High-fidelity ghost diffraction and transmission in free space through scattering media

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ABSTRACT

We report a different class of ghost, called ghost diffraction and transmission with compressed spectrum coefficients, for ghost (e.g., analog-signal) transmission in free space through scattering media using a single-pixel detector. The ghost, e.g., analog signal, is first transformed to its spectral domain, such as Hadamard domain. The generated Hadamard spectrum coefficients can be flexibly compressed in order to reduce the number of random patterns to be illuminated and transmitted in free space, and the selected Hadamard spectrum coefficients are sequentially encoded into random amplitude-only patterns as information carriers. In the experiments, high-quality Hadamard spectrum transmission using coherent light source is realized in different scattering environments, and subsequently high-fidelity ghosts are further retrieved from the received Hadamard spectrum coefficients. Experimental results demonstrate that the proposed method processes high robustness against wave diffraction, multi-layer scattering and noise. This class of ghost provides a different insight about quantum and classical optics for analog-signal transmission in free space, and an avenue towards many applications, e.g., quantum ghost transmission and communication, could be opened up.

Since ghost or ghost diffraction concept was theoretically proposed[1,2], it has been experimentally demonstrated in quantum optics by using entangled photon pairs generated in the spontaneous parametric down-conversion[3,4]. Subsequently, it was found that ghost imaging (GI) can be realized by using thermal light in classical domain[5,6]. The GI is an unconventional method which is able to extract spatially resolved information by using single-pixel detector[7,8]. The single-pixel detector in the GI is a promising tool for imaging objects under the conditions of non-visible wavelength band[9–13] and complex environment[14–18] where pixelated detectors could be insufficient or not effective. The appearance of GI facilitates some potential applications, and three-dimensional GI[19], electron GI[20], GI with atoms[21] and ghost cytometry[22] have also been realized.

It is a major challenge to realize high-fidelity analog-signal transmission in free space by ghost diffraction. Although a series of random patterns are widely used in ghost diffraction, they have not been effectively implemented as information carriers since high controllability cannot be achieved. When random patterns are used in ghost diffraction, background of the retrieved data is always noisy which results in low signal-to-noise ratio. Other related methods[23-27], e.g., differential ghost[23], also cannot fully overcome the challenge. When coherent light source is used, the noise, e.g., speckle noise, is usually inevitable and it is always difficult to transmit and directly retrieve high-fidelity ghosts through scattering media in free space. It is significant and meaningful to further explore new approaches which can transmit and retrieve the ghosts with high fidelity and high robustness against noise at the receiving end when coherent light source and random patterns are applied. No method has been developed before to directly realize high-fidelity ghost transmission in free space in different wave propagation environments. In terms of analog-signal transmission rather than imaging, it is always concerned that the ghosts cannot be transmitted with high fidelity in free space through scattering media.

In this Letter, we report the observation and realization of an entirely different class of ghost, called ghost diffraction and transmission with compressed Hadamard spectrum coefficients, for analog-signal transmission in free space through multi-layer scattering media by using coherent light source and a series of random amplitude-only patterns. Since a few Hadamard spectrum coefficients enable a faithful retrieval of signals, the ghost, e.g., analog signal, is first transformed to its spectral domain, i.e., Hadamard domain. In the proposed method, only a few Hadamard spectrum coefficients are selected and further used, and then are sequentially encoded into random amplitude-only patterns as information carriers. Therefore, the number of random amplitude-only patterns to be illuminated and transmitted in free space can be flexibly reduced owing to the spectral compression. Another remarkable feature of the proposed method is that the compressed Hadamard spectrum coefficients can be transmitted with high fidelity in free space through scattering media. After high-quality Hadamard spectrum coefficients are collected by using a single-pixel detector, the retrieval of high-fidelity ghost from the received Hadamard spectrum coefficients can be realized. This entirely different class of ghost is capable of transmitting and directly retrieving high-quality Hadamard spectrum coefficients at the receiving end without complex post-processing algorithms even through multi-layer scattering media in free space, and is highly robust against the noise arising from wave propagation environments. The theory and experimental observation offer an opportunity for the transmission in free space using ghost diffraction, and are promising for high-fidelity ghost (e.g., analog-signal) transmission in different wave propagation environments.

A schematic experimental setup for the proposed ghost transmission in free space is shown in Fig. 1, where the series of random amplitude-only patterns as information carriers is sequentially illuminated to propagate in free space through scattering media and then the intensity values recorded by single-pixel detector can directly produce high-quality Hadamard spectrum coefficients at the receiving end.

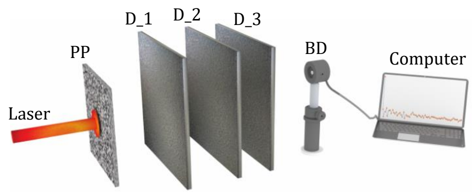

FIG. 1. A schematic experimental setup for the proposed ghost diffraction and transmission in free space through scattering media: PP, pattern; D, diffuser; BD, single-pixel (bucket) detector. The generated patterns are sequentially embedded into a spatial light modulator (SLM).

A method is reported in this study to transmit Hadamard spectrum coefficients of the ghost in free space through scattering media as shown in Fig. 1. For a given analog signal, it is easy to describe it in spectral domain. As a typical example, Hadamard transform is used here to generate Hadamard spectrum of the given ghost. It is worth noting that other kinds of transformations can also be flexibly used. After the transformation, only a few Hadamard spectrum coefficients are selected and further used. Instead of directly transmitting Hadamard spectrum coefficients, the compressed Hadamard spectrum coefficients are sequentially encoded into random amplitude-only patterns. A flow chart shown in Fig. 2 illustrates how each Hadamard spectrum coefficient is encoded into one 2D random amplitude-only pattern. It can be seen in Fig. 2 that an initial guess with real values is first randomly generated and Fourier transformed, and zero-frequency component of the Fourier spectrum is replaced by one Hadamard spectrum coefficient, i.e., acting as a constraint. Subsequently, inverse Fourier transform is applied to generate an updated random amplitude-only pattern. Therefore, each Hadamard spectrum coefficient can be encoded into one 2D random amplitude-only pattern which serves as information carrier for the proposed ghost transmission in free space (rather than imaging) through multi-layer scattering media.

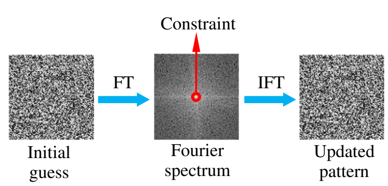

FIG. 2. A flow chart for generating one 2D random amplitude-only pattern for each Hadamard spectrum coefficient: FT, Fourier transform; IFT, inverse Fourier transform.

When the generated amplitude-only pattern is illuminated to propagate in free space and then collected by a single-pixel detector, the recorded intensity can be proportional to each Hadamard spectrum coefficient. In the proposed method, size of the generated 2D amplitude-only patterns can be arbitrarily adjusted. In addition, it is found that the generated amplitude-only patterns as information carriers show high robustness for the transmission in various wave propagation environments, e.g., transmissive or reflective scattering media.

Two aspects need to be further considered in the experiments: (1) negative values existing in the generated patterns which cannot be directly displayed by the SLM; (2) noise arising from the transmission environment and optical detection. Here, a strategy is developed to divide each generated pattern P into two amplitude-only patterns, i.e., (a+P) and (a-P), where a denotes a constant. Advantage of this strategy is to remove negative values and realize the suppression of noise. At the receiving end, two intensity values are respectively collected corresponding to the two patterns, which can be subtracted to directly produce one Hadamard spectrum coefficient followed by high-fidelity ghost retrieval. To quantitatively evaluate quality of the retrieved ghosts, peak signal-to-noise ratio (PSNR) and mean squared error (MSE) are calculated. It is worth noting that although the generated random patterns are noise-like, the retrieved ghosts are of high quality and there is no noise background. This point is significantly different from conventional methods with ghost imaging concepts.

In optical experiments, a He-Ne laser with wavelength of 633.0 nm is used to illuminate the SLM (Holoeye, LC-R720) with pixel size of 20.0 μm, and the generated random amplitude-only patterns (a+P) and (a-P) displayed by the SLM are sequentially illuminated to propagate in free space through scattering media. A number of experimental results have been obtained to show feasibility and effectiveness of the proposed method. Three different 1D analog signals with 128 pixels, i.e., acting as ghosts, are respectively tested in three wave propagation environments, i.e., free space without scattering, through scattering media with one diffuser and through scattering media with three cascaded diffusers. After Hadamard transform is applied to the given ghosts (i.e., analog signals), only 64 points in the Hadamard spectrum coefficients are selected here as a typical example and further encoded. Therefore, the number of random amplitude-only patterns to be illuminated and transmitted in free space can be flexibly reduced in the proposed method. In different wave propagation environments, intensity values are sequentially recorded by using single-pixel detector (Newport, 918D-UV-OD3R). Figures 3(a) and 3(b) show the collected Hadamard spectrum coefficients and the retrieved ghost (analog signals) in free space without any diffuser, respectively. The experimental results in Figs. 3(c) and 3(d) are obtained, when only one diffuser (Thorlabs, DG10-1500) with diameter of 25.4 mm and thickness of 2.0 mm is placed in the setup as shown in Fig. 1. In a strongly scattering environment with three cascaded diffusers, high-quality Hadamard spectrum coefficients and high-fidelity ghosts are also obtained, as shown in Figs. 3(e) and 3(f). When three cascaded diffusers

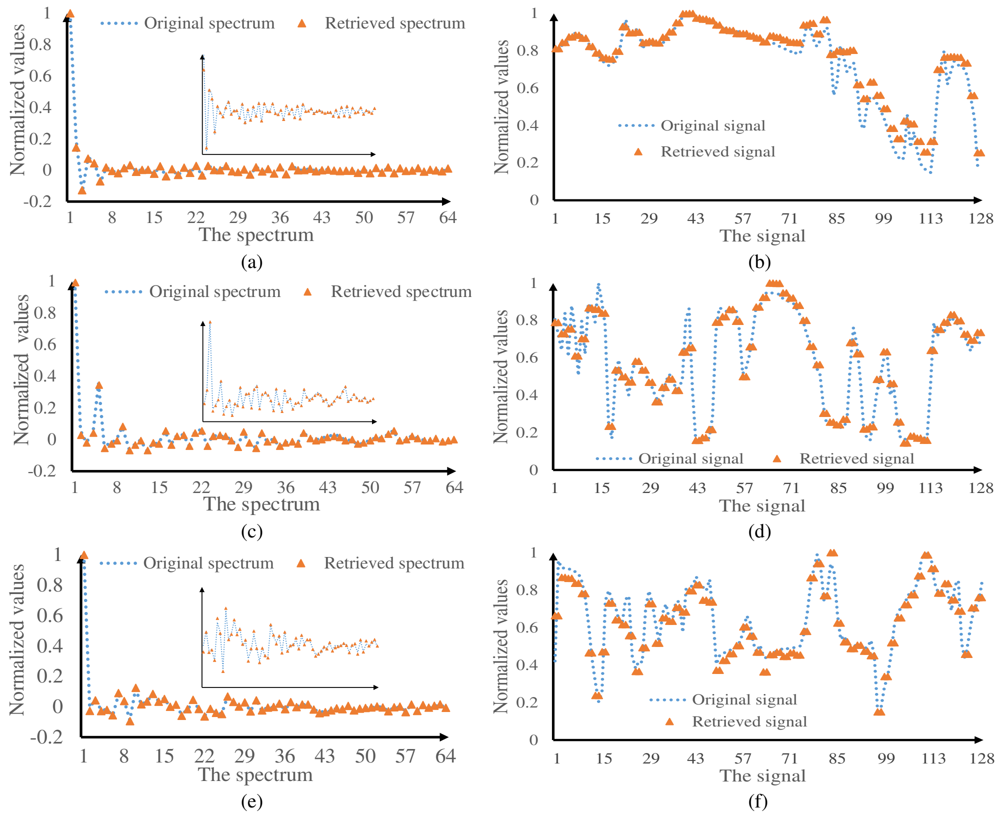

FIG. 3. Experimental results obtained at the receiving end: (a), (c) and (e) comparisons between the experimentally collected Hadamard spectrum coefficients and original Hadamard spectrum coefficients in three different wave propagation environments. The insets in (a), (c) and (e) show the comparisons in a range from point 2 to point 64. (b), (d) and (f) Comparisons between the retrieved analog signals and original ghosts in three different wave propagation environments. The PSNR values for the collected spectrum coefficients shown in (a), (c) and (e) are 42.76 dB, 47.02 dB, and 45.06 dB, respectively. The MSE values for the collected spectrum coefficients shown in (a), (c) and (e) are 5.30×10^{-5}, 1.98×10^{-5}, and 3.12×10^{-5}, respectively. The PSNR values for the retrieved ghosts shown in (b), (d) and (f) are 23.82 dB, 23.80 dB, and 22.09 dB, respectively. The MSE values for the retrieved ghosts shown in (b), (d) and (f) are 4.10×10^{-3}, 4.20×10^{-3}, and 5.90×10^{-3}, respectively.

are applied, the axial distance between the first diffuser and the second diffuser is 25.0 mm, and axial distance between the second diffuser and the third diffuser is 10.0 mm. The axial distance between the final diffuser and the single-pixel detector is 3.5cm. It is worth noting that the transmission distances can be flexibly adjusted. It can be observed from Figs. 3(a), 3(c) and 3(e) that the Hadamard spectrum coefficients collected at the receiving end are of high quality in different wave propagation environments, which are also verified by high PSNR values and low MSE values given in Fig. 3. Using the collected Hadamard spectrum coefficients, it can be seen in Figs. 3(b), 3(d) and 3(f) that high-fidelity ghosts can be further retrieved. For a comparison, normalization operation is used for the collected Hadamard spectrum coefficients (or the retrieved ghosts) and original Hadamard spectrum coefficients (or original ghosts).

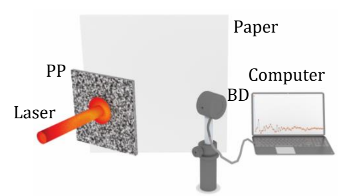

FIG. 4. A schematic experimental setup for the proposed ghost transmission in free space through reflective scattering media.

The proposed ghost transmission method is also studied, when reflective scattering medium is used. A schematic experimental setup is shown in Fig. 4. In reflective scattering environment, the generated random amplitude-only patterns are sequentially embedded into the SLM, and are illuminated to propagate in free space towards a white paper where the propagating wave suffers from scattering and reflection. A single-pixel detector (Newport, 918D-UV-OD3R) is also used to record the light intensity reflected from the paper.

Hadamard spectrum coefficients obtained at the receiving end are shown in Fig. 5(a). Only 64 points in the Hadamard spectrum coefficients are used here as a typical example and are transmitted as shown in Fig. 5(a). High-fidelity ghost (i.e., analog signal) retrieved from the experimentally collected Hadamard spectrum coefficients is shown in Fig. 5(b). The PSNR values and MSE values for the collected Hadamard spectrum coefficients and the retrieved ghost are given in Fig. 5. The experimental results demonstrate that high-fidelity ghost transmission through reflective scattering media can also be realized and observed.

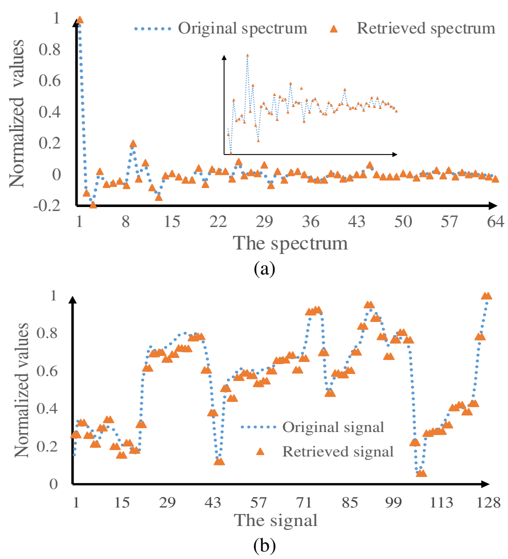

FIG. 5. Experimental results obtained at the receiving end: (a) a comparison between the experimentally collected Hadamard spectrum coefficients through reflective scattering media and original Hadamard spectrum coefficients. The inset in (a) shows the comparison in a range from point 2 to point 64. (b) A comparison between the retrieved ghost and original analog signal. The PSNR values for (a) and (b) are 41.32 dB and 23.81 dB, respectively. The MSE values for (a) and (b) are 7.38×10^{-5} and 4.20×10^{-3}, respectively.

Different types of analog signals can also be used as ghosts to be transmitted in free space by using the proposed method. Here, two grayscale images with 64x64 pixels are further transmitted in free space in two scattering environments, i.e., transmissive scattering media with one diffuser and reflective scattering media. The grayscale images are first transformed to Hadamard domain, and 50% pixels of their Hadamard spectrum coefficient map are respectively selected here as a typical example and further encoded. The collected Hamadard spectrum coefficients obtained in the experiments at the receiving end are respectively shown in Figs. 6(a) and 6(b),

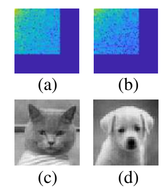

FIG. 6. Experimental results obtained at the receiving end: the received Hadamard spectrum coefficients obtained in (a) transmissive and (b) reflective scattering environment, and (c) and (d) the retrieved ghosts (64x64 pixels) respectively corresponding to (a) and (b). The PSNR values for (a)-(d) are 67.69 dB, 64.02 dB, 29.46 dB, and 22.89 dB, respectively. The MSE values for (a)-(d) are 1.70×10^{-7}, 3.96×10^{-7}, 1.10×10^{-3}, and 5.10×10^{-3}, respectively.

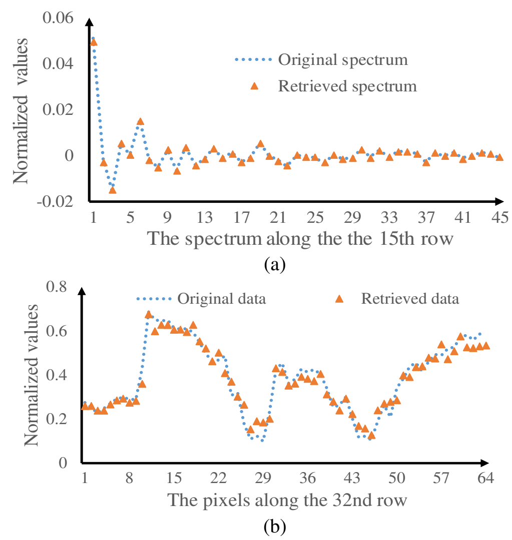

FIG. 7. (a) A typical comparison between the Hadamard spectrum coefficients along the 15th row in Fig. 6(a) and those original Hadamard spectrum coefficients, and (b) a typical comparison between the pixel values along the 32nd row in Fig. 6(c) and those in original grayscale image.

and the ghosts retrieved from the collected Hadamard spectrum coefficients are shown in Figs. 6(c) and 6(d), respectively. The PSNR values and MSE values for the collected Hadamard spectrum coefficients and the retrieved ghosts are calculated and shown in Fig. 6. The experimental results demonstrate that high-fidelity compressed ghost transmission is realized and observed, when 2D analog signals are transmitted in free space by using the proposed method. To clearly illustrate experimental results, comparisons between original analog signals and the retrieved ghosts are further conducted and shown in Fig. 7. Figure 7(a) shows a typical comparison between Hadamard spectrum coefficients along the 15th row in Fig. 6(a) and those original Hadamard spectrum coefficients. Figure 7(b) shows a typical comparison between the pixel values along the 32nd row in Fig. 6(c) and those in original grayscale image. These experimental results further demonstrate that the proposed method is feasible and effective for transmitting different types of ghosts in free space through scattering media.

As shown in Figs. 3, 5 and 6, 50% Hadamard spectrum coefficients are used, and high-fidelity ghost retrieval is realized. The 50% Hadamard spectrum coefficients are used here as a typical example, and the number of spectrum coefficients can be flexibly adjusted according to practical demands. A large number of Hadamard spectrum coefficients could ensure high-fidelity ghost retrieval, and too few spectrum coefficients could result in an unacceptable quality. A remarkable feature of the proposed method is that it is able to retrieve the transmitted spectrum coefficients with high fidelity in complex environments, which further ensures the accurate retrieval of original ghost based on the transmitted Hadamard spectrum coefficients in practical applications.

In conventional methods using ghost imaging with laser source, the quality of retrieved ghosts is always low, since speckle is generated and random patterns used in conventional methods result in noise background in the retrieved ghosts[23-27]. In the proposed method, the generated random patterns are used to retrieve signals with high fidelity as illustrated in the optical experimental results. Although the random patterns generated in the proposed method are noise-like, the retrieved ghosts are of high quality and there is no noise background. This high-fidelity ghost retrieval feature cannot be realized in conventional methods with ghost imaging. In addition, the proposed method shows high robustness against complex scattering in free-space optical transmission, and can effectively suppress various noise (e.g., environmental noise and detection noise etc.) to realize high-fidelity ghost transmission.

In conclusion, we have proposed a different class of ghost, i.e., ghost diffraction and transmission with compressed Hadamard spectrum coefficients, which is able to transmit and retrieve high-fidelity ghosts in free space through scattering media when coherent light source and random amplitude-only patterns are applied. The generated Hadamard spectrum coefficients can be flexibly compressed in order to reduce the number of random amplitude-only patterns to be illuminated and transmitted in free space, and the high-quality Hadamard spectrum coefficients collected by single-pixel detector enable a retrieval of high-fidelity ghosts. The experiments demonstrate that high-fidelity ghost diffraction and transmission can be realized and observed in different wave propagation environments. It is expected that an avenue towards many applications, e.g., quantum ghost transmission and communication, could be opened up.

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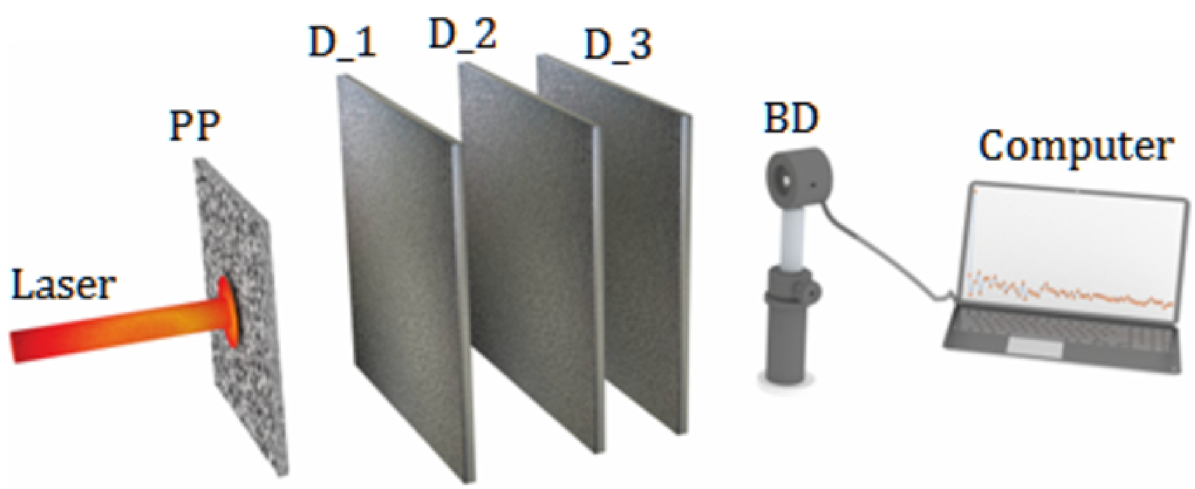
Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

REFERENCES

[1]D. N. Klyshko, Sov. Phys. JETP **67**, 1131 (1988).
[2]A. V. Belinskii and D. N. Klyshko, Sov. Phys. JETP **78**, 259 (1994).
[3]T. B. Pittman, Y. H. Shih, D. V. Strekalov, and A. V. Sergienko, Phys. Rev. A **52**, R3429 (1995).
[4]D. V. Strekalov, A. V. Sergienko, D. N. Klyshko, and Y. H. Shih, Phys. Rev. Lett. **74**, 3600 (1995).
[5]R. S. Bennink, S. J. Bentley, and R. W. Boyd, Phys. Rev. Lett. **89**, 113601(2002).
[6]A. Gatti, E. Brambilla, M. Bache, and L. A. Lugiato, Phys. Rev. Lett. **93**, 93602 (2004).
[7]H. S. Jeffrey, Phys. Rev. A **78**, 061802(R) (2008).
[8]Y. Bromberg, O. Katz, and Y. Silberberg, Phys. Rev. A **79**, 053840 (2009).
[9]D. Pelliccia, A. Rack, M. Scheel, V. Cantelli, and D. M. Paganin, Phys. Rev. Lett. **117**, 113902 (2016).
[10]H. Yu, R. H. Lu, S. S. Han, H. L. Xie, G. H. Du, T. Q. Xiao, and D. M. Zhu, Phys. Rev. Lett. **117**, 113901 (2016).
[11]C. M. Watts, D. Shrekenhamer, J. Montoya, G. Lipworth, J. Hunt, T. Sleasman, S. Krishna, D. R. Smith, and Willie J. Padilla, Nat. Photonics **8**,605 (2014).
[12]W. L. Chan, K. Charan, D. Takhar, K. F. Kelly, R. G. Baraniuk, and D. M. Mittleman, Appl. Phys. Lett. **93**, 121105 (2008).
[13]R. I. Stantchev, B. Q. Sun, S. M. Hornett, P. A. Hobson, G. M. Gibson, M. J. Padgett, and E. Hendry, Sci. Adv. **2**, e1600190 (2016).
[14]P. Zhang, W. Gong, X. Shen, and S. Han, Phys. Rev. A **82**, 033817 (2010).
[15]R. E. Meyers, K. S. Deacon, and Y. Shih, Appl. Phys. Lett. **98**, 111115 (2011).
[16]P. B. Dixon, G. A. Howland, K. W. C. Chan, C. O'Sullivan-Hale, B. Rodenburg, N. D. Hardy, J. H. Shapiro, D. S. Simon, A. V. Sergienko, R. W. Boyd, and J. C. Howell, Phys. Rev. A **83**, 051803 (2011).
[17]M. Bina, D. Magatti, M. Molteni, A. Gatti, L. A. Lugiato, and F. Ferri, Phys. Rev. Lett. **110**, 083901 (2013).
[18]H. Li, J. Shi, Y. Zhu, and G. Zeng, Appl. Phys. Lett. **103**, 051901 (2013).
[19]B. Q. Sun, M. P. Edgar, R. Bowman, L. E. Vittert, S. Welsh, A. Bowman, and M. J. Padgett, Science **340**, 844 (2013).
[20]S. Li, F. Cropp, K. Kabra, T. J. Lane, G. Wetzstein, P. Musumeci, and D. Ratner, Phys. Rev. Lett. **121**, 114801 (2018).
[21]R. I. Khakimov, B. M. Henson, D. K. Shin, S. S. Hodgman, R. G. Dall, K. G. H. Baldwin, and A. G. Truscott, Nature **540**, 100 (2016).
[22]S. Ota, R. Horisaki, Y. Kawamura, M. Ugawa, I. Sato, K. Hashimoto, R. Kamesawa, K. Setoyama, S. Yamaguchi, K. Fujiu, K. Waki, and H. Noji, Science **360**, 1246 (2018).
[23]F. Ferri, D. Magatti, L. A. Lugiato, and A. Gatti, Phys. Rev. Lett. **104**, 253603 (2010).
[24]B. Q. Sun, S. S. Welsh, M. P. Edgar, J. H. Shapiro, and M. J. Padgett, Opt. Express **20**, 16892 (2012).
[25]O. Katz, Y. Bromberg, and Y. Silberberg, Appl. Phys. Lett. **95**,131110 (2009).
[26]A. M. Paniagua-Diaz, I. Starshynov, N. Fayard, A. Goetschy, R. Pierrat, R. Carminati, and J. Bertolotti, Optica **6**, 460 (2019).
[27]F. Q. Li, M. Zhao, Z. M. Tian, F. Willomitzer, and O. Crossairt, Opt. Express **28**, 17395 (2020).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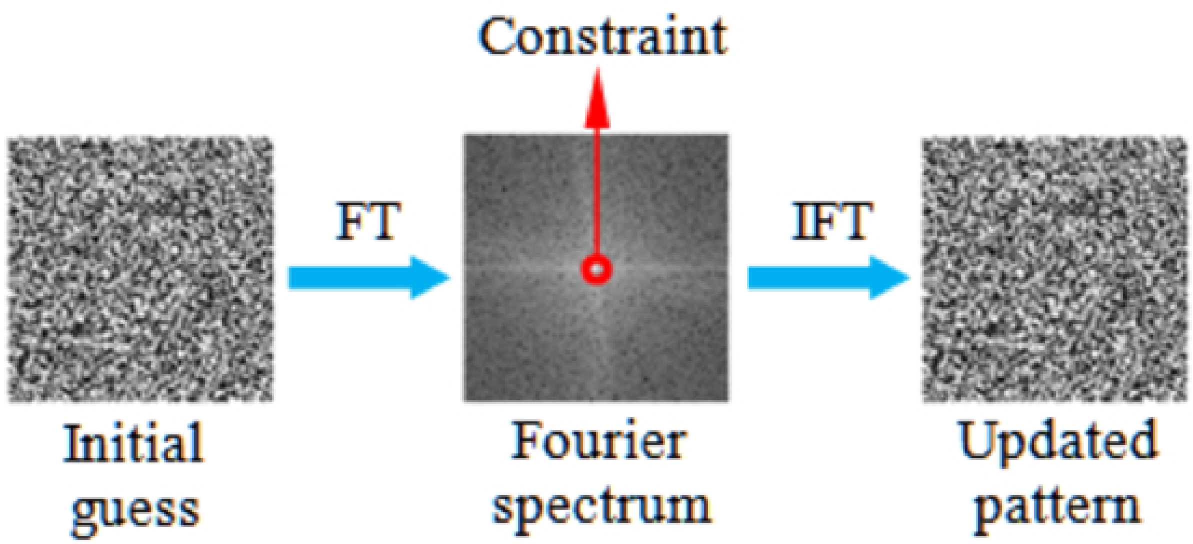
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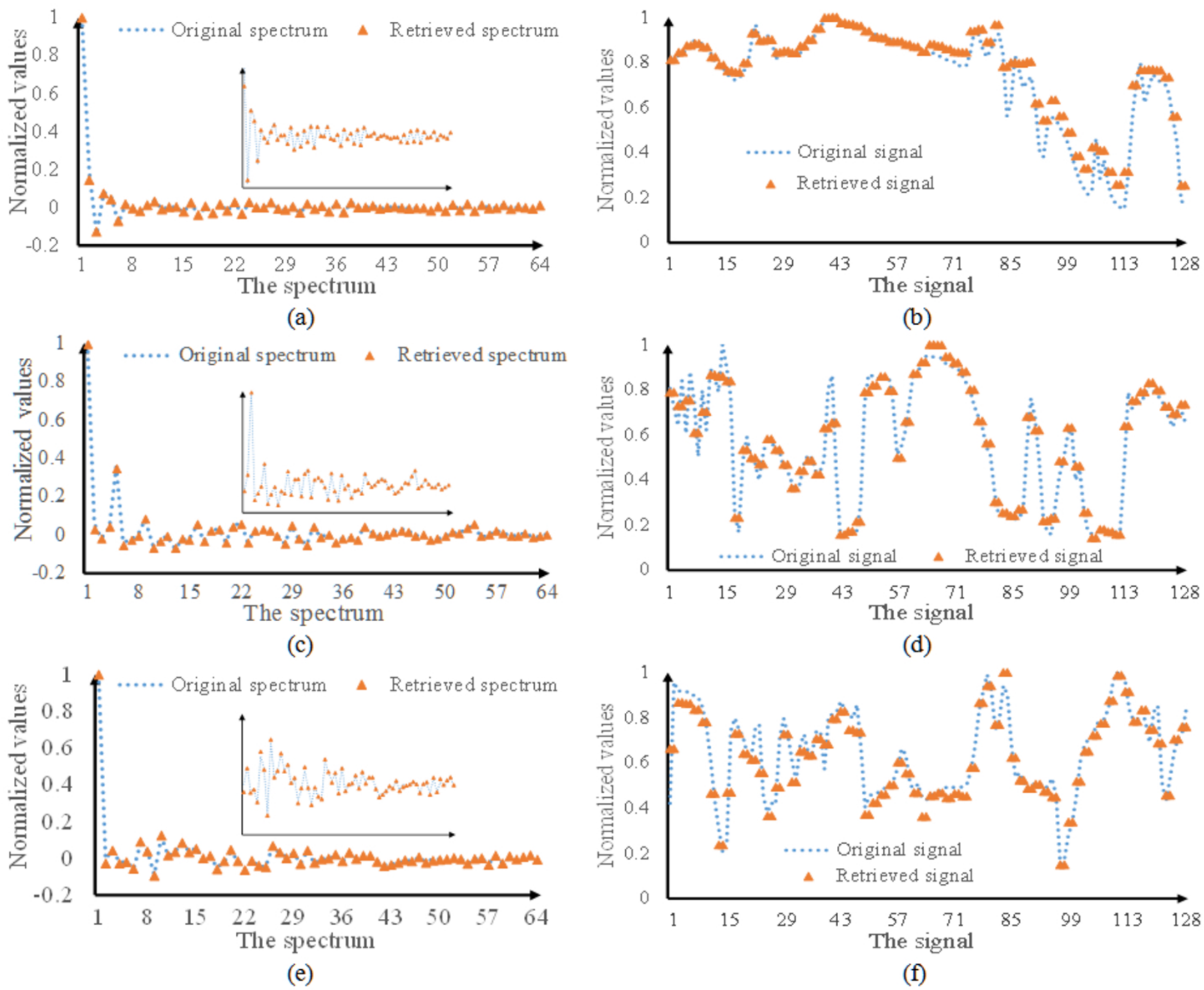
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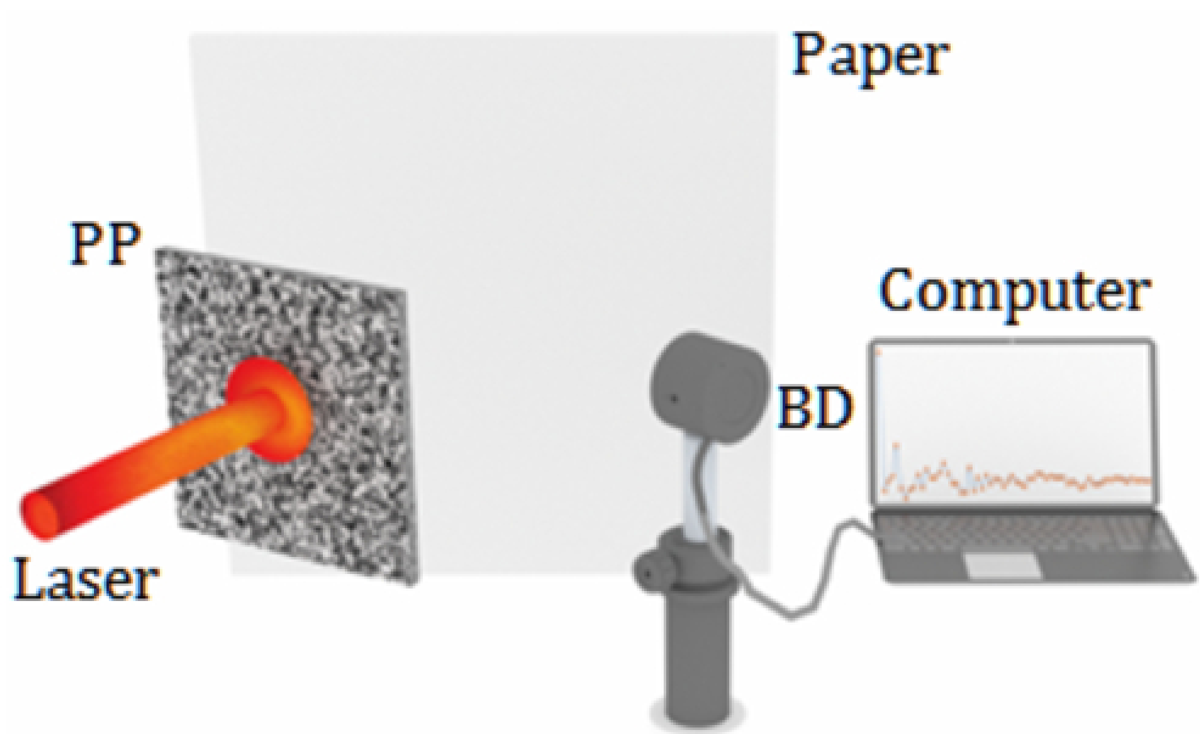
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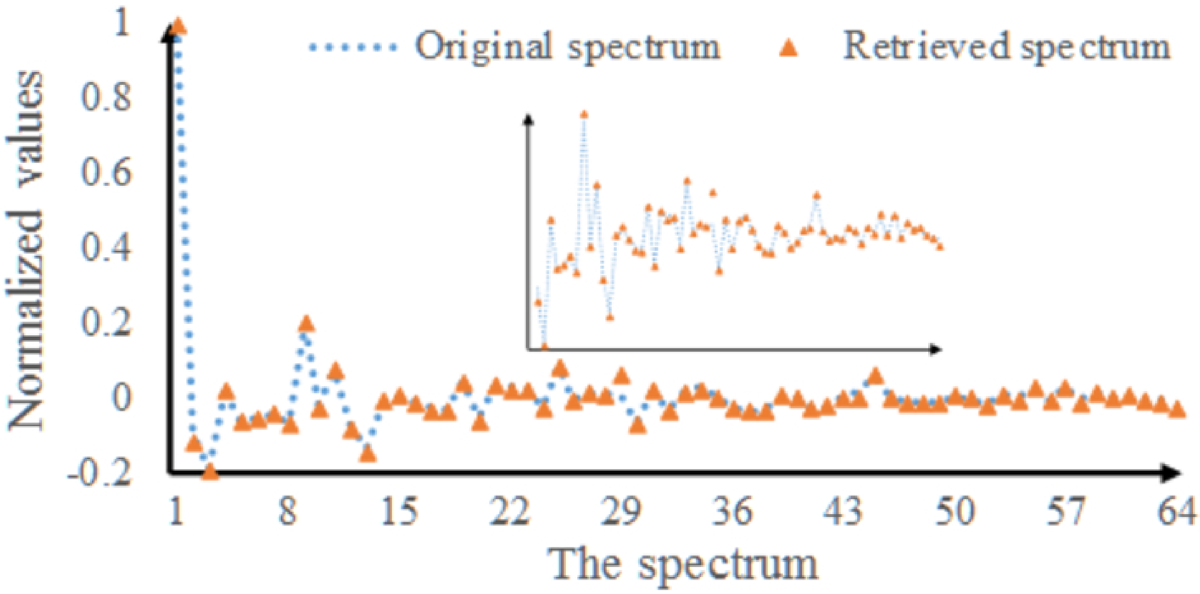
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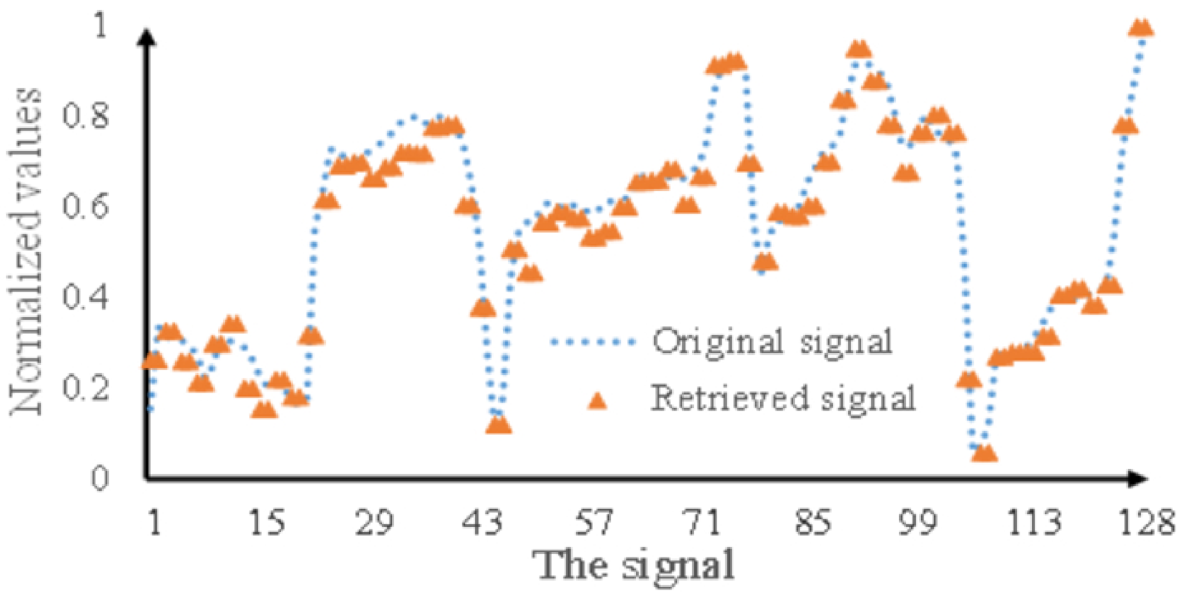
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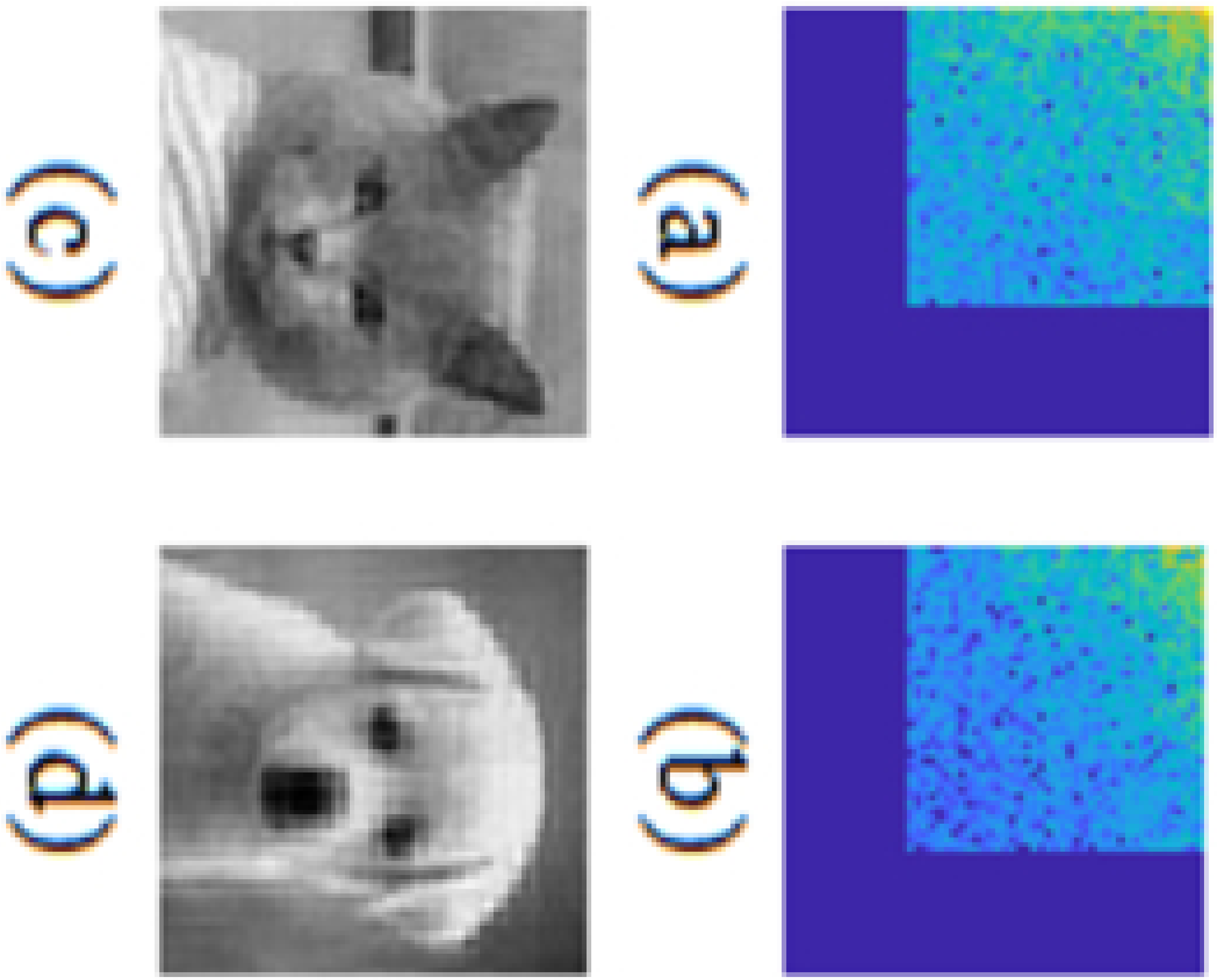

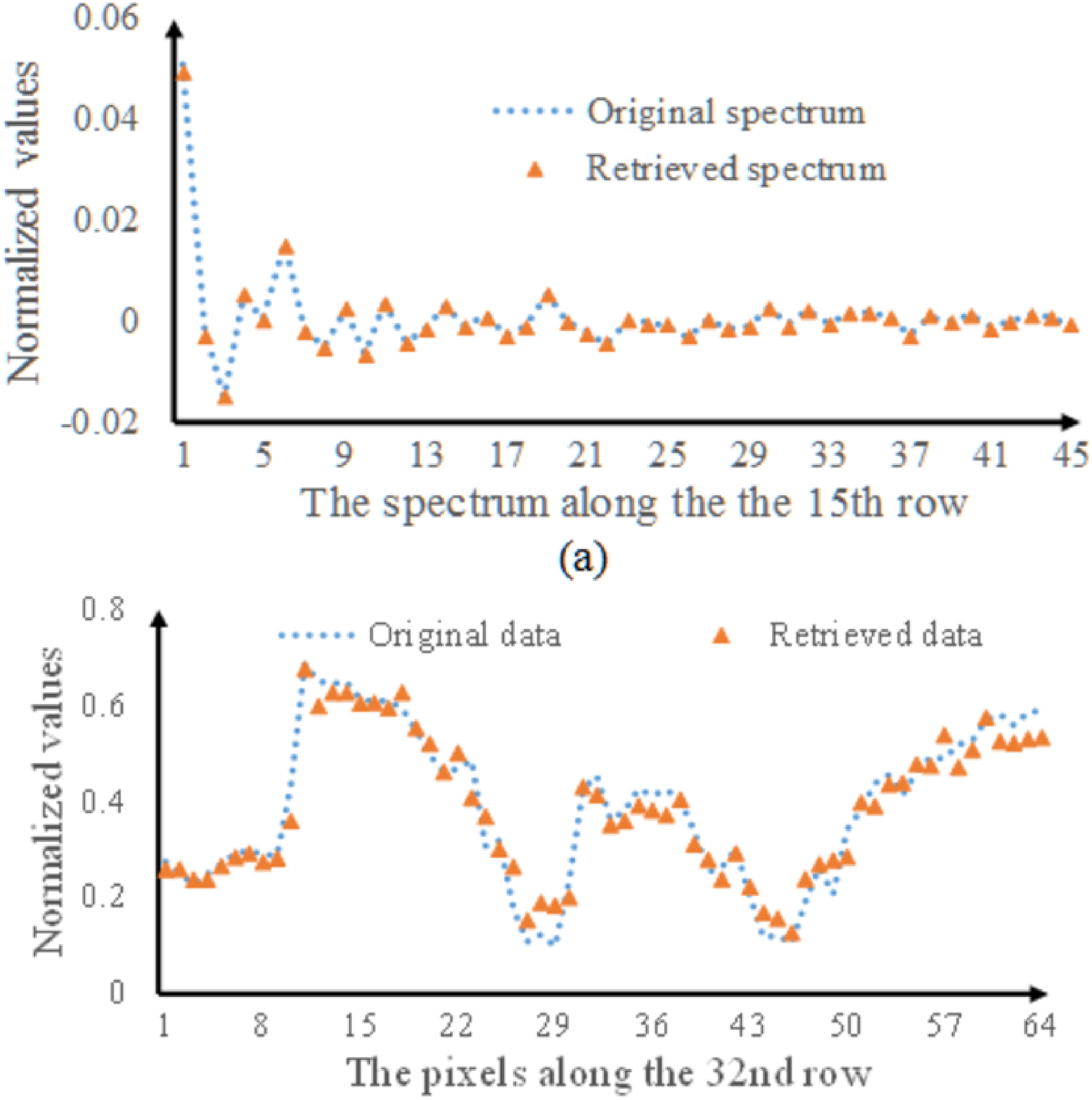
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The pixels along the 32nd row
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