

Ultraviolet–visible bipolar photodetector for hardware–software collaborative encrypted information transmission

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ABSTRACT: Secure optical communication increasingly demands encryption strategies that go beyond software-based algorithms and penetrate the physical layer. Here, we demonstrate an ultraviolet–visible bipolar photodetector that enables hardware–software collaborative encrypted information transmission by introducing signal polarity as an intrinsic physical key. The device is constructed using a vertical back-to-back N–I–P–I–N (N, I, and P denote n-type semiconductor, intrinsic layer, and p-type semiconductor, respectively) architecture based on a perovskite/organic hybrid heterojunction, where a thin p-type interlayer reconstructs the built-in electric field distribution and enables wavelength-dependent polarity reversal. As a result, the photodetector exhibits balanced bipolar responsivity with peak values of -0.16 and $+0.13$ A·W⁻¹ in the ultraviolet and visible regions, respectively, microsecond-level response time, and a high specific detectivity exceeding 10^{12} Jones. By combining polarity-encoded optical signals with software-based principal component analysis and spatial permutation, a multi-key image transmission system is realized. Image reconstruction requires simultaneous access to both the material-defined polarity key and the algorithmic key. The image reconstructed after decryption at the receiving end has high fidelity (the peak signal-to-noise ratio (PSNR) > 30 dB). This work demonstrates how rational device architecture design can elevate photodetectors from passive receivers to active security primitives, opening a new avenue for physical-layer encryption in high-speed and covert optical communication.

KEYWORDS: bipolar photodetector, encrypted optical communication, perovskite, organic heterojunction, back-to-back structure

1 Introduction

Free-space optical communication, with its advantages of high bandwidth, low crosstalk, and resistance to electromagnetic

interference, has become an important technology for high-speed information transmission [1–3]. A typical optical communication link consists of a transmitter, a transmission channel, and a receiver [4]. The photodetector (PD) at the receiver is responsible for converting optical signals into electrical signals and is crucial in determining the sensitivity and reliability of the link [5]. However, traditional detectors typically only have a single polarity output, posing a significant risk of information leakage [6]. Developed secure optical communication detectors mainly carry physical layer keys through multi-dimensional distinguishable responses, such as wavelength/polarization or specific responses modulated by

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external fields [7, 8]. However, the former often relies on additional optical/complex structures and is prone to crosstalk, while the latter introduces energy consumption issues [9, 10]. In contrast, bipolar responsive PDs can directly output positive/negative polarity signals in different wavelength bands, using signal polarity as the physical key dimension for decision-making [11, 12]. This improves encryption flexibility and anti-eavesdropping capabilities without significantly increasing system complexity [13].

From a device mechanism perspective, bipolar response PDs can generally be classified into three types: photoconductive, transistor, and diode [14]. Although the implementation paths differ, their essence is the same [15]. Under different illumination conditions, the dominant transport and extraction paths inside the device are reconstructed, causing the collection direction of photogenerated carriers between electrodes to change, thus exhibiting a reversal of photocurrent polarity in the external circuit [14, 16]. Photoconductive devices typically operate under external bias [17]. Modulation in wavelength or light intensity alters trap occupancy and space charge distribution, thereby modulating the local electric field and equivalent injection/extraction conditions, altering the dominant carrier and effective drift direction, ultimately leading to a reversal of the net collection direction. While simple in structure and high in signal amplitude, their output is highly dependent on bias and the trapping process, prone to hysteresis and drift, and sensitive to light intensity and environmental factors [18]. Transistor devices rely on gate voltage to regulate channel carrier density and injection barrier, switching carrier transport between electron-dominated and hole-dominated modes, thus achieving tunable bipolar output. Polarity and amplitude can be continuously adjusted with gate voltage [19–21]. However, hysteresis and uniformity issues caused by the gate dielectric and interface states are more pronounced, and parasitic capacitance and channel modulation limit high-frequency response [22]. Diode-type devices, based on bandgap engineering, utilize a vertically stacked structure to control carrier generation sites and the built-in electric field within the film [23]. When the incident wavelength changes, photogenerated carrier generation sites migrate, and the directions of the built-in electric field differ at different sites, leading to a reversal of the external current polarity. Their compact structure eliminates the need for external bias/gate voltage, facilitating integration with high-speed circuits. However, the bipolar output is highly sensitive to the internal electric field distribution and interface band bending. If the potential drop is concentrated at the interface and the effective bulk electric field is insufficient, bulk recombination enhancement occurs, resulting in unclear switching and difficulty in achieving both positive and negative responses (Fig. 1(a)). In addition, from the perspective of secure optical communication, most existing photodetection systems remain fundamentally constrained by unipolar signal reception, where information is encoded solely in signal amplitude and protected by software-based keys [24–26]. Such architectures lack intrinsic physical-layer distinguishability, making them vulnerable once algorithmic keys are compromised. Bipolar PDs, capable of delivering opposite polarity outputs under different excitation conditions, offer an opportunity to introduce an additional, material-defined information dimension. However, achieving a fast, balanced, and spectrally resolvable bipolar response in a compact, bias-free diode-structured device remains challenging due to the difficulty of simultaneously controlling carrier generation depth, internal electric field distribution, and carrier extraction pathways [11–13].

In this work, we address these challenges by designing a vertical

back-to-back N–I–P–I–N (N, I, and P denote n-type semiconductor, intrinsic layer, and p-type semiconductor, respectively) PD based on a perovskite/organic hybrid heterojunction. By inserting a thin p-type copper thiocyanate (CuSCN) layer within the photoactive region, the built-in potential is deliberately reconstructed, forming two internal electric field regions with opposite polarities. Coupled with the complementary ultraviolet–visible (UV–vis) absorption characteristics of the perovskite and organic layers, this architecture enables wavelength-dependent carrier generation and deterministic polarity reversal with high symmetry and stability. More importantly, the resulting bipolar polarity is elevated from a device characteristic to a physical-layer encryption key that cannot be emulated by unipolar detectors. By integrating this material-enabled polarity key with lightweight software obfuscation, we demonstrate a hardware–software collaborative encryption paradigm that achieves secure, high-speed, and covert optical image transmission.

2 Experimental

2.1 Materials

Lead(II) chloride (PbCl_2), methylamine hydrochloride (MAH), poly(3-hexylthiophene-2,5-diyl) (P3HT), cassiterite (SnO_2), and phenyl-C61-butyric acid methyl ester (PCBM) were purchased from Xi'an Polymer Light Technology Corp. CuSCN was purchased from Aladdin. Dimethyl sulfoxide (DMSO), N,N-dimethylformamide (DMF), isopropanol (IPA), and chlorobenzene (CB) were purchased from Sigma-Aldrich. Diethyl sulfide was purchased from J&K Scientific.

2.2 Fabrication of PDs

First, an aqueous dispersion of SnO_2 was spin-coated onto a clean indium-tin oxide (ITO) substrate at 3000 rpm for 30 s. Then, the SnO_2 -coated ITO substrate was annealed at 150 °C for 30 min to form an electron transport layer. Simultaneously, a MAPbCl_3 precursor solution was prepared: 278.4 mg PbCl_2 and 67.5 mg MAH were dissolved in 1 mL of a mixed solvent of DMF and DMSO (volume ratio 1:1) and stirred until completely dissolved. 50 μL of this precursor solution was added dropwise to the substrate and spin-coated at 2000 and 5000 rpm for 10 and 20 s, respectively. In the last 5 s of the spin-coating process, 150 μL of chlorobenzene antisolvent was added dropwise. After annealing at 100 °C for 10 min, a MAPbCl_3 perovskite layer was obtained. Then, 50 μL of CuSCN solution (30 mg CuSCN dissolved in 1 mL diethyl sulfide) was spin-coated onto a perovskite substrate at 3000 rpm for 30 s, followed by annealing at 100 °C for 2 min to form a p-type intermediate layer. Next, 50 μL of organic bulk heterojunction (OBHJ) solution (36 $\text{mg}\cdot\text{mL}^{-1}$, P3HT:PCBM = 1:0.8 w/w) was spin-coated at 1000 rpm for 60 s, followed by annealing at 100 °C for 10 min to obtain an OBHJ layer. Then, 30 μL of bathocuproine (BCP) solution (0.5 $\text{mg}\cdot\text{mL}^{-1}$ dissolved in isopropanol) was spin-coated at 3000 rpm for 30 s to deposit an electron transport layer. Finally, a 90 nm thick silver electrode was deposited by thermal evaporation.

2.3 Characterization and measurement

The field-emission scanning electron microscopy (FESEM, SU8100, Hitachi) was utilized to characterize the morphology of different functional layers. The X-ray diffraction (XRD) patterns were

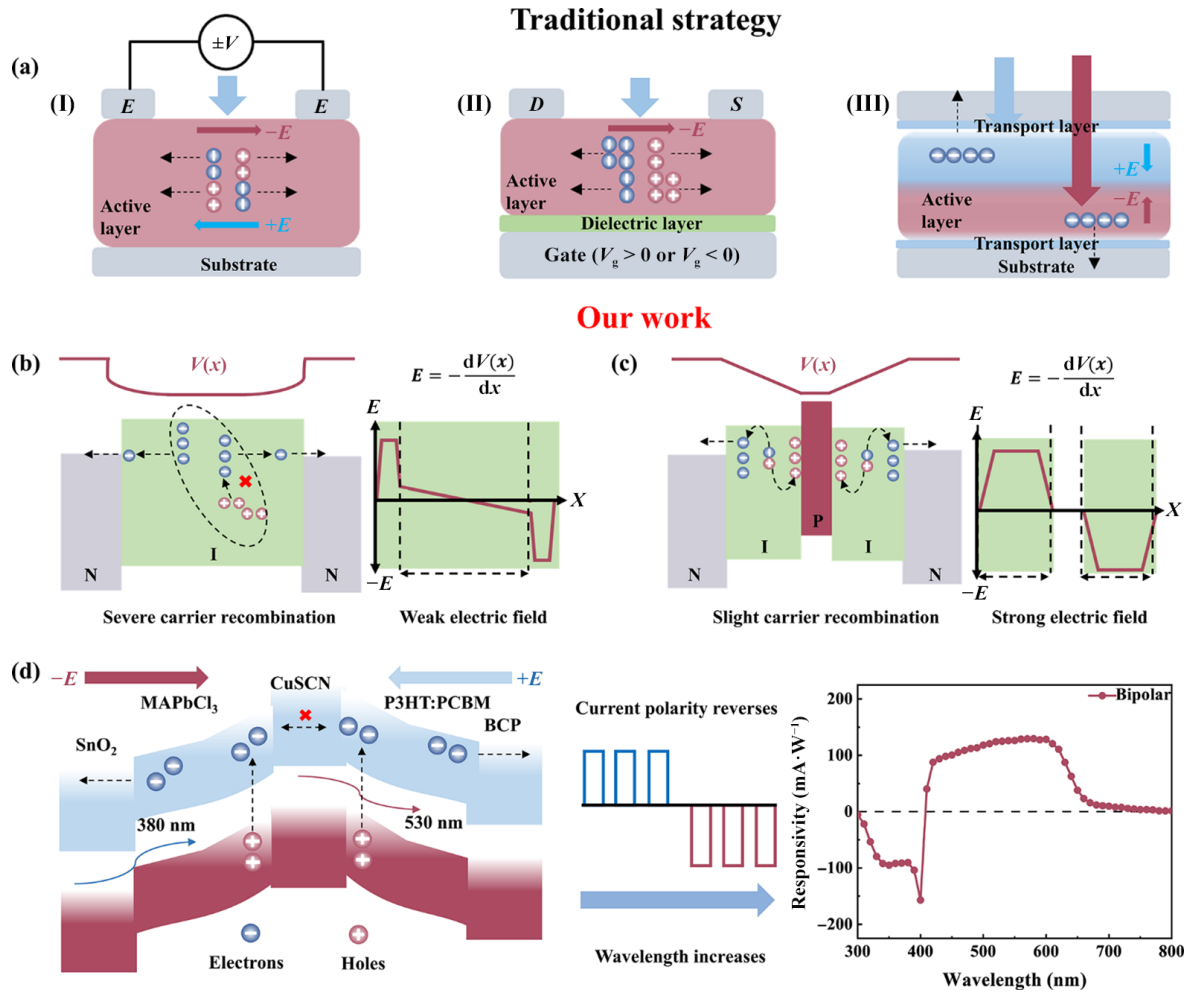


Figure 1 Different design strategies for bipolar PD. (a) Different conventional bipolar PDs: (I) photoconductive bipolar PD, (II) transistor-type bipolar PD, and (III) diode-type bipolar PDs. (b) Built-in field and carrier transport in a N-I-N device. (c) Built-in field and carrier transport in a N-I-P-I-N device. (d) Wavelength-dependent bipolar response mechanism.

characterized by an X-ray diffractometer (Bruker D8-Advance A25). An UV-vis spectrophotometer (Shimadzu, UV-3600) was used to measure the absorbance spectra. Ultraviolet photoelectron spectroscopy (UPS) of different functional layers was characterized by X-ray photoelectron spectroscopy (Thermo Fisher Scientific, Escalab 250Xi). The cross-sectional potential of the PD was measured by the Kelvin probe force microscopy (KPFM, Bruker, Multimode 8). The photoresponse of the PDs was acquired using a semiconductor analyzer (Keithley 4200). The response time is measured by the signal generator (RIDEN RD6006P) controlling the light-emitting diode (LED) to emit high-frequency light, the oscilloscope (UNI-T MSO7204X) acquiring the device's response waveform, and analyzing its rise and fall times. Signal transmission utilizes an STM32 microcontroller to drive an LED to emit an optical signal, which is then converted into an electric signal by a photodetector, and finally sampled from the electrical signal by an AD9200.

3 Results and discussion

3.1 Device structure design

For vertical bipolar photodiode structures, Fig. 1(b) illustrates the limitations of N-I-N architectures which has the thick photoactive

layer and numerous bulk defects: The built-in potential is more likely to drop primarily near the interface of the transportation layer and perovskite, resulting in insufficient potential gradient within the bulk phase, thus weakening the separation and directional extraction of photogenerated carriers in the bulk phase. Therefore, with the extension of the carrier transit time in the bulk phase, the recombination probability increases, leading to reduced collection efficiency of carriers and low bipolar response. This phenomenon indicates that when the electric field is primarily confined to the vicinity of the interface, cross-wavelength polarity reversal is difficult to maintain repeatability and exhibit clear polarity discrimination. Therefore, the depletion region needs to extend sufficiently into the film to cover the main absorption layer, thereby ensuring a reliable bipolar response. To address this issue, we introduce a thin p-type layer into the vertical photodiode structure to construct an N-I-P-I-N back-to-back structure. Its core function is reflected in the reconstruction of the built-in potential and electric field distribution shown in Fig. 1(c). Due to the significant difference in Fermi levels, the electron blocking layer inside the film and the electron transport layer at both ends form two strong built-in electric fields in opposite directions. This strong electric field promotes carrier separation and reduces recombination losses. The bipolar response originates from the

differences in light penetration depth and opposite electric field distributions within the device. Light of different wavelengths exhibits different penetration depths, and consequently, the primary generation sites of photogenerated carriers vary accordingly. The reverse built-in electric field in the N-I-P-I-N structure can directionally extract charge carriers generated in different regions to the approaching electrodes, thus exhibiting a bipolar response with wavelength-switching polarity (Fig. 1(d)).

Furthermore, Fig. 1(d) also emphasizes the spatial constraint of electron transport by the intermediate p-type layer, which can act as an electron barrier, inhibiting electron migration across the middle region to the other side, thereby reducing coupling and mixing of electron collection under different excitation conditions. This mechanism helps improve the reliability of polarity determination, making the wavelength distinction between positive and negative outputs clearer, and further improving the accuracy and repeatability of polarity output.

3.2 Material characterization of the photodetector

As shown in Fig. 2(a), we constructed a vertically stacked multilayer device ITO/SnO₂/MAPbCl₃/CuSCN/P3HT:PCBM/BCP/Ag. SnO₂ and BCP were employed as electron transport layers, respectively. CuSCN, as a p-type layer, was inserted between two photoactive layers, transforming the device from a N-I-N architecture to a N-I-P-I-N structure. This creates two tandem junction/depletion regions within the film, corresponding to built-in electric field regions with opposite polarities. Cross-sectional SEM images show that each functional layer forms a continuous and dense film with

clear interlayer interfaces. No obvious voids or large-area delamination gaps were observed, indicating that the multilayer structure achieves good interlayer contact in the vertical direction. Such interfacial continuity is important for the stable operation of bipolar devices: The continuous and compact layer-to-layer contact helps maintain the intended interfacial potential distribution and reduces the risk of shunting caused by pinholes, voids, or local delamination, thereby providing a structural basis for suppressing the dark current. The XRD patterns in Fig. 2(b) show three diffraction peaks at 15.4°, 31.3°, and 48°, corresponding to the (100), (200), and (300) planes of MAPbCl₃, respectively [24, 25]. This indicates that the MAPbCl₃ film exhibits clearly distinguishable crystalline phase diffraction peaks, reflecting its good crystalline order and phase purity. The diffraction signal of the OBHJ blend film is generally weak and exhibits broad peak characteristics, indicating limited long-range order. This phenomenon is consistent with the general structural characteristics of OBHJ blend systems: Acceptor incorporation weakens the crystallinity of P3HT, reducing the intensity of crystallization-related peaks in XRD and causing peak broadening. In most reports, the characteristic (100) diffraction peak of P3HT at 5.4° can still be observed in the blend film [26, 27]. Figure 2(c) shows the UV-vis absorption spectra, indicating that the absorption edge of the MAPbCl₃ layer is located in the ultraviolet region (300–400 nm), while the absorption edge of the OBHJ layer extends to the visible region (400–650 nm). The optical band gaps of the perovskite and OBHJ films are 3.1 and 1.9 eV [28–30], respectively, calculated from the Tauc plot (Fig. S1 in the Electronic Supplementary Material (ESM)). Based on the

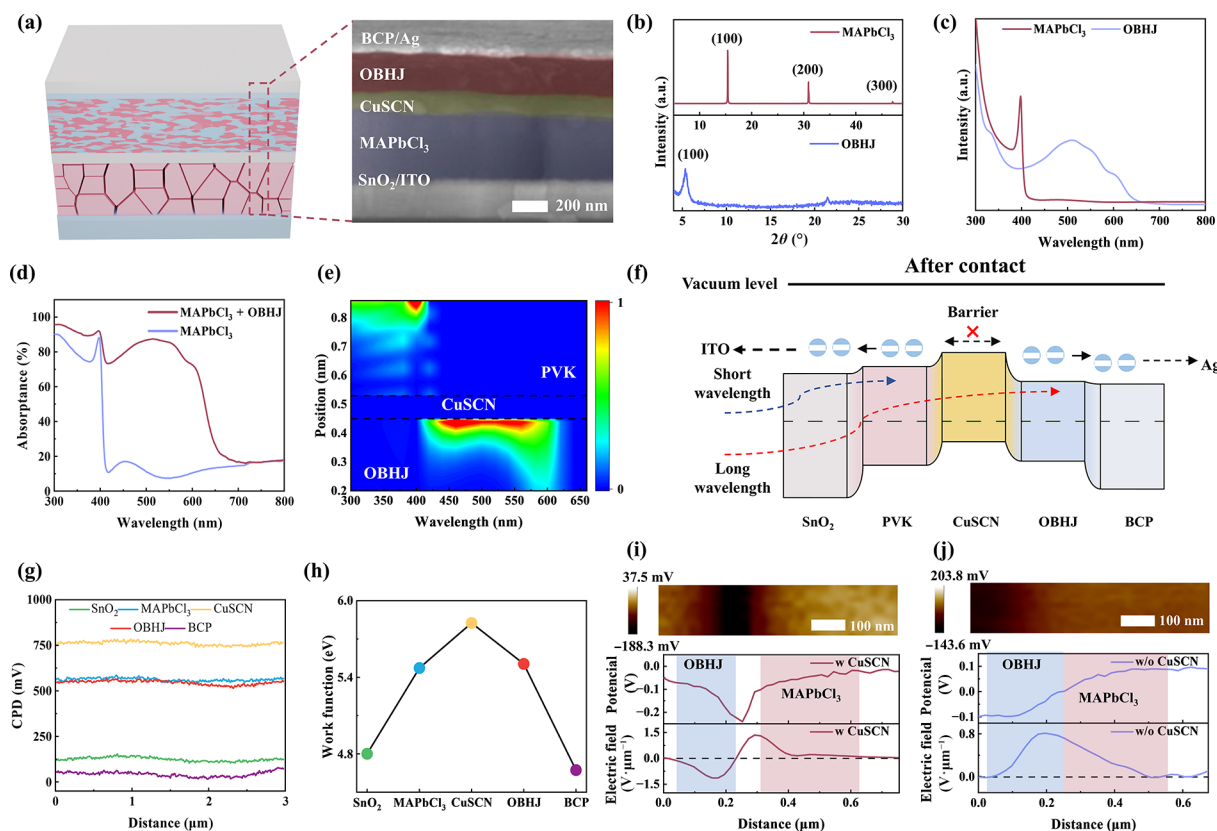


Figure 2 Characterization of the device structure. (a) Device structure diagram and its cross-sectional SEM image. (b) XRD patterns of MAPbCl₃ and OBHJ films. (c) UV-vis absorption spectra of MAPbCl₃ and OBHJ films. (d) Absorbance of MAPbCl₃ layer and MAPbCl₃ + OBHJ layer. (e) Simulation of distribution of carriers generated in the device. (f) Schematics of energy level alignment of the functional layers. (g) The CPD of different functional layers. (h) Work function of different functional layers. The cross-sectional KPFM of the device (i) with CuSCN (w CuSCN) and (j) without CuSCN layer.

measurements of transmittance and reflectance of pure MAPbCl₃ films and the fabricated stacked devices (Fig. S2 in the ESM), the light absorption rates of different films in the range of 300–800 nm were calculated (Fig. 2(d)). The calculation formula can be found in Note S1 in the ESM. The MAPbCl₃ layer exhibits a high absorbance of up to 90% for ultraviolet light but a low absorbance of only 18% for visible light. In contrast, the absorption of the OBHJ layer in the visible region exceeds 80%. The complementary absorption spectra of these two layers demonstrate the differences in the internal optical field distribution resulting from the stacking of materials with different band gaps. Besides, the transmittance tests on different layers demonstrated that the electron-blocking layer CuSCN inside the device contributed little to light absorption (Fig. S3 in the ESM). We calculated the penetration depths of light at different wavelengths (Fig. S4 in the ESM), with detailed calculation procedures provided in Note S2 in the ESM. Light shorter than 400 nm has a penetration depth of only 126 nm, which fails to penetrate the perovskite layer; in comparison, light above 400 nm features a penetration depth over 414 nm and can pass through the perovskite layer to reach the organic active layer. This is consistent with our simulation results of light absorption (Fig. S5 in the ESM). Carrier generation locations inside the device were also simulated (Fig. 2(e)), and relevant simulation methods are described in Note S3 in the ESM. The simulated results are in good agreement with the above variation trend of light penetration depth, where ultraviolet-excited carriers are mainly distributed in the wide-bandgap perovskite layer, and visible-light-induced carriers concentrate in the narrow-bandgap OBHJ. The close correlation between carrier generation sites and optical field distribution lays a solid foundation for realizing wavelength-dependent bipolar photoresponse. After elucidating the wavelength-dependent absorption and carrier generation distributions, we next probe the role of internal electric field in modulating carrier extraction and transport. The key to achieving wavelength-dependent bipolar response lies in the fact that photocarriers generated at distinct depths exhibit opposite drift directions, driven by a spatially modulated built-in electric field. To elucidate the energy alignment governing this transport, UPS is performed on each layer (Fig. S6 in the ESM). The Fermi levels across the heterostructure exhibit a distinct V-shaped alignment: Gradually shifting downwards from SnO₂ to MAPbCl₃, reaching a minimum at CuSCN, and then shifting upwards again in P3HT:PCBM and BCP, as shown in Fig. S7 in the ESM. This V-shaped Fermi level arrangement can form local electric field regions with opposite polarities inside the device.

The KPFM testing reflects the difference in work function between the probe and the sample, and can be used to characterize the relative surface potential changes of each layer (Fig. S8 in the ESM). The simulation process is detailed in Note S4 in the ESM. A larger contact potential difference (CPD) is conducive to the transfer and extraction of electrons, reflecting a stronger electron extraction driving force. Upon contact between different functional layers, Fermi level alignment induces carrier migration, which further gives rise to oppositely directed internal electric fields and energy band bending inside the device. This effect lays a solid physical foundation for the reverse extraction of photogenerated carriers in different wavebands (Fig. 2(f)). Figures 2(g) and 2(h) show the surface potential and work function of SnO₂, MAPbCl₃, CuSCN, P3HT:PCBM, and BCP films, respectively. The work function of different materials shows significant differences: CuSCN

has the highest work function, while BCP has the lowest one, and SnO₂, MAPbCl₃, and P3HT:PCBM are in between and show a gradient distribution. This trend is consistent with the measurement results of UPS.

Cross-sectional KPFM testing can directly reflect the potential changes inside the film, and the first-order derivative of the potential can be further used to obtain the corresponding local electric field distribution. Considering that the generation and separation of photogenerated carriers mainly occur in the absorption layer region, we focus on the potential/electric field changes in the relevant regions of MAPbCl₃ and OBHJ, as shown in Figs. 2(i) and 2(j). With the introduction of the CuSCN layer, the potential profile displays a characteristic V-shaped evolution. Consequently, the internal electric field derived from the potential gradient reverses its sign across the distinct absorption layers, indicating the establishment of a local field region with opposing direction. The cross-sectional potential of the device without CuSCN (w/o CuSCN) layer shows a monotonic trend of change in the absorption layer, and the corresponding electric field maintains the same polarity inside the bulk phase. The above results reflect the necessity of introducing CuSCN to construct the bipolar built-in electric field.

3.3 Photoresponse of the bipolar PD

Our designed back-to-back device exhibits a wavelength-dependent bipolar response under illumination of different wavelengths of light. This is verified by the responsivity spectrum of the bipolar PD measured in the wavelength range of 300–800 nm without external bias (Fig. 3(a)). The calculation formula can be found in Note S5 in the ESM. The response spectrum exhibits a sign reversal, changing from negative values in the ultraviolet region to positive values in the visible region, with a rapid and steep polarity reversal occurring near 400–410 nm. This clearly separates the two bands, which is beneficial for improving the accuracy of signal identification and enhancing the anti-interference capability of communication. In contrast, the device without CuSCN layer exhibits a monotonic negative polarity response. Furthermore, we systematically investigated the effects of the thickness of the perovskite layer and the organic blend layer on the amplitude of the device's bipolar response and the balance between positive and negative responses. Except for the film thickness, all other conditions were kept consistent. The thickness was controlled by adjusting the concentrations of the perovskite and organic layer precursor solutions. First, when the perovskite precursor concentration increased from 0.8 to 1.4 M, cross-sectional SEM showed that the perovskite layer thickness increased from 274 to 410 nm (Fig. S9 in the ESM). In the corresponding XRD patterns, films of all concentrations exhibited clear characteristic diffraction peaks, with no additional impurity peaks observed. This confirms that both high crystallinity and phase purity are preserved across the concentration range (Fig. S10(a) in the ESM). Further optical characterization reveals that increasing the perovskite layer thickness enhances ultraviolet absorption but leads to a concomitant reduction in visible transmittance (Figs. S10(b) and S10(c) in the ESM). With the OBHJ layer fixed at 253 nm, the spectral response exhibits a pronounced dependence on perovskite thickness. Specifically, the ultraviolet responsivity shows a slight initial increase before reaching saturation, whereas the visible responsivity displays a continuous monotonic decline (Fig. S11 in the ESM). This trend indicates that perovskite thickness plays a

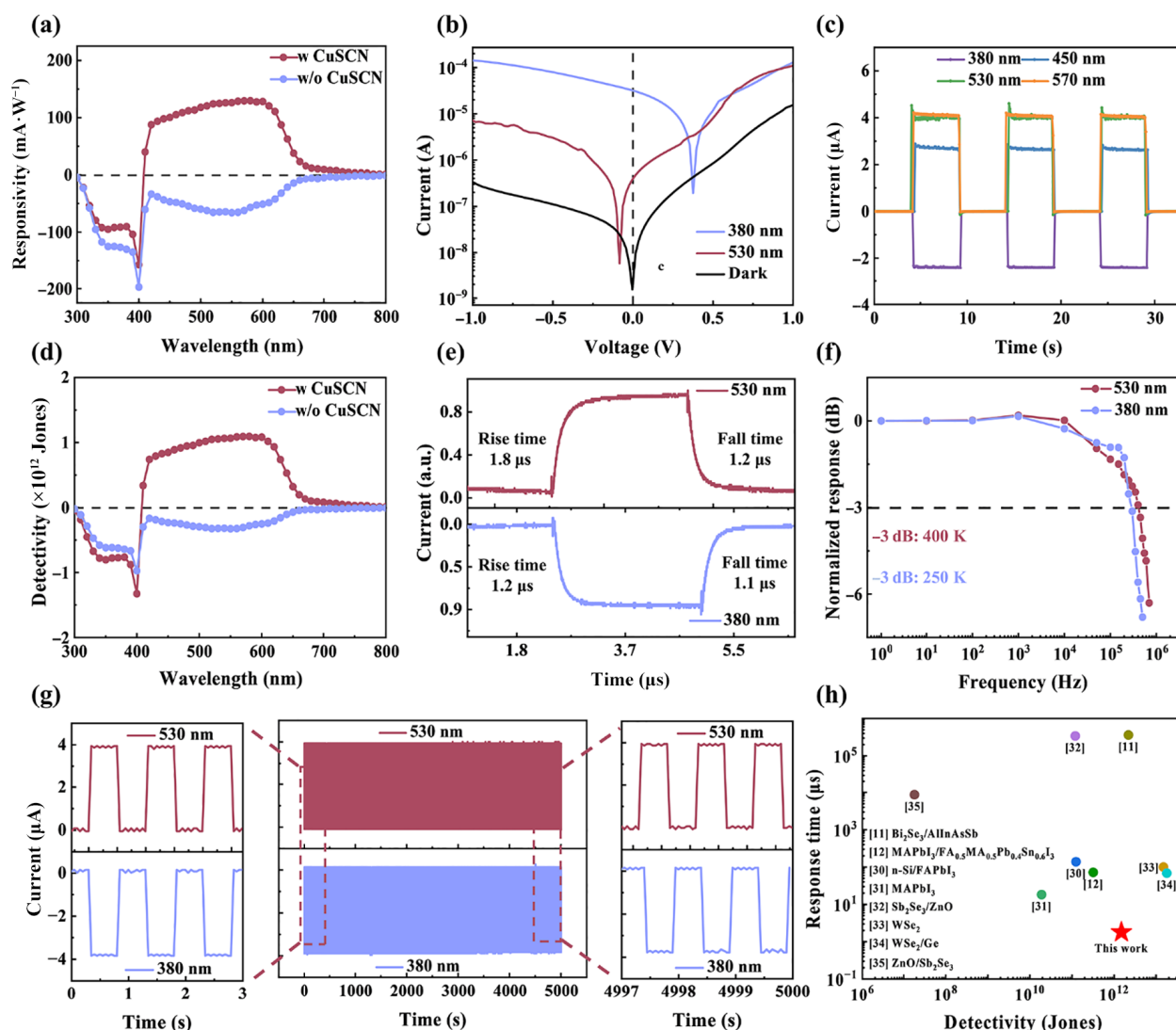


Figure 3 Photoreponse of the bipolar PD measured at room temperature in ambient air. (a) Responsivity of the bipolar/unipolar PD at different wavelengths from 300 to 800 nm at zero bias. (b) I - V curves of the bipolar PDs under 380 and 530 nm laser irradiation (incident light intensity: 380 nm: $0.27 \text{ mW}\cdot\text{cm}^{-2}$, 530 nm: $0.38 \text{ mW}\cdot\text{cm}^{-2}$). (c) I - t cycle curves of the bipolar PD under 380, 450, 530, and 570 nm laser irradiation (incident light intensity: 380 nm: $0.27 \text{ mW}\cdot\text{cm}^{-2}$, 450 nm: $0.31 \text{ mW}\cdot\text{cm}^{-2}$, 530 nm: $0.38 \text{ mW}\cdot\text{cm}^{-2}$, 570 nm: $0.35 \text{ mW}\cdot\text{cm}^{-2}$). (d) The specific detectivity of the bipolar/unipolar PD. (e) The response time of the bipolar PD at different wavelengths. (f) The frequency-dependent response of the bipolar PD at different wavelengths. (g) 5000 cycles switching optical cycle I - t curves of the bipolar PD at different wavelengths (incident light intensity: 380 nm: $0.49 \text{ mW}\cdot\text{cm}^{-2}$, 530 nm: $0.39 \text{ mW}\cdot\text{cm}^{-2}$). (h) Performance comparison of bipolar PDs.

crucial regulatory role in the positive/negative balance of the bipolar response. When the perovskite is too thin, ultraviolet absorption is insufficient, leading to limited generation of ultraviolet photogenerated carriers. As the thickness increases, ultraviolet absorption becomes sufficient, and the ultraviolet response enters a plateau region. However, excessively thick perovskite significantly weakens visible light transmission, reducing the visible light flux entering the overlying OBHJ layer. This reduces the photogenerated contribution of the organic layer to the visible band and leads to a decrease in the visible positive response (Fig. S11 in the ESM). Similarly, the film thickness of the organic material varies from 120 to 694 nm with increasing precursor solution concentration (Fig. S12 in the ESM). With the perovskite thickness maintained at 310 nm, increasing the OBHJ layer thickness significantly enhances visible absorption (Fig. S13 in the ESM). However, its visible responsivity reached its maximum at 253 nm and decreased with further thickness (Fig. S14 in the ESM). Besides, we provided the

light intensity in different bands during responsivity testing and investigated the effect of light intensity on positive and negative response photocurrents. It was found that light intensity only affects the magnitude of positive and negative photocurrents and does not alter the bipolar response characteristics of the device (Fig. S15 in the ESM). This reflects a typical characteristic of OBHJ devices. While thicker films improve optical absorption, they simultaneously lengthen carrier transport pathway and increase bulk/series resistance. Consequently, charge extraction is impeded by elevated recombination losses, leading to a reduction in the overall photoelectric output. Whether the active layer is too thin or too thick, it causes a severe imbalance in the positive and negative responses. Therefore, a suitable active layer thickness is crucial for bipolar response characteristics. The optimized bipolar device exhibits high responsivity, displaying responsivity peaks of -0.16 and $0.13 \text{ A}\cdot\text{W}^{-1}$ at 400 and 570 nm, respectively, with a positive-to-negative responsivity ratio approaching 1:1. This device achieves a

highly balanced bipolar photoelectric response, providing a reliable physical basis for polarity-based optoelectronic functions and information processing. Under 380 and 530 nm illumination, the current–voltage (I – V) curves (Fig. 3(b)) of the perovskite device show open-circuit voltages of opposite polarities under ultraviolet and visible light illumination, which are 0.3 and -0.07 V, respectively, consistent with typical bipolar PD characteristics. Figure 3(c) shows three on/off optical cycles of the device containing the CuSCN layer under illumination of different wavelengths of light, indicating that the device generates currents of opposite polarities under illumination of different wavelengths of light. In contrast, the device without the CuSCN layer exhibits unipolar characteristics, with its open-circuit voltage and photocurrent having the same polarity under illumination of different wavelengths of light (Fig. S17 in the ESM). To evaluate the noise characteristics of the device, we measured the noise current at different frequencies (Fig. S18 in the ESM). For devices containing the CuSCN layer, the noise current at 10 Hz is 1.12×10^{-13} A·Hz $^{-1/2}$; for the device without the CuSCN layer, the noise current at 10 Hz is 1.92×10^{-13} A·Hz $^{-1/2}$. The calculation formula can be found in Note S6 in the ESM. The device achieves high specific detectivity output in both the ultraviolet negative polarity and visible light positive polarity response ranges, with peak specific detectivity exceeding 10^{12} Jones (Fig. 3(d)), demonstrating excellent photodetection sensitivity. In addition to high sensitivity, PDs also need to have fast time response capabilities in high-speed information acquisition and transmission scenarios. Consequently, we further characterized the device's response speed and frequency bandwidth. Figure 3(e) shows the rise and fall processes of the device under periodic illumination conditions, where rise time and fall time are defined as the time required for the photocurrent to increase from 10% to 90% and decrease from 90% to 10%, respectively. The results show that under different polarity conditions, the device exhibits a clear and symmetrical rise and fall process, with rise/fall times of 1.2/1.1 μ s (380 nm) and 1.8/1.2 μ s (530 nm), respectively, indicating that there is no significant kinetic hysteresis in the bipolar response process. The frequency response characteristics were evaluated by measuring the photocurrent amplitude as a function of the incident light modulation frequency. Figure 3(f) shows the frequency response curves of the device under 380 and 530 nm illumination conditions. At low frequencies, the photoelectric response amplitude remains stable as the modulation frequency increases until it begins to decay significantly in the high-frequency range. Using the $\sqrt{2}/2$ of the response amplitude decreasing to a low-frequency value as the criterion, the -3 dB bandwidth of the device under 380 and 530 nm illumination is approximately 250 and 400 kHz, respectively. Combining fast time response and wide frequency characteristics, this performance enables the device to effectively capture transient optical signals and support high-speed data transmission. These attributes underscore its potential for applications in free-space optical communication.

In addition to excellent transient response performance, the stability of the device during long-term cyclic operation is also a key indicator for evaluating its practicality. Therefore, we further investigated its cyclic stability. Figure 3(g) shows the on/off optical cycling current–time (I – t) curves of the device at different wavelengths. The results show that after 5000 consecutive illumination cycles, the photocurrent showed no apparent decay, indicating that it can still maintain a stable signal output under long-term cyclic stimulation. To further evaluate the consistency and

repeatability of the devices, we fabricated ten independent devices and performed responsivity tests (Fig. S19 in the ESM). The results show that all devices exhibited stable bipolar response characteristics. The polarity switching point did not shift, and the peak values of positive and negative responsivity did not change significantly, indicating that the bipolar response performance of the fabricated devices has good consistency and repeatability. To evaluate the competitive status of our device, its response time and specific detectivity are compared with state-of-the-art bipolar photodetectors [12, 13, 31–37] as shown in Fig. 3(h). It is worth noting that the response times of these bipolar PDs range from a few milliseconds to tens of microseconds, with only a few reaching the microsecond level; and most of them have specific detectivity less than 10^{12} Jones. The bipolar PD in this work not only exhibits a fast response speed but also a high specific detectivity. Therefore, our designed bipolar PD shows great potential in applications, such as real-time detection and optical communication.

3.4 Image encryption transmission system

To demonstrate the application potential of our device, we constructed a hardware–software co-processing encrypted optical communication system for image transmission. This system utilizes the polarity change of a bipolar PD to divide the received signal into three states, corresponding to “1”, “0”, and “–1”; while traditional unipolar PDs, limited by the singularity of the signal, can only achieve “0” and “1”. Given that positive and negative values naturally arise during image processing, such as image encoding and principal component analysis (PCA), we mapped “1” and “–1” to two LED emission channels at 530 and 380 nm, respectively. This strategy achieves the simultaneous transmission and discrimination of positive and negative polarities. After image encoding, the transmitting computer sends the data to a microcontroller (STM32), which drives the two LEDs for optical emission via a power amplifier. The receiving bipolar PD performs broadcast signal conversion, samples the signal using an analog-to-digital converter (ADC), converts it into a digital signal, and the receiving computer decodes it to reconstruct the transmitted image. Figure S20 in the ESM shows a photograph of the transmission system.

Figure 4(a) briefly illustrates the working principle of the encryption system. Initially, we perform PCA on the original image. This is because the main structural information of an image is often concentrated in a few principal directions. PCA compresses this key information into fewer coefficients, so we only need to transmit a smaller coefficient matrix Y , which significantly reduces the amount of data transmitted while maintaining high image reconstruction quality. In this step, the image is first mean-centered, and then two sets of orthogonal projection bases determined by the sample covariance are calculated along the horizontal and vertical directions, respectively. The image is then projected onto this low-dimensional subspace to obtain the required PCA coefficient matrix (Fig. S21 in the ESM). The equation used is as follows

$$Y = P_r(P_v^T(X - M)P_h)P_c \quad (1)$$

where Y is the original matrix, X is the transformed matrix, P_v and P_h are the PCA projection matrices in the horizontal and vertical directions, respectively, P_c and P_r are the column and row spatial permutation (SP) index sequences, respectively, and M is the mean matrix. Subsequently, we spatially scramble the obtained coefficient matrix to further break the deterministic correspondence between

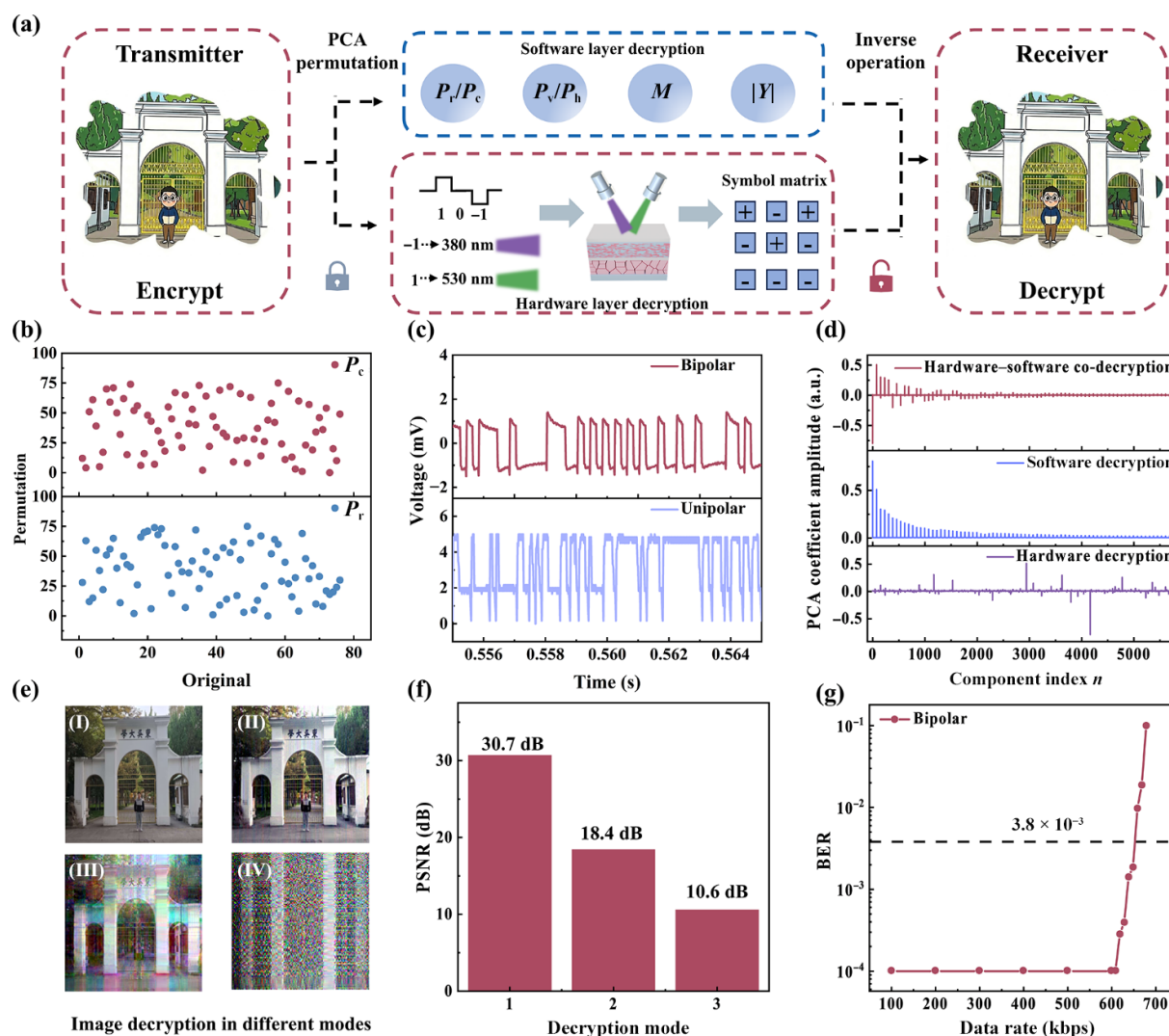


Figure 4 Secure optical communication system for transmitting images. (a) The strategy for achieving hardware and software collaborative encrypted image optical communication. (b) SP index sequence. (c) Enlarged view of the transmitted signal. (d) One-dimensional flattened PCA coefficients obtained under different decryption modes. (e) Reconstructed images under different decryption modes. (f) PSNR of reconstructed images under different decryption modes. 1 represents hardware-software co-decryption, 2 represents software decryption, and 3 represents hardware decryption. (g) BER of optical communication systems at different data rates.

coefficients and spatial positions. The corresponding SP index sequence is generated by algorithm called Hash-based Message Authentication Code (HMAC)-based Extract-and-Expand Key Derivation Function (HKDF) + X25519, ensuring unpredictability and randomness in the communication process. Next, we split the encrypted PCA coefficient matrix and used the transformation matrices used in the transformation process, such as the projection matrix, mean matrix, SP index sequence, and the absolute value matrix of PCA coefficients ($|Y|$), as the shared software key for both the encryption and decryption ends. We mapped the symbolic information in the PCA coefficient matrix to the positive/negative light signals of the bipolar detector, and used the light signal polarity of the device as the hardware key. Finally, at the decryption end, we reconstructed the transmitted image by merging the software and hardware keys. Figure 4(b) shows the SP indices P_r and P_c in the encryption process. They are approximately uniformly distributed, indicating that the scrambling mapping is statistically close to random. It does not change the numerical value of the coefficients, but only rearranges the row and column positions of the coefficients and breaks the neighborhood relationship, thereby

suppressing the leakage of structural information and increasing the difficulty of keyless reconstruction. The overall transmission signal is shown in Fig. S22 in the ESM. To facilitate comparative analysis, we selected the same local emission signal sequence from this signal and showed the photovoltage output comparison of unipolar and bipolar devices under this light stimulation in Fig. 4(c). Bipolar photodetector can output two signals of opposite polarities, while a unipolar photodetector can only output one signal of the same polarity. This means that when receiving the same light signal sequence, only bipolar photodetectors can accurately reproduce the original information, while monopolar detectors, unable to output negative signals, will obtain information with numerous errors. Figure 4(d) shows the PCA coefficient sequences under different decryption modes. The coefficient sequence after hardware and software co-decryption exhibits typical PCA coefficient distribution characteristics: Large coefficients are concentrated in the early part, rapidly approaching zero in the later part, while the positive and negative signs are distributed around zero. This is because PCA compresses the main structural information into a few key projection directions; when flattened by rows, these coefficients

naturally concentrate in the early part. As the index increases, the sequence gradually shifts towards the part with smaller information contribution, and the amplitude therefore rapidly decays and approaches zero. Mean centering causes the coefficient representation to deviate from the mean; thus, the positive and negative signs are distributed around zero. While software-based decryption preserves the amplitude distribution, it results in an erroneous polarity reversal for negative coefficients. In contrast, although hardware-based decryption effectively resolves both positive and negative polarities, it suffers from severe coefficient misalignment due to the absence of software-assisted reconstruction parameters. Figure 4(e) compares the original color image with the reconstructed color images under different decryption modes. The color images were obtained by merging the red, green, and blue (RGB) three channels separately (Fig. S23 in the ESM). The results show that only the double-decrypted image is clearly distinguishable, while the image captured from any single layer exhibits obvious stripes or chaos. To quantify the image fidelity across different decryption modes, Fig. 4(f) presents the peak signal-to-noise ratio (PSNR) values. Notably, the hardware–software co-decryption strategy achieves a superior PSNR of 30.7 dB, indicating high-quality reconstruction with minimal distortion. In order to further quantify the anti-eavesdropping and anti-attack capabilities of encrypted optical communication systems, we analyzed the image recovery capabilities under different interception scenarios. It can be found that when signals are intercepted, due to the lack of keys, the difference rate of image recovery reaches 100%, and the mean squared error (MSE) of pixels exceeds the order of 10^3 , showing huge distortion (Figs. S24 and S25 in the ESM). However, the software and hardware system decrypts and reconstructs the image with a difference rate of less than 10% and a lower MSE (Fig. S26 in the ESM). Furthermore, the established hardware–software co-encryption scheme possesses a key space of 3×2^{256} . Such an ultra-large key space effectively endows the optical transmission system with outstanding intrinsic transmission security and robust confidentiality.

To evaluate the stability and accuracy of the optical communication system, we measured the bit error rate (BER) of the bipolar device at different transmission rates (Fig. 4(g)). We analyzed the eye diagram of the device at different transmission rates (Fig. S27 in the ESM). As the data rate increased from 200 to 800 kilobits per second (kbps), the eye in the diagram gradually closed. This indicates that at higher rates, signal fluctuations are more pronounced, inter-symbol interference (ISI) gradually increases, leading to a narrower available sampling window and making it easier for sampling points to fall within the bit error rate range. Ultimately, this manifests as an increase in the BER with increasing data rate. At a transmission rate of 650 kbps, the system's bit error ratio (BER) is 0.19%, which is lower than the benchmark of 0.38%. Here, 0.38% corresponds to the commonly used forward-error-correction (FEC) limit BER reference threshold, which is used to evaluate the reliability of a communication system; a BER lower than this threshold usually indicates that the communication system has higher transmission accuracy, demonstrating high-speed information transmission performance. Furthermore, by improving the frequency response of the device and optimizing the bandwidth matching of the readout link, the decision threshold at the receiver, and the clock synchronization strategy, it is expected to maintain a low BER at higher code rates. At the same time, the introduction of

adaptive equalization and stronger error correction coding can enhance the robustness of the system under noise, timing jitter, and ambient light disturbance conditions, providing support for faster and more reliable secure optical communication.

4 Conclusions

In summary, we constructed a bipolar PD based on an N–I–P–I–N structure by introducing an additional p-type layer. The oppositely oriented p–n junctions reverse the polarity of the internal electric field, resulting in a controllable bipolar response in the UV–vis spectra. Under wavelength-dependent illumination, photogenerated carriers within distinct active layers drift in opposing directions driven by their respective electric fields, yielding currents with switchable polarities. This strategy allows the built-in electric field to penetrate deep into the photoactive layer, optimizing the separation and extraction of charge carriers, which is beneficial for achieving a fast and sensitive photoresponse and broadening the application scenarios of the bipolar PD. Based on this, we demonstrate a hardware–software co-encrypted image transmission system that leverages the fabricated bipolar PD to generate polarity-tunable signals as hardware keys. When synergized with a PCA- and SP-based software encryption algorithm, the system ensures robust security; partial interception at either the hardware or software level yields heavily distorted images (PSNR < 20 dB). Furthermore, even at a high-speed transmission rate of 650 kbps, it can still maintain stable and accurate information transmission, highlighting its application potential in the fields of security and next-generation optical communication.

Electronic Supplementary Material: Supplementary material (the calculation method of light absorption rates and light incidence depth; the simulation of light absorption and carrier generation; the CPD calculation formula; the calculation method of the responsivity and the specific detectivity; the bandgap of MAPbCl₃ and OBHJ; the light transmittance and reflectance of different devices; the light transmittance of the device after stacking different functional layers; light penetration depth at different wavelengths; simulation of light absorption sites of different wavelengths; UPS spectra, energy levels, and KPFM on the surface of different functional layers; the cross-sectional SEM images, XRD patterns, absorption spectrum, and transmission spectrum of the perovskite prepared from precursor solutions of different concentrations; responsivity spectra of bipolar devices prepared from different concentrations of perovskite precursor solutions; the cross-sectional SEM images of OBHJ thin films prepared from precursor solutions of different concentrations; absorption spectrum and responsivity of stacked devices prepared from precursor solutions of OBHJ with different concentrations; light intensity at different wavelengths. *I*–*t* cycle curves of the device under different illumination; photoresponse of the unipolar PD; noise current of different devices; the reproducibility of bipolar PDs; photograph of encrypted optical communication system; schematic diagram of PCA; photoresponse from the same optical signal received by bipolar and unipolar devices; RGB three-channel reconstructed images under different decryption modes; difference rate, MSE, and PSNR of reconstructed images from different decryption; and eye diagrams at different transmission rates) is available in the online version of this article at <https://doi.org/10.26599/NR.2026.94908867>.

Data availability

All data needed to support the conclusions in the paper are presented in the manuscript and the Electronic Supplementary Material. Additional data related to this paper may be requested from the corresponding author upon request.

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Declaration of competing interest

All the contributing authors report no conflict of interests in this work.

Author contribution statement

S. T. L.: Data curation, project administration, validation, writing manuscript, experimental design. W. C. W.: Validation, investigation. S. H. L.: Validation, investigation. Y. Q. W.: Validation, investigation. J. A.: Validation, investigation. S. M. A.: Validation, investigation. W. T.: Project administration, funding acquisition, supervision, review & editing. L. L.: Project administration, funding acquisition, supervision, review & editing. All the authors have approved the final manuscript.

Use of AI statement

None.

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