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Unlocking Secure Optical Multiplexing with Spatially Incoherent Light

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While coherent light holds promise for optical multiplexing via orthogonal degrees of freedom, its vulnerability to disturbances often results in information loss and retrieval hurdles, primarily due to its reliance on first-order optical parameters. Herein, an incoherent optical information multiplexing and retrieval protocol is proposed theoretically and verified experimentally by harnessing the two-point field correlations of structured random light. The optical information is securely stored in the multiplexed field correlations which are inaccessible to a direct capture by a camera and retrieved only through rigorous statistical processing. The inherently incoherent nature of random waves makes this protocol crosstalk-free in principle and guarantees its high fidelity even in an extremely noisy environment. The advanced protocol opens new horizons in an array of fields, such as optical cryptography and optical imaging, and it can be relevant for information processing with random waves of diverse physical nature, including acoustic and matter waves.

1. Introduction

Securely storing, mining, and transmitting massive amounts of data has become indispensable in the information age. In this context, optical information multiplexing, which relies on sculpting the physical degrees of freedom (DoFs) of a light field, such as its complex amplitude,[1,2] frequency,[3,4] polarization,[5,6] or the orbital angular momentum,[7,8] has been recognized to carry great promise.[9–11] Consequently, protocols for multiplexing conventional DoFs have been developed and proven to boost optical information capacity within the framework of numerous applications in holography,[7,12] optical encryption and storage,[13–16] as well as optical data transmission.[17–19] However, the so far proposed multiplexing protocols have invariably employed coherent optical fields as information carriers, which open the door to deleterious crosstalk among coherently coupled multiplexed modes (channels). The latter leads to inevitable information loss and channel distortions.[6,7,12] Moreover, the coherent field DoFs are vulnerable to external perturbations,[20–22] thereby setting another roadblock in the way of high-fidelity optical data multiplexing and retrieval.

At the same time, structured random light, manifested by an ensemble of dynamic speckle patterns,[23] carries a wealth of nontrivial information encapsulated into the two-point correlations of fluctuating electromagnetic fields.[24] Importantly, the field correlations furnish a DoF unique to random light and inaccessible to a direct detection device that can only capture single-point quantities, such as the intensity of light. Therefore, employing two-point field correlations in information processing enhances security of the latter. In addition, structured random light is extremely resilient to environmental fluctuations, such as atmospheric turbulence.[25–27] To date, structuring optical field correlations has enabled efficient number factorization,[28] as well

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as noninvasive,[29,30] volumetric,[31] and ghost imaging[32] with classical light. On the other hand, the intrinsic lack of coherence of random fields can be utilized to eliminate coherent coupling effects to implement high-resolution imaging,[12,33] 3D projection holography,[34] and 3D super-resolution microscopy.[35] In addition, there have been noteworthy advances in employing random waves for super-resolution imaging, spatiotemporal wavepacket engineering, and optical metrology.[36–41] Despite field correlation has been proposed as a single information encryption carrier,[29,30,39] the number of information channels it can support is limited and implementing it as a flexible multiplexing degree of freedom of light has yet been achieved.

In this manuscript, we propose to tap into two-point optical field correlations to realize a paradigm shift from coherent to incoherent information multiplexing and retrieval which inhibits pernicious interchannel crosstalk. To this end, we encode all target information into the multiplexed field correlations (MFC) of structured random light. The encoded information, which is crosstalk-free, can then be securely retrieved via statistical processing. We verify our protocol experimentally and demonstrate outstanding robustness of the structured light MFC to noise which empowers optical multiplexing and retrieval even in an extremely noisy environment. We remark that the emerging programmable metasurface technology to structure random waves[6,13,42,43] can facilitate the extension of our protocol not only to electromagnetic waves outside the visible spectral range, but also to acoustic and even matter waves.

2. Theoretical Analysis and Principle

We introduce a (normalized) electric field correlation function $\gamma\ (\mathbf{r}_1, \mathbf{r}_2; t_1 - t_2) = \langle E^*(\mathbf{r}_1, t_1)E(\mathbf{r}_2, t_2)\rangle / \sqrt{I(\mathbf{r}_1, t_1)I(\mathbf{r}_2, t_2)}$ of an ensemble of classical random light beams at a pair of space–time points $(\mathbf{r}_1, t_1)$, $(\mathbf{r}_2, t_2)$ where the angle brackets denote ensemble averaging. In the fully coherent limit, $|\gamma(\mathbf{r}_1, \mathbf{r}_2; t_1 - t_2)| \equiv 1$,[44,45] and the correlation function carries no nontrivial information about the field structure. Mathematically, any bona fide equal-time field correlation $\gamma\ (\mathbf{r}_1, \mathbf{r}_2) = \gamma(\mathbf{r}_1, \mathbf{r}_2; t_1 - t_2)|_{t_1=t_2} = \gamma(\mathbf{r}_1, \mathbf{r}_2; 0)$ of such an ensemble must be expressed as[44,46]

$$\gamma\ \left(\mathbf{r}_1, \mathbf{r}_2\right) = \iint \mathrm{d}\mathbf{v} p\left(\mathbf{v}\right) K^*\left(\mathbf{r}_1, \mathbf{v}\right) K\left(\mathbf{r}_2, \mathbf{v}\right) \tag{1}$$

Hereafter, we restrict ourselves to "equal-time" field correlations to focus on spatial variables. Here $p(\mathbf{v})$ is a (non-negative) power spectrum density normalized to unity, $\iint \mathrm{d}\mathbf{v}p(\mathbf{v}) = 1$ and $K(\mathbf{r}, \mathbf{v})$ is an arbitrary unimodular complex function.

We can then consider an ensemble of electric fields $E(\mathbf{r})$ of a random light beam that is composed of subensembles $\{\Psi_n\}$, such that $E\ (\mathbf{r}) = \sum_n c_n\Psi_n(\mathbf{r}) / \sum_n \overline{c_n^2}$, where $\{c_n\}$ is a set of real uncorrelated random numbers of unit variance that obey the second-order statistic as $\langle c_m c_n^*\rangle = \delta_{mn}$. The bar denotes averaging over the set. It follows that the MFC of the beam is given by

$$\gamma_{\mathrm{multi}}\ \left(\mathbf{r}_1, \mathbf{r}_2\right) = \sum_n \overline{c_n^2}\gamma_n\left(\mathbf{r}_1, \mathbf{r}_2\right) / \sum_n \overline{c_n^2} \tag{2}$$

where $\gamma_n\ (\mathbf{r}_1, \mathbf{r}_2) = \langle\Psi_n^*(\mathbf{r}_1)\Psi_n(\mathbf{r}_2)\rangle$. In our protocol, we treat the power spectrum density $p(\mathbf{v})$ and arbitrary unimodular complex function $K(\mathbf{r}, \mathbf{v})$ as pre-encoded optical information and the encoding rules (keys), respectively. As such, the field correlation function γ_n of each subensemble $\{\Psi_n\}$ is still described by Equation (1) with a specific choice of p_n and K_n and it serves as a generalized mode encapsulating independent ciphertext; see Section S1 (Supporting Information) for further mathematical details.[46] We can infer from Equation (2) that the MFC, which serve as information carriers in our proposal, are inaccessible directly to a camera as second-order correlation functions of classical fields. The recovery of γ_{multi} requires accurate measurements and rigorous mathematical postprocessing, which ensures the security of stored information. Owing to a theoretically unlimited number of self-defined keys K_n, the number of generalized modes γ_n in our MFC protocol is, in principle, unlimited.

In **Figure 1**, we illustrate a protocol for secure information multiplexing and retrieval through encoding and decoding optical field correlations. To generate structured random light with desired MFC, we first associate a complex random matrix with any pictorial element of the information to be stored and transform a set of resulting noisy pictures into a set of subensembles (complex field amplitudes) $\{\Psi_n\}$ with the aid of the corresponding encoding rules (keys) K_n. Next, we form a linear superposition of complex amplitudes $\{\Psi_n\}$ with random coefficients $\{c_n\}$ to synthesize a complex-amplitude random electric field serving as an ensemble realization of structured random light depicted in Figure 1a. The complete ensemble is generated by repeating the above steps. At every step, we only refresh the random matrices and random coefficients $\{c_n\}$ which are created by the scientific computing software MATLAB. At last, we convert each complex amplitude ensemble realization into a phase hologram via the complex-amplitude modulation encoding algorithm, resulting in a holographic video. A structured random light beam with tailored MFC can then be perfectly reproduced with the aid of a light modulation device, such as a spatial light modulator or digital micromirror, employing digital holography; we schematically illustrate this step in Figure 1b. We can recover the MFC by statistically processing the generated random light. We stress that the encoded information can only be recovered from the MFC by applying the corresponding set of encryption keys $\{K_n\}$ (Figure 1c).

In the experiment, we experimentally synthesize such structured random light with MFC based on incoherent superposition of ensemble realization $E(\mathbf{r})$.[47,48] The modulation of the magnitude and phase of each realization are achieved by employing a spatial light modulator (SLM). **Figure 2** illustrates the experimental apparatus used for synthesizing incoherent light and measuring its MFC. A linearly polarized light beam, emitted from a He–Ne Laser (THORLABS, model HNLS008L-EC) operating at a carrier wavelength of 632.8 nm, is transmitted through a half-wave plate (HP) and is expanded by the beam expander (BE, with a 5× magnification). The light beam is then transmitted through the first beam splitter (BS_1) and it illuminates the phase-only spatial light modulator 1 (SLM_1, Meadowlark Optics, 8-bit and 1920×1200 pixels with 8 $\mu\mathrm{m}^2$). To produce high-quality optical fields, the SLM_1 must be calibrated to a linear 2π phase response over the 256 gray level at a wavelength of 632.8 nm. The prepared holographic video is loaded on SLM_1, and the reflected speckles in the first—positive or negative—diffraction order constitute our structured random light. We employ a 4f optical imaging system with an iris to select the desired

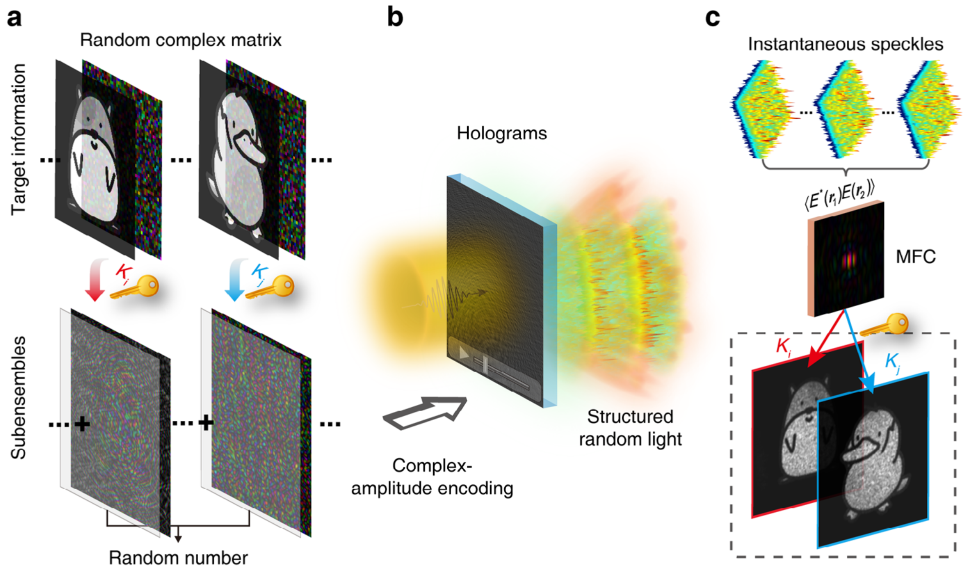

Figure 1. Principles of information multiplexing and retrieval with field correlation multiplexing protocol. a,b) Schematics of a protocol for encoding multiple optical images into a structured random light beam using Equation (2). c) Instantaneous speckles of the structured optical field and the recovered information from the MFC by applying encoding rules.

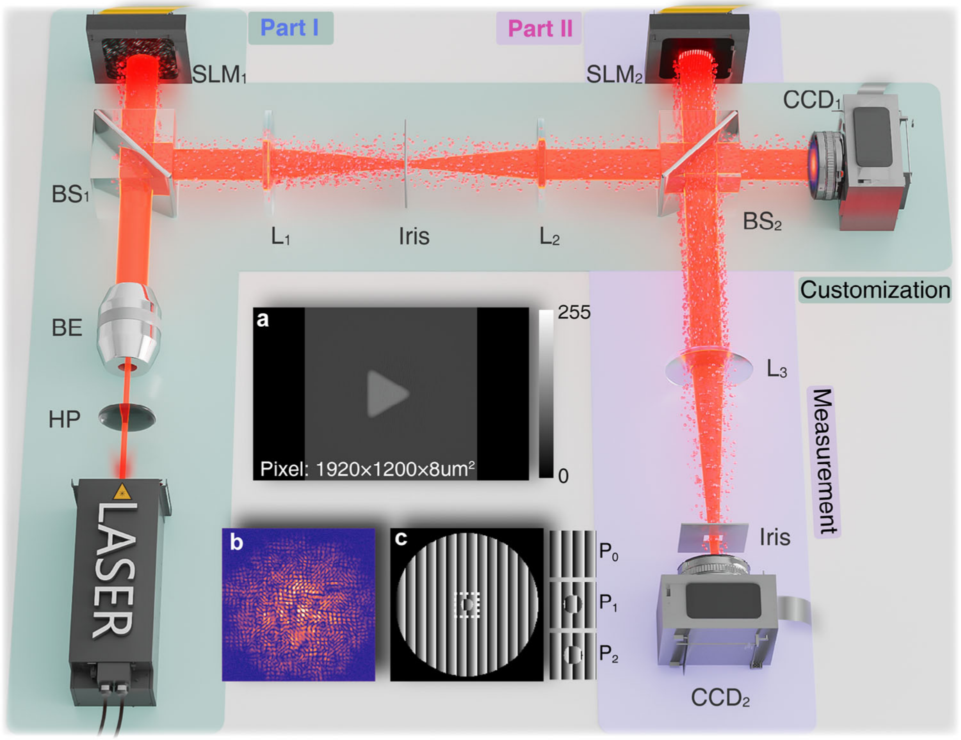

Figure 2. Experimental setup for customization (part (I) in cyan background) and measurement (part (II) in light lavender background) of a structured random light with the desired MFC. a) Screenshot of the holographic video loaded onto the SLM_1 screen. b) Example of an instantaneous intensity recorded by the CCD_1 camera. c) Holograms on the SLM_2 with three imparted phase patterns: HP, half-wave plate; BE, beam expander; BS_1 and BS_2, beam splitters; SLM_1 and SLM_2, spatial light modulators; L_1, L_2, and L_3, thin lenses with focal lengths f_1 and f_2 = 15 cm and f_3 = 10 cm; and CCD_1 and CCD_2, charge-coupled device cameras.

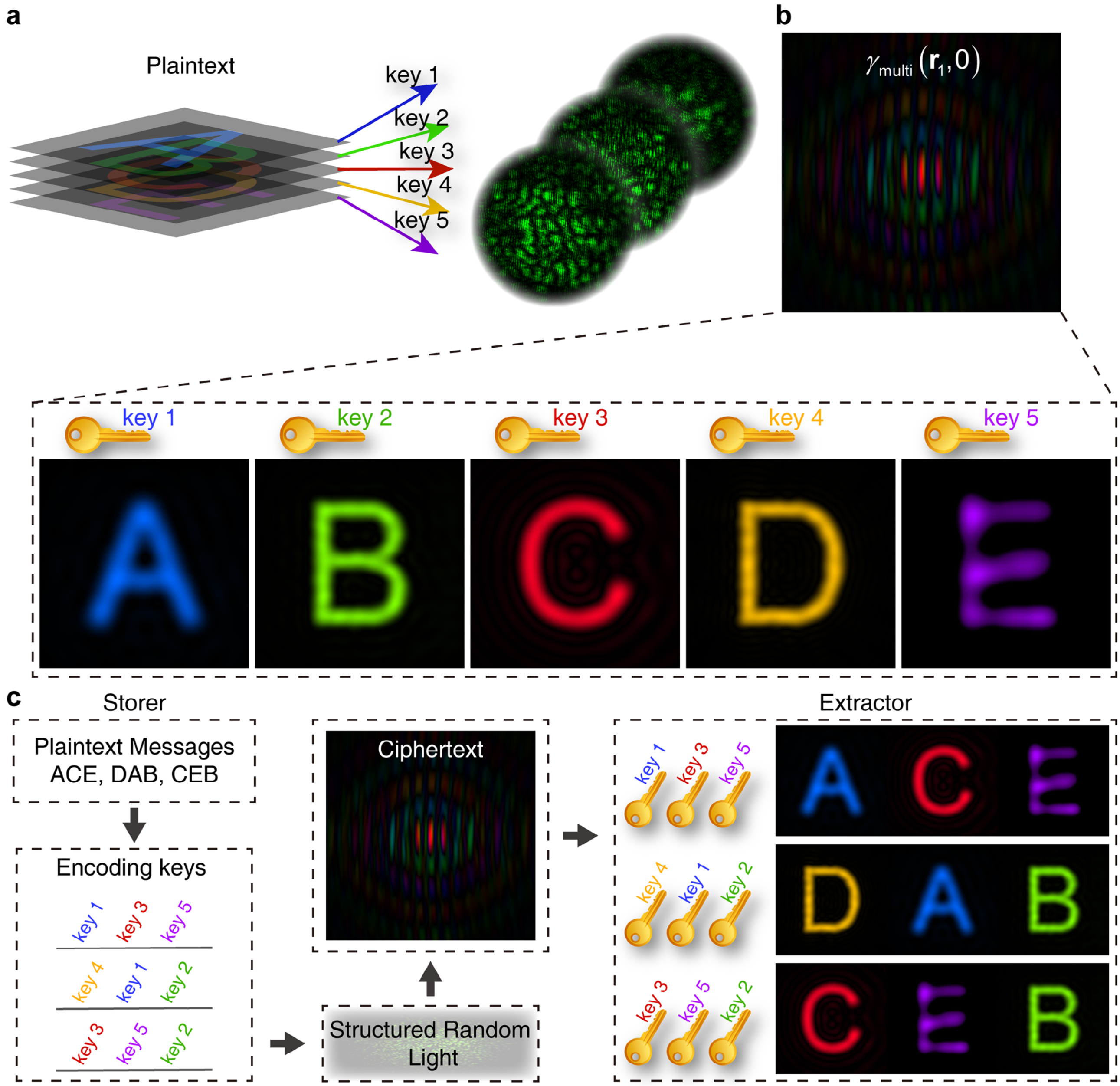

Figure 3. Proof-of-concept experimental demonstration of employing the MFC of structured random light to store and retrieve optical information. a) The plaintexts (“A,” “B,” “C,” “D,” and “E”) are encoded into structured random light (some examples of the dynamic speckle patterns are displayed on the right). b) All information stored in the MFC of the beam can be experimentally retrieved with the aid of the perturbed Fourier intensity method (see the Section S1 in the Supporting Information for details). The plaintexts are extracted from the MFC of light with respective matched encryption keys. c) Secure information encryption and decryption protocol between the storer and retriever.

structured random light (or speckles). The dynamic speckles $I^{\text{sp}}(\mathbf{r})$ are recorded by a charge-coupled device (CCD$_1$) camera (Sony IMX252, 2048 × 1536 pixels with 3.45 μm^2). We obtain a smooth intensity profile of the generated spatially incoherent light, i.e., $S(\mathbf{r}) = \int I^{\text{sp}}(\mathbf{r},t)\text{d}t \approx \sum_{n=1}^{N} I^{\text{sp}}(\mathbf{r})/N$, because of the ergodicity of statistically stationary light. The equality only holds if the number of ensemble realizations N is large enough, and we take $N = 5000$ in the experiments. We exhibit our experimental procedure for structuring a random light in the module with cyan background in Figure 2. The setup for measuring the MFC of the generated structured random light is illustrated in part II of Figure 2 (light lavender background). The generated structured random light with the MFC reflected by the BS$_2$ is imaged onto the screen of the second phase-only SLM (SLM$_2$, Meadowlark Optics, 1920×1200 pixels with 8 μm^2) by the 4f optical imaging system. We encode three phase functions $O_\beta(\mathbf{r})$ into the holograms with the values of 1, $\exp(\text{i}2\pi/3)$ and $\exp(-\text{i}2\pi/3)$ of P_0, P_1, and P_2, respectively (Figure 2c). The beam reflected by the SLM$_2$, which

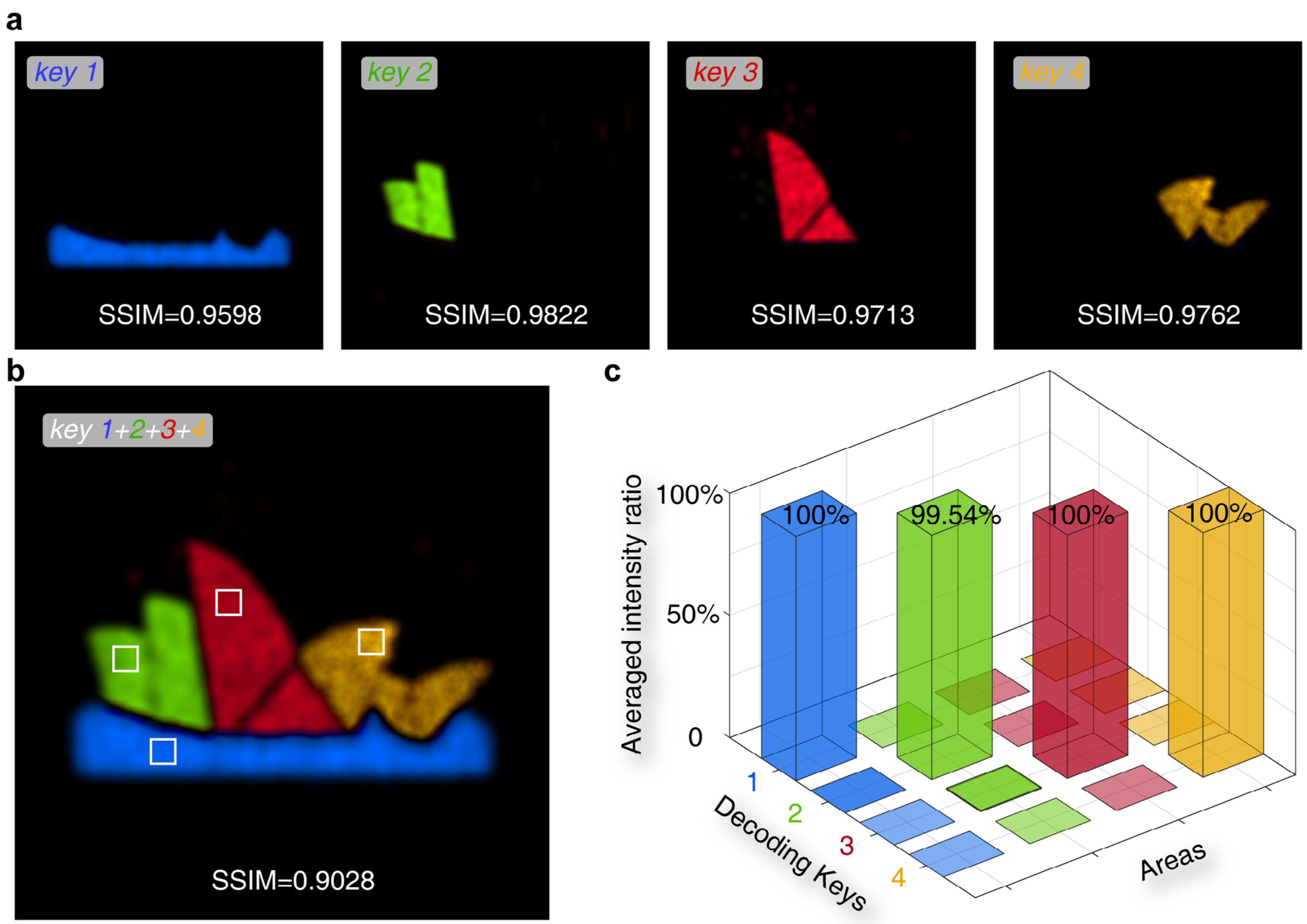

Figure 4. Multiplexing field correlations for target image segment multiplexing. a) Experimental decryption of individual segments of the Sydney Opera House image from a structured random light beam with the help of matched encryption keys. The SSIM index adopted to evaluate the quality of image recovery is given in each panel. b) The image of the entire Sydney Opera House is decoded as we apply all encryption keys simultaneously. c) Decoded channel crosstalk analysis of randomly selected areas marked by the white rectangles in panel (b).

is loaded with the above-said holograms, is focused by the lens L_3, and an iris is used to select the first positive diffraction order (the desired perturbed field). The CCD$_2$ (Sony IMX252, 2048×1536 pixels with 3.45 μm^2) camera is in the rear focal plane of the lens, whereas the SLM$_2$ is situated in its front focal plane. The intensity of light captured by the CCD$_2$ is given by Equation (S11) (Supporting Information). Finally, we can obtain the measured MFC of the structured random light with the aid of Equation (S12) (Supporting Information). We describe the details of hologram design, statistical processing method, and information retrieval behind our protocol in Sections S2–S4 (Supporting Information).

3. Experimental Demonstration

We now outline the experimental verification of our protocol which can access a range of key-dependent information pieces encoded into a structured random light beam. In **Figure** 3a, we display the plaintexts "A," "B," "C," "D," and "E" encoded into the beam, following the above encryption rules. We mark matching encryption keys and MFC channels with the same color. We provide the cumulative holographic video (Movie S1, Supporting Information) and the video stream (Movie S2, Supporting Information) of the generated dynamic speckles in the Supporting Information. The corresponding customized encryption keys are furnished in Table S1 (Supporting Information). The MFC of generated structured random light can be accurately recovered by using a perturbed Fourier intensity method as shown in Figure 3b. Next, we employ the said encryption keys to extract the plaintexts from the recovered MFC (see Section S4 in the Supporting Information for technical details). A strict one-to-one mapping of the encryption keys and decryption results ensures the reliability of our protocol (see the bottom of Figure 3b).

Informed by our customized code chart, we propose the following secure information encryption and decryption protocol between a storer (Tom) and retriever (Amy). Let us assume that Tom wants to store a set of confidential messages "ACE," "DAB," and "CEB" for Amy to retrieve later. According to the code chart in Figure 3b, he first defines three key sequences for his messages and encodes all essential letters into the MFC of a structured random light beam (left panel of Figure 3c). Amy can successfully retrieve the correct (plaintext) messages with the defined encryption key sequences (right panel of Figure 3c) once she receives

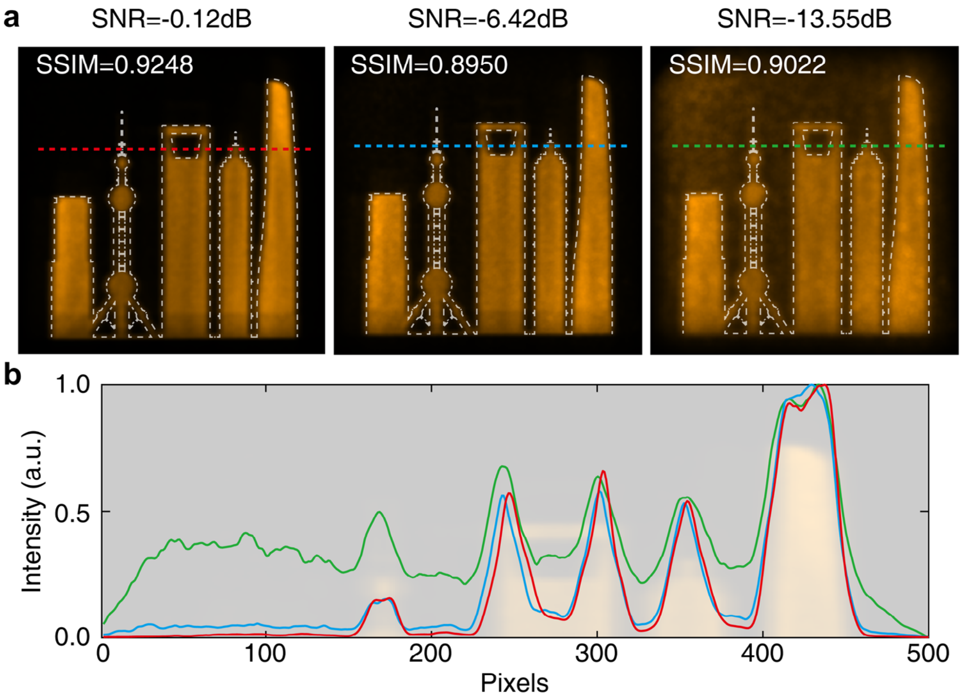

Figure 5. Robustness to noise of the information retrieved from structured random light. a) Experimentally recovered images of the Oriental Pearl TV Tower complex in a white noise environment of adjustable signal-to-noise ratio. b) Normalized visibility curves (cross sections) of the retrieved images along the dashed lines indicated in panel (a).

such beam through a public channel and then recovers the MFC (ciphertext). In addition, a chronological set of encryption key sequences can enable video message display via the above scenario as illustrated in Movie S3 (Supporting Information).

Heretofore, we have demonstrated how to extract information by applying the encryption keys in a chronological sequence. By the same token, we can apply certain encryption keys at once to retrieve certain slivers of encoded information. To illustrate this possibility, we divide a target image, the Sydney Opera House, say, as an example of nontrivial shape, into four individual segments (Figure S3a, Supporting Information). All segments of the target image are encoded into the MFC via matching keys (Table S2, Supporting Information). We show the dynamic speckles of such a structured random field in Movie S4 (Supporting Information), and we exhibit the experimentally recovered MFC in Figure S3b (Supporting Information). Next, we show in **Figure 4** a four individual segments of the Sydney Opera House image which are reconstructed from the MFC by adopting the matching keys, respectively. If all encryption keys, that is $\{K\} = \sum_{n=1}^{5} K_n$, are applied simultaneously, the entire Sydney Opera House image can be faithfully reproduced (Figure 4b). We adopt a structural similarity index (SSIM, see Section S5 in the Supporting Information for details) to evaluate the quality of the retrieved image. Moreover, the image quality can be boosted even further by increasing the size of the speckle ensemble (Figure S4, Supporting Information). We have also quantitatively analyzed the channel crosstalk for the image segment reconstruction among randomly selected areas (50 × 50 pixels) that are marked by white rectangles in Figure 4b. The averaged intensity ratios of the segments, reconstructed with the corresponding encryption keys, are nearly equal to unity, and the mismatched ones are virtually equal to zero, as illustrated in Figure 4c. The scheme demonstrates ultralow crosstalk due to the fact that each field-correlation channel in incoherent light is ensured to be independent by multiplying with a random number. In practice, however, it is subjected to a finite number of random electric fields. In addition, our protocol can also be applied to store and retrieve high contrast color images by employing only three distinct field correlation patterns to represent three primary colors (red, green, and blue) (Figure S5, Supporting Information).

4. Robustness to Noise Demonstration

Structured random light is known to be robust against random perturbations.[26,27] We now demonstrate the prominent advantage of our protocol over the competition—its remarkable resilience to noise. Here we consider white noise as a generic example. We then add white noise to a structured random light beam and vary signal-to-noise ratio, defined as SNR $= 10\log_{10}[\int I^{\mathrm{s}}(\mathbf{r})\mathrm{d}\mathbf{r} / \int I^{\mathrm{N}}(\mathbf{r})\mathrm{d}\mathbf{r}]$, where $I^{\mathrm{s}}(\mathbf{r})$ and $I^{\mathrm{N}}(\mathbf{r})$ denote the intensity of an image encoded into a random light beam at the source, and that of additive noise, respectively. The signal corresponds to an elaborate image of the Oriental Pearl TV Tower complex in Shanghai. We supply the associated encoding key list in Table S3 (Supporting Information). Further, we provide experimentally captured dynamic speckles of the structured random light beam of variable SNR in Movie S5 (Supporting Information). We also display the corresponding experimentally recovered MFC with additive white noise in Figure S6 (Supporting Information). In **Figure 5**, we exhibit our retrieved images (top row) and their normalized visibility curves (bottom panel) that correspond to the locations marked by the colored dashed lines in the top row. The retrieved images for SNR = −0.12 and −6.42 dB (signal energy is 49.31% and 18.57% of the total energy, respectively) have a high resolution. Remarkably, even as SNR sharply drops to −13.55 dB (signal energy is as low as about 4.2% of the total energy), the target images are still easily recognizable, although the image background appears a little hazy. We can eliminate the background noise to a certain extent by the zeroing operation. Finally, we evaluate the SSIM indices of the simulated and experimental results for the retrieved images and present them in each panel to the figure. The indices can reach values as high as 0.92 and 0.9 for the simulated (see Figure S7 in the Supporting Information) and experimental (Figure 5) results, respectively. It is worth noting that the SSIM index only gently tapers off from 0.9314 to 0.9077 as the fraction of signal energy relative to noise plunges from 100% to 4.2% (see Figure S7 in the Supporting Information). The experimental SSIM index of the middle image is slightly lower than that of simulation due to residual background noise.

5. Discussion

We have proposed and implemented an efficient protocol for secure information multiplexing and retrieval that utilizes a unique DoF of the structured random light, the two-point field correlations. In the proposed protocol, we treat multiplexed field correlations as our ciphertext, with each (normalized) field correlation function carrying an independent sliver of information. The intermode crosstalk has been suppressed due to the inherently incoherent structure of random light fields. The capacity of our protocol is limited in practice by the pixel size of the available spatial light modulator, which sets an upper bound on the number of generalized modes that can be reliably multiplexed. We can boost the capacity by employing a suitably designed metasurface in lieu of a standard liquid-crystal display (see Section S6 in the Supporting Information for details). Our protocol can also be readily extended to incorporate additional DoFs (e.g., frequency[31] and polarization[34]) of light to further enhance information multiplexing capacity. At the same time, our approach guarantees security of information multiplexing and retrieval even with a simple set of encryption keys because the two-point field correlations, encapsulating our ciphertext, are inaccessible to direct capture with a camera. Finally, by taking advantage of the resilience of structured random light to external perturbations, we can achieve high-fidelity information retrieval in a very noisy environment. Although the phase-only liquid-crystal SLM with a slow response time limits the synthesis speed of incoherent light, this constraint can be overcome by using high-speed spatial light modulators, such as amplitude-only digital micromirror devices.[49] We anticipate that our protocol can be extended to encompass noisy acoustic or matter waves with the aid of the appropriate metasurface technology.[43]

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Y.C. and C.L. contributed equally to conceptualization. X.L. and S.A.P. contributed equally to methodology. X.L., X.F.L., and X.P. contributed equally to investigation. X.L. and F.W. contributed equally to data curation and software. S.A.P., Y.C., and C.L. contributed equally to supervision and project administration. X.L. contributed to visualization. X.L., C.L., and S.A.P. contributed equally to writing the original draft. All authors contributed equally to writing the review and editing.

Data Availability Statement

All other data are available in the article and its supplementary files or from the corresponding authors upon request.

Keywords

field correlation, light manipulation, optical coherence, optical encryption, optical multiplexing, structured random light

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