types: back lighting and front lighting. We find that the indirect interaction between light waves through

a seeded potential is presented in different forms, namely positively logical image reconstruction and inversely logical image reconstruction. The logical image operation can recover both the noise-hidden bright objects and the noise-hidden dark objects under various experimental conditions. Especially, the inversely logical image reconstruction can achieve both the signal reversal and the image reconstruction, which is of importance to the crack detection in scattering environment. Furthermore, the demonstration of the logical image reconstruction of the images scattered by fogs further promotes the application of the nonlinear technology in actual imaging.

REFERENCES

[1] X. Qiu, F. Li, W. Zhang, Z. Zhu, and L. Chen, “Spiral phase contrast imaging in nonlinear optics: Seeing phase objects using invisible illumination,” Optica, vol. 5, no. 2, pp. 208–212, 2018.

[2] T. Zhu, Y. Zhou, Y. Lou, H. Ye, M. Qiu, Z. Ruan, and S. Fan, “Plasmonic computing of spatial differentiation,” Nature Commun., vol. 8, no. 1, p. 15391, Aug. 2017.

[3] M. Y. Shih, A. Shishido, P. H. Chen, M. V. Wood, and I. C. Kho, “All-optical image processing with a supernonlinear dye-doped liquid-crystal film,” Opt. Lett., vol. 25, no. 13, pp. 978–980, 2000.

[4] H. Gan, N. Xu, J. Li, T. Xu, Y. Wang, Z. Sun, C. Ma, J. Wang, F. Song, M. Sun, L. Li, and C. Sheng, “Hidden image recovery using a biased photorefractive crystal in the Fourier plane of an optical imaging system,” Opt. Express, vol. 23, no. 3, pp. 2070–2075, 2015.

[5] K. Murall, S. Sinha, W. L. Dito, and A. R. Bulsara, “Reliable logic circuit elements that exploit nonlinearity in the presence of a noise floor,” Phys. Rev. Lett., vol. 102, no. 10, Mar. 2009, Art. no. 104101.

[6] T. Schwarz, T. Carmon, H. Buljan, and M. Segev, “Spontaneous pattern formation with incoherent white light,” Phys. Rev. Lett., vol. 93, no. 22, Nov. 2004, Art. no. 223901.

[7] Y. Y. Schechner and Y. Averbuch, “Regularized image recovery in scattering media,” IEEE Trans. Pattern Anal. Mach. Intell., vol. 29, no. 9, pp. 1655–1660, Sep. 2007.

[8] B. Zheng, N. Wang, H. Zheng, Z. Yu, and J. Wang, “Object extraction from underwater images through logical stochastic resonance,” Opt. Lett., vol. 41, no. 21, pp. 4967–4970, 2016.

[9] T. Kim, R. Zhou, M. Mir, S. D. Babacan, P. S. Carney, L. L. Goddard, and G. Popescu, “White-light diffraction tomography of unlabelled live cells,” Nature Photon., vol. 8, no. 3, pp. 256–263, Mar. 2014.

[10] D. V. Dylov and J. W. Fleischer, “Nonlinear self-filtering of noisy images via dynamical stochastic resonance,” Nature Photon., vol. 4, no. 5, pp. 323–328, May 2010.

[11] D. V. Dylov, L. Waller, and J. W. Fleischer, “Instability-driven recovery of diffused images,” Opt. Lett., vol. 36, no. 18, pp. 3711–3713, 2011.

[12] D. V. Dylov, L. Waller, and J. W. Fleischer, “Nonlinear restoration of diffused images via seeded instability,” IEEE J. Sel. Topics Quantum Electron., vol. 18, no. 2, pp. 916–925, Mar. 2012.
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