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Article

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**Posted Date:** March 16th, 2023

**DOI:** https://doi.org/10.21203/rs.3.rs-2597093/v1
Additional Declarations: There is NO Competing Interest.
High-Speed Flexible Near-Infrared Organic Photodiode Beyond Silicon for Optical Communication

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Abstract

Optical communication is a particularly compelling technology to tackle the speed and capacity bottlenecks in data communication in modern society. Currently, silicon photodetector plays a dominant role in the high-speed optical communication across the visible-near infrared spectrum. However, its intrinsic rigid structure, high working bias, and low responsivity largely limit its applications in the next-generation flexible optoelectronic devices. Herein, we report a solution-processed flexible organic photodetector (OPD) based on a narrow-bandgap nonfullerene acceptors, which exhibits a remarkable response time of 91 ns and peaking responsivity of 0.53 A W⁻¹ (λ = 830 nm) at zero bias, exceeding the values obtained in the state-of-the-art high-speed commercial Si photodetector (326 ns; 0.26 A W⁻¹). This exceptional performance benefits from the low parasitic capacitance and high charge mobility due to low trap states and energetic disorder in the organic photoactive film. More significantly, the flexible OPD exhibits negligible performance attenuation (<1%) after bending for 500 cycles, and maintain 96% of its initial performance even after 550 h of indoor exposure. Furthermore, it also demonstrates a high data transmission rate of 80 MHz with a bit-error-rate of 3.5×10⁻⁴, offering great potential in next-generation high-speed flexible optical communication system.
**Introduction**

Optical communication, also named as Light Fidelity (LiFi), is no doubt one of the most compelling wireless communication technologies for high-speed and large-capacity data communication without external electromagnetic interference and safety issues\(^1\),\(^2\),\(^3\),\(^4\). Moreover, visible (Vis) -infrared (NIR) light have frequencies extending from 400 Terahertz (THz) to 800 THz, offering 10,000 times higher available frequency spectrum than the current radio frequency\(^5\),\(^6\). Thus, LiFi is, in particular, widely expected to tackle the current bottlenecks in high-speed data transmission existing in the Internet of Things, light detection and ranging (LiDAR), big data, and consumer electronics\(^6\),\(^7\). Photodetectors (PDs) are core building blocks of LiFi system, which function as optical receivers that convert optical signal into electrical signals and also play a central role in the speed, capacity, and accuracy of data transmission\(^8\),\(^9\),\(^10\). Owing to the advances in mature design and fabrication expertise, silicon (Si) PDs currently play a dominant role in optical communication and remain unbeatable in terms of performance, infrastructure, and practical applications\(^9\). However, to achieve high-speed photoresponse, it generally requires to reduce Si device thickness, resulting in a low responsivity due to the weak absorption efficiency, particularly in the near infrared region\(^7\). More importantly, Si PDs commonly suffer from mechanical rigidity, small area, high working bias voltage, and fixed bandgap, which are not ideally suited in typical burgeoning fields, particularly in wearable electronics, soft robotics, intelligent transport system (ITS), and implanted electronics; those requiring, for example, mechanical flexibility, large active area, spectrum tunability, low cost, and efficient energy consumption\(^7\),\(^9\),\(^11\),\(^12\),\(^13\).

Solution-processed organic photodetectors (OPDs) offer significant mechanical flexibility, tailorable bandgap, and large-area fabrication capability, suitable for various non-standard substrates\(^13\),\(^14\),\(^15\),\(^16\). Moreover, OPDs have a high optical coefficient (>10\(^5\) cm\(^-1\)), ensuring an ultrathin photoactive film (~100 nm) for high-efficiency and fast photodetection\(^16\). These attractive characteristics enable them promising alternatives
for low-cost flexible, and low-power information receivers in next-generation integrated and scalable LiFi modules. Benefiting from the rapid development of photovoltaic materials, particularly the non-fullerene acceptors (NFAs) with acceptor-donor-acceptor (A-D-A) architectures, OPDs have achieved considerable breakthroughs in terms of visible and infrared light communication and some metrics are even beyond inorganic photodetectors. However, the data transmission speed of OPD still lags behind inorganic counterparts due to its relatively slower response speed compared with crystalline inorganic semiconductors. The fundamental reason lies in the low charge mobility and high parasitic capacitance in OPD, originating from the high-density trapping states, large energetic disorder, and polaron formation in organic semiconductors. Even though considerable efforts have been dedicated to develop high-speed OPD, including synthesizing new materials and designing novel device, the development high-speed OPD is still rather slow due to the shortage of suitable organic semiconductors. Besides, the accuracy of previously reported response time obtained via transit photocurrent (TPC) is always overestimated as the photocurrent usually does not reach saturation before switching off irradiation light. Furthermore, the key factors that dominate the response speed of OPD are seldomly investigated and studied, resulting in the lack of principles guiding high-speed OPD fabrication and optimization, and thus, hindering their practical applications in flexible LiFi communication system for high-speed and large-capacity data transmission.

Here, we successfully fabricated a flexible Vis-NIR OPD by introducing a novel NFA with a compact 3D molecular packing network, which efficiently reduced energetic disorder and trap density, and also simultaneously decreased capacitance and improving charge transport in the vertical direction, thus leading to a huge improvement of response speed. We conducted detailed optoelectronic performance comparison of OPD with commercial Si PD to evaluate OPD’s future practical application in flexible LiFi system; and made a comprehensive study on the crucial factors dominating the response speed. The resulting OPD exhibits significantly fast photoresponse time of
ns, low noise current of 3 pA, peaking responsivity of 0.53 A W$^{-1}$ at 830 nm, and large linear dynamic range of over 130 dB. Both responsivity and speed are more than two times higher than the state-of-the-art high-speed Si PD and all previously reported OPDs prepared with NFAs. Furthermore, compared with rigid silicon photodiode, the flexible OPD demonstrates negligible performance degradation (<1%) after mechanically bending for 500 cycles and maintains more than 96% of its initial performance after working for 550 h under indoor exposure. On the basis of the excellent optoelectronic performance, we designed and assembled a LiFi system with flexible OPDs, achieving a high-speed data communication of 80 Mbps with a bit-error-rate (BER) of $3.5 \times 10^{-4}$, which demonstrates the great potential of OPD in the emerging applications of ITS for various optical communication.

Results and Discussion

Photoresponse Speed and Responsivity Performance of OPD

Fig. 1a illustrates the structure of the designed OPD with a normal architecture. The photoactive blend, composed of PM6 and CH17 (Supplementary Fig. 1), has already been utilized in organic photovoltaic device$^{25}$, which exhibited high mobility, balanced electron/hole mobility ratio, and low disorder energy, demonstrating the great potential in high-speed OPDs. Here, a layer of poly(3,4-ethylenedioxythiophene):poly(4-styrenesulfonate) (PSS:PEDOT) on an ITO substrate serves as hole transporting layer (HTL) and concurrently reduces the surface roughness, whereas N,N'-Bis(N,N-dimethylpropan-1-amine oxide) perylene-3,4,9,10-tetracarboxylic diimide (PDINO) film works as electron transporting layer (EHL) and blocks holes owing to proper energy level$^{25}$. The detailed process of device fabrication and optimizations are all described in Methods. Fig. 1b presents the profiles of responsivity of OPD and the commercial high-speed Si PD (Model Hamamatsu S1226-5BK), showing a broad photoresponse spectrum ranging from 400 to 950 nm. It is worth
noting that OPD exhibits much higher peak responsivity of 0.53 A W\(^{-1}\) (~85% EQE at 830 nm) than the value of commercial Si photodiode (~0.26 A W\(^{-1}\)), owing to its high light absorption efficiency.

**Fig. 1** | Structure and performance of OPD and Si PD. **a**, Device structure of OPD based on PM6:CH17. **b**, Profile of spectral responsivity of OPD and Si PD. **c**, Time domain response of OPD and **d**, Si PD (S1226-5BK) at zero bias under 880 nm illumination based on steady state analysis, the inset of Fig. **c** and **d** are optical pictures of OPD (4 mm\(^2\)) and Si PD (5.76 mm\(^2\)). **e**, Frequency domain response of OPD and Si PD. **f**, Time domain response of OPD with an area size of 1 mm\(^2\).

As the response speed of OPD play the most important role in determining the data transmission speed, capacity, and accuracy in the LiFi system, it is required to accurately examine the speed performance of OPD And Si PD. Here, we introduced a steady-state current measurement in dark and under NIR illumination (\(\lambda = 880\) nm) instead of commonly reported TPC test\(^{28}\), which could largely avoid the speed performance overestimation. A detailed methodology to characterize OPD and Si PD is presented in **Supplementary Note 1 and 2**. As shown in **Fig. 1c**, the response time of the optimal OPD achieves as fast as 168 ns and a fall time of 173 ns at zero bias, exceeding the commercial high-speed Si PD with a corresponding value of 326 ns and
265 ns, respectively (Fig. 1d and Extended Data Fig. 1), measured under the same conditions and method. To our best knowledge, this is the first-time report about OPD that exhibits superior optoelectronic performance that exceeds the commercial Si PD in terms of responsivity and response speed, simultaneously (Extended Data Fig. 2d).

Extended Data Fig. 2a displays the response/recover time distribution for 17 independently measured OPDs, indicating the evidently reproducible high-speed performance of our devices. Theoretically, the data transmission speed and capacity are determined by -3dB cut-off frequency of OPD estimated from the equation of \( f = \frac{0.35}{t} \), where \( t \) is the transit time of OPD\(^{19} \). Here, we adopt a modulated optical signal at a wavelength of 880 nm to measure cutoff frequency without any pre-equalization and weighting techniques\(^{29} \), effectively avoiding overestimation or underestimation of the frequency measurement (Supplementary Fig. 2 and 3). Fig. 1e displays the -3dB cutoff frequency of OPD and Si photodiode of 3.24 and 2.84 MHz at zero bias, respectively, which is consistent with the measured response time. Moreover, OPD has a high cutoff frequency over the entire visible range, demonstrating a great potential in high-speed optical communication across Vis-NIR region (Extended Data Fig. 2b). To further improve the speed performance of OPD, we reduce the pixel size to 1*1 mm\(^2\), which shows a faster response time of 91 ns with a cutoff frequency of over 4 MHz, exceeding most of commercial Si PDs and literarily reported OPDs with a detection range of over 850 nm (Extended Data Fig. 2c, 2d, and Supplementary Table S1).

Mechanism of High-performance OPD

Accordingly, the response bandwidth of p-i-n (PIN) photodiode is mainly determined by both the charge-carrier transit time (\( t \)) across i-region and the RC time constant shown as follows\(^{30} \):

\[
\tau_r = \sqrt{\tau_{RC}^2 + \tau_{drift}^2 + \tau_{diff}^2} \quad (1)
\]

Where \( \tau_{RC} \) is the time constant caused by total series resistance (\( R_s \)) and the sum of the capacitance of device (\( C \)), \( \tau_{drift} \) is the drift time in the depletion region, and
\[ \tau_{\text{diff}} \] is the diffusion time of carriers to depletion region. Generally, the diffusion time of carriers is negligible in the PIN photodiode as the i region is fully depleted\(^3\). To explore the underlying factors that determine the response speed of OPD, we investigate the response time of OPDs by modulating the RC time constant and charge transit time via tuning device capacitance, series resistance, charge mobility, and charge drift length.

**Fig. 2 | Capacitance and mobility characterizations of OPD.**

- **a**, The capacitance of OPD with different sizes and silicon photodetector under various reverse bias.
- **b**, Time domain response of OPD with different sizes.
- **c**, The box chart of rise time in different device area.
- **d**, The response time of the OPD and Si PD integrating with the external resistance at zero bias under 880 nm illumination (OPD area = 2*2 mm\(^2\)).
- **e**, -3dB cutoff frequency of OPD operating at different temperatures ranging from -10 to 100 °C at zero bias under 880 nm illumination.

As shown in **Fig. 2a**, the geometrical capacitance of OPD is proportionate to the area size of the device, which decreases with the reducing area of the device. Unexpectedly, the OPD shows significantly lower capacitance than the commercial Si
PD, implying low trap states in OPD\textsuperscript{20,31}. An analysis of the response time versus pixel area shown in Fig. 2b reveals that the response time decrease with the pixel size and does not plateau even at the size of 1 mm\textsuperscript{2}, indicating that geometrical capacitance plays a critical role in determining response speed, maintaining consistent responsivity (Supplementary Fig. 4). Another key factor to determine the RC time constant is the series resistance of the device. By integrating external resistors with OPD and Si PD, both photodetectors demonstrate expectedly increasing response time, which further confirm that the response speed performance of OPD is dominated by RC time constant.

The drift time is primarily determined by the charge velocity and drift length, where the charge mobility in organic semiconductors, according to Gaussian disorder model, heavily depends on the working temperature\textsuperscript{32}. As shown in extended Fig. 3a, the electron charge mobility demonstrates a significant increase at higher temperature, leading to a significant increase of -3dB cutoff frequency (Fig. 2d and Extended Data Fig. 3a). Remarkably, the -3dB cutoff frequency of OPD at 373 K achieves as high as 4 MHz, ranking the highest value ever reported in OPDs operating at high temperature (Supplementary Fig. 6). The outstanding response speed performance at high temperature also ensures the ability of OPD to operate in harsh environments for high-speed optical communication\textsuperscript{32}. By applying high reverse bias, the OPD demonstrates a constant response time, which is owing to the saturation of charge velocity and negligible capacitance change in OPDs (Supplementary Fig. 7). The thickness of photoactive film is another key factor that determines $\tau_{\text{drift}}$. Benefiting from the high optical absorption coefficient of photoactive materials, together with the large space charge region (107 nm) (Supplementary Fig. 8), the optimal device with the thickness of 95 nm exhibits fast response time of 168 ns and high peak responsivity of 0.53 A W\textsuperscript{-1}, simultaneously (Supplementary Table S2). The thicker device has a longer the charge transit length, whereas the thinner device exhibits a weak optical absorption efficiency, resulting in either slow response or low responsivity (Extended Figure 3b, 3c and Supplementary Fig. 9 and Table 2). On the basis of the above analysis, we
conclude that the capacitance and charge mobility of photoactive film simultaneously contribute to the response speed performance of OPDs. Therefore, it is crucially important to develop strategies via material science and device engineering to circumvent the geometrical capacitance and increase charge mobility to improve photoresponse speed in the future study.

Parasitic capacitance and charge mobility of the device are intrinsically related to trap density and energetic disorder of the blend. As it is rather difficult to directly measure traps in organic solids due to the lack of simple techniques to access their concentration and distribution. Here, we performed capacitance-voltage (C-V) measurement and corresponding Mott-Schottkley analysis to extract the trap density by the formula of $N_t = \frac{2}{q\varepsilon_0\varepsilon_r} \left(\frac{d(C/A)}{dV}\right)^{-1}$, where $\varepsilon_r$ is the relative dielectric constant of the BHJ film (assuming $\varepsilon_r = 3.5$), $\varepsilon_0$ is the vacuum permittivity, and $A$ is device area$^{33}$. As shown in Supplementary Fig. 8, the resulting trap density in OPD reaches as low as 7.12 x10$^{15}$ cm$^3$, leading to a reduced capacitance and hence decreasing RC constant. According to the result of charge mobility at various temperature, the energetic disorder is as low as 40.1 meV extracted by Gaussian disorder model$^{32}$, largely reducing charge recombination and efficiently improving charge transport (Extended Data Fig. 3a). All these outstanding performances are contributed to highly ordered molecular packing in the PM6:CH17 blend. Accordingly, CH17 molecule with A-D-A architecture is designed and constructed by extending π conjugation in both directions of the central and end units, inducing an effective and compact 3D molecular packing with a distinctive dual “end unit to central unit” packing mode. This much favorable molecular packing, to a large extent, facilitate the charge transfer in the vertical direction, and thus improving charge mobility and reducing energetic disorders in CH17 blends$^{25}$.
Dark current and rectification ratio (RR) are critical metrics of OPD that determine the specific detectivity ($D^*$), linear dynamic range (LDR), noise equivalent power (NEP), and rectifying characters of photodetectors.\textsuperscript{34} \textbf{Fig. 3a} presents the dark current-voltage ($J-V$) characteristics of OPD and Si PD, showing a comparable dark current and RR of these two PDs at zero bias. Moreover, the solution-processed OPDs demonstrate extremely high reproducibility with small variation of dark current and RR, with a median of 41 pA and $10^5$ for 25 devices, respectively (\textbf{Fig. 3b}). On the basis of the obtained responsivity and dark current, we quantified the sensitivity of OPD by calculating the NEP and $D^*$ of OPD, which shows remarkable values of $10^{-11}$ W and over $10^{10}$ cm·Hz$^{1/2}$W$^{-1}$, respectively (\textbf{Supplementary Fig. 10}). This value is comparable with commercial Si PD shown in \textbf{Fig. 3c}. LDR is another important parameter determined by measuring the photocurrent under a series of light intensities, which is extracted by $LDR = 20\log(I_{\text{max}}/I_{\text{min}})$. As shown in \textbf{Fig. 3d} and \textbf{Extended Data Fig. 4}, OPD exhibits a linear response covering almost eight orders of magnitude under illumination of 880 nm, yielding a significantly large LDR of over 130 dB owing to the low dark current of OPD, which is quite close to the value of commercial Si PD (140 dB).
Fig. 3 | Sensitivity of OPD and Si PD. **a**, Current density–voltage ($J$–$V$) curves of OPD and S1226-5BK in dark; **b**, Variation of dark current and RR of 25 independent OPDs; **c**, LDR of OPD and Si PD under the irradiation of NIR light ($\lambda=880$ nm) at zero bias; **d**, specific detectivity of OPD and Si PD at wavelengths ranging from 300 nm to 1000 nm.

**Photodetection Performance of Flexible OPD**

Flexible high-speed OPD simultaneously targeting mechanical stability and fast response is a prerequisite to achieve high-speed optical communication in wearable electronics. Taking the advantages of exceptional mechanical flexibility of organic semiconductors, we prepared flexible high-speed OPD that simultaneously achieve a high cutoff frequency and outstanding mechanical stability for optical communication. Figure 4a displays the schematic of device structure and materials of OPD, where ITO/PET film works as flexible conducting electrode due to its high conductivity, excellent flexible durability, and high transparency. By optimizing the thickness of ITO electrodes and device fabrication process (**Supplementary Fig. 11**), the optimal
flexible OPD exhibit extremely fast response time of 189.5 ns and fall time of 175.9 ns, -3dB cutoff frequency of ~3 MHz, and high responsivity of 0.47 A W⁻¹ (Supplementary Fig. 12), whose performance is quite close to the corresponding rigid OPD, exceeding the response speed of commercial rigid Si PD (Fig. 4b and Extended Data Fig. 5). To the best our knowledge, this is the fastest flexible OPD that have been ever reported (Supplementary Table 3).

Despite the outstanding performance of OPDs, the path to the commercialization of OPD has been impeded by their limited mechanical durability and electrical stability. To assess commercial prospective of flexible OPDs, we examined the electrical stability of flexible OPD under severe mechanical bending, ensuring continuous optical communication under conditions of mechanical movement. Fig. 4c displays the optical photograph of the mechanical durability test under bending, where the flexible OPD is mounted on a home-made durability tester machine controlled by a microcontroller. After bending 500 cycles with a bending angle ranging from 0º to 140º, flexible OPD demonstrates negligible degradation in photocurrent (<1%) and response speed (Fig. 4d). Moreover, our device maintains over 96% of its initial response speed, photocurrent, and dark current after exposure indoor for 550 h. All these remarkable mechanical durability and electrical stability present its compelling advantages over Si PD and ensure its great potential application in wearable optical communication systems.
**Fig. 4 | Performance of flexible OPD.**

**a**, Schematic of flexible OPD. **b**, Time domain response of flexible OPD at zero bias under 880 nm illumination. **c**, Optical graph of mechanical durability test setup (device area: $2 \times 2$ mm$^2$, scale bar: 1 cm). **d**, Photoresponse of flexible device before and after bending for 500 cycles (irradiation pulse frequency: 0.5 Hz, zero bias, 880 nm). **e**, Optoelectronic performance of flexible device under indoor exposure.
Optical Communication Performance of Flexible OPD

To demonstrate the feasibility of using OPD in realistic NIR optical communication, we integrated the OPD as an optical signal receiver into the optical communication system for wireless data transmission at the wavelength of 880 nm. **Fig. 5a** displays the potential applications of flexible OPD in optical communication systems, such as wearable electronics, implanted devices, indoor optical communication, and ITS. We first evaluated the data transmission performance by measuring the bit-error-rate (BER) using a non-return to zero (NRZ) modulation scheme. Generally, to achieve a reliable optical communication, the BER should be less than $3.8 \times 10^{-3}$, which is under 7% pre-forward-error-correction (pre-FEC). As shown in **Fig. 5b**, our device demonstrates a maximum achievable data rate of 80 Mbps with a BER of $3.5 \times 10^{-4}$. To visualize the BER of OPD at different transmission rate, we also performed an eye-diagram measurement with an intrinsic rate of 10 and 80 Mbps, which showed open and clear eye-diagram, indicating that the flexible OPD can be readily used for practical optical communication (**Fig. 5b** and **Supplementary Fig. 13**).

Optical communication has superior advantages in ITS in comparison with current radio frequency wireless technology, particularly in achieving the high-speed and efficient communication among vehicles via taillights or near infrared light for emergency braking warning, intersection collision warning, emergency call in the appalling weather. Taking full advantages of the our OPD in high-speed response and high responsivity, we designed a text communication system using OPD, which combined the modern radio communication technology with optical communication, achieving a long-distance optical communication between two cars via NIR light. For example, the mobile phone sends the command of “Hello, World!” to the microcontroller that can modulate NIR LED to send optical signal. Then OPD receive the optical signal emitted from NIR LED and convert it to text of “Hello, world!” (**Supplementary Video S1 and Video S2**). This encouraging result directly prove that our flexible high-speed OPDs have a great potential in future high-speed optical
communication system from the visible to NIR range.

**Fig. 5 | Optical communication of flexible OPD.** a, Application scenario of optical communication based on flexible OPD: (i) schematic of flexible OPD, (ii) Flexible OPD attached on skin, (iii) Flexible OPD implanted under skin, (iv) OPD used in indoor communication, (v) OPD for intelligent traffic system. b, The BER of OPD application in high-speed communication. c, Eye diagram at the communication rate of 80 Mbps. d, Schematic of infrared light communication. e, Vehicle interconnection based on OPD in infrared light.
In conclusion, we have successfully fabricated a flexible high-speed OPD by introducing a novel NFA with a compact 3D molecular packing network, enabling the speed performance to be greatly improved beyond that of previously reported OPDs and the state-of-the-art Si PD. The achieved response time of 91 ns, 3dB bandwidth of 4 MHz, and responsivity of 0.53 A W$^{-1}$ are two times higher than the commercial Si PD at zero bias. More importantly, flexible OPD displays outstanding mechanical and electrical stability after mechanical bending for 500 times with negligible performance degradation (<1%) and maintained over 95% initial photoresponse after working in ambient for 550 h. All these outstanding performances are contributed to the novel NFA that forms a favorable 3D molecular packing in the blend, leading to low trap density and reduced energetic disorder, and thus resulting in low RC constant and high charge mobility. In addition, the flexible OPD-based LiFi system for high-speed optical communication demonstrated a high data transmission rate of 80 Mbps with a BER of $3.5 \times 10^{-4}$, achieving accurate optical communication between two vehicles. The excellent optoelectronic performance and outstanding mechanical stability of flexible OPDs showcase the strong potential practical applications in next-generation optical communication technologies, particular in flexible electronics, soft robotics, autopilot, and implanted devices.
References


**Methods**

1. Material synthesis

Polymeric donor PM6 from Solarmer Material (Beijing) Inc., and chloronaphthalene were purchased from Sigma Aldrich. PDINO is from eFlexPV Limited and Seniormaterial, respectively. CH17 was synthesized according to our previously reported method\textsuperscript{25}. All the other reagents and chemicals used in this work were purchased from commercial suppliers and were used directly without further purification. Flexible ITO/PET transparent electrodes with various ITO thickness of 12, 23, 125, 135, 185 nm were purchased from Advanced Election Technology CO., Ltd and Xiangchen Technology.

2. Device fabrication

Organic Photodetectors based on PM6:CH17 were fabricated with a normal architecture of glass/ITO/PEDOT:PSS(4083)/PM6:CH17/PDINO/Ag. Firstly, the glass/ITO substrate was sequentially pre-cleaned in an ultrasonic bath of detergent, deionized water, acetone and isopropanol, followed by drying using N\textsubscript{2} gas. Then the ITO substrate was irradiated by UV light in an ultraviolet-ozone chamber (Jelight Company) for 15 min. A thin layer of hole transport layer was prepared by spin coating the poly(3,4-ethylene dioxythiophene):poly(styrene sulfonate) (PEDOT:PSS, Baytron PVP Al 4083) solution at 4300 rpm for 20 s on the ITO substrate, followed by baking 150\degree C for 20 min in air and then transferred to a glove box filled with argon. The PM6:CH17 mixture was fully dissolved in chloroform (CF) at 50\degree C with 0.5\% of 1-chloronaphthalene (CN) as additive at a concentration of 8 mg/mL of PM6. To remove CN existing in the photoactive film, the obtained device was annealed at 110 \degree C for 10 min on hot plate. Devices with different thickness of active layers are obtained by tuning the spin-coating speed ranging from 500 rpm to 2500 rpm for 30 s, and the optimal speed is 2000 rpm. After that, PDINO (dissolved in methanol with the
concentration of 1 mg/mL) solution was spin-coated on the top of the active layer and obtained a layer of electron transporting layer with a thickness of 15 nm. Finally, Ag electrode with the thickness of 100 nm was prepared by thermal evaporation technique under $2 \times 10^{-6}$ Pa. The active area of the final device was 4 mm$^2$ determined by a predesigned mask. For long-term stability test, device was encapsulated by an epoxy resin (Norland Optical Adhesive 81) under UV of 365 nm exposure for 2 mins. To prepare flexible OPD device, a thin layer of Polydimethylsiloxane (PDMS) film was prepared by spin-coating the mixture of precursors and crosslinkers (10:1) on precleaned glass at 5000 rpm for 30 s, then the unsolidified film was baked at 80 °C for 10 min to get the final PDMS. Then the flexible ITO/PET substrate was attached on PDMS for flexible OPD fabrication. The fabrication process of flexible OPD follows the procedure of rigid device. The optimal flexible device is prepared by spin-coating PM6:CH17 solution at 2000 rpm for 30 s.

3. Device Characterizations

Current density-Voltage ($J$-$V$) in dark and Current-Time (I-T) curves under irradiation of 880 nm at a pulse frequency of 0.5 Hz and zero bias were tested by semiconductor parameter analyzer (B1500A, Keysight) and source meter (Keithley 2400 controlled by the Software developed by Wuhan Zeal Young Technology Co., Ltd.). The dependency of responsivity with wavelength was performed on QE-R (Enli Technology Co. Ltd.). The noise current of the devices was measured using electrometer (6517B, Keysight). The capacitance of device was measured by electrochemical workstation (Zennium-E, Zahner). Response time and -3dB cutoff frequency was measured by high resolution oscilloscope (MDO4104C, Tektronix) through square wave modulated 880 nm LED controlled by signal generator (DG990, RIGOL). The DC bias module (PBM42, Thorlab) and variable resistance BNC terminator (VT2, Thorlab) were employed in investigation to effects of bias and resistance on response time. The thickness of device was tested by profilometer (Dektak
Variable temperature test for cutoff frequency was carried out by dry thermostat (GC-100, Yooning). The UV-Vis spectrometric absorption of PM6 and CH17 films were measured using UV-Vis spectrometer (Cary 3000, Agilent).

The space-charge-limited current (SCLC) method was used to measure the hole and electron mobilities, by using a diode configuration of ITO/PEDOT:PSS/active layer/MoO3/Al for hole and ITO/ZnO/active layer/Al for electron. The mobilities were estimated by taking current-voltage curves and fitting the results based on the equation listed below:

\[ J = \frac{9\varepsilon_0 \varepsilon_r \mu V^2}{8L^3} \]

where \( J \) is the current density, \( \varepsilon_0 \) is the vacuum permittivity, \( \varepsilon_r \) is the relative dielectric constant, \( \mu \) is the mobility, and \( L \) is the film thickness. \( V (=V_{\text{app}} - V_{\text{bi}}) \) is the internal voltage in the device, where \( V_{\text{app}} \) is the applied voltage to the device and \( V_{\text{bi}} \) is the built-in voltage due to the relative work function difference of the two electrodes. The long-term stability was carried out by measuring response time every other hour. The BER and eye diagram of OPD in high-speed communication are simulated using Optisystem software. The flow chart is shown in Supplementary Fig. 12.

4. Mechanical stability characterizations

Mechanical durability is conducted by bending flexible OPD via a stage transmission, which is controlled by a single-chip microcomputer. The bending angle is controlled by tuning the distance of the two stages. The photoelectronic performance was characterized before and after mechanical bending.

5. Optical communication measurement

Infrared light text communication system based on organic photodetector is composed of transmitter circuitry (Tx) and receiver circuitry (Rx). The circuit detail can be seen in Supplementary Fig. 14. In order to simulate actual circumstance, we
connected the phone with the transmitter via Bluetooth wireless technology to input signals. By texting the desired information in the phone, it can transmit the signal to the single-chip microcomputer and then modulate infrared LED (880 nm). Then, OPD received the infrared light signal and transferred it to an electric signal, which was converted to text displaying on Liquid Crystal Display (LCD).

In practical applications, the signal transmitting distance is a key metric to evaluate the performance of optical communication system, which is determined by the responsivity of OPD, irradiation power of LED, and the background environment. Under the low-bias driving (3V) of LED, the infrared light text communication system can perform well and the maximum communication distance is up to 5 m. Furthermore, we applied this system in vehicle communication by installing the LED and OPD on two cars.

Acknowledgements

We gratefully acknowledge the financial support from NSFC (21935007, 52025033) and MoST (2019YFA0705900) of China, Tianjin city (20JCZDJC00740), 111 Project (B12015).

Author contributions

Prof. Yongsheng Chen and Prof. Guanghui Li conceived and designed the project. Yu Zhu fabricated the high-speed photodetector and carried out all of the performance studies. The manuscript was mainly prepared by Prof. Yongsheng Chen, Prof. Guanghui Li, and Yu Zhu, and all authors participated in the manuscript preparation.

Competing interests

The authors declare no competing interests.
Extended Data

Extended Data Fig. 1 | Response time measurement of OPD and Si PD via steady-state analysis method. a, Error analysis of optical steady state and dark steady state of OPD. b, Error analysis of optical steady state and dark steady state of Si PD (S1226-5BK). (The details are in Supplementary Note 1)
Extended Data Fig. 2 | Performance comparison of OPDs and Si PDs. a, Summary of the response time of high-speed OPDs based on PM6:CH17 at zero bias. b, -3dB cutoff frequency of OPDs under illumination at different wavelength. c, -3dB cutoff frequency of device with area of 1*1mm² that exceeds 4M Hz. d, Performance comparison of literarily reported OPDs and commercial Si PDs, where devices of 1,3,4,5,6 are from OPDs reported in literatures and devices of 2,7,8,9,10,11 are from Si PDs (Hamamatsu)
Extended Data Fig. 3 | Effect of spin speed on the performance of OPD devices. a, Mobility dependence on temperature. The energetic disorders of OPD are quantitatively measured based on model of Gaussian distribution of DOS: \( \mu = \mu_\infty \exp\left(-\frac{2\sigma^2}{3k_BT}\right) \) at zero field. The energetic disorders \( \sigma \) is 41 meV. b, -3dB cutoff frequency of devices with various thickness. c, responsivity of devices with various thickness.

Extended Data Fig. 4 | Linear response range of OPD (left) and Si PD (S1226-5BK) (right).
Extended Data Fig. 5 | **a**, Responsivity of flexible OPD. **b**, -3dB cutoff frequency of flexible OPD (~3M Hz).
Supplementary Files

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