245 MHz bandwidth organic light-emitting diodes used in a gigabit optical wireless data link

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Organic optoelectronic devices combine high-performance, simple fabrication and distinctive form factors. They are widely integrated in smart devices and wearables as flexible, high pixel density organic light emitting diode (OLED) displays, and may be scaled to large area by roll-to-roll printing for lightweight solar power systems. Exceptionally thin and flexible organic devices may enable future integrated bioelectronics and security features. However, as a result of their low charge mobility, these are generally thought to be slow devices with microsecond response times, thereby limiting their full scope of potential applications. By investigating the factors limiting their bandwidth and overcoming them, we demonstrate here exceptionally fast OLEDs with bandwidths in the hundreds of MHz range. This opens up a wide range of potential applications in spectroscopy, communications, sensing and optical ranging. As an illustration of this, we have demonstrated visible light communication using OLEDs with data rates exceeding 1 gigabit per second.
Organic semiconductors are now well established as a thin-film electronics platform for displays, solar power, and printed electronics\textsuperscript{3,4}. Their optical and electronic properties can be tailored through molecular design to give very efficient light emission, and to tune the band gap energy or thin film morphology\textsuperscript{5-7}. Organic electronics and organic light-emitting diodes (OLEDs) in particular are now widely adopted in smart devices and wearables\textsuperscript{8-11}. They can be produced in very high volumes on very thin, flexible plastic substrates, at low cost\textsuperscript{12,13}, with high density integration of pixels of different materials or for very large area electronics. While high power efficiency has been achieved for OLEDs, organic solar cells, and photodiodes, their temporal performance is generally thought to be intrinsically slow. For example, in comparison to inorganic LEDs, OLEDs have low modulation bandwidth which is mainly attributed to their low charge mobility and high capacitance. The charge mobility of organic semiconductor materials (especially the ones used in OLEDs) is several orders of magnitude lower than for inorganic semiconductors\textsuperscript{14}. In addition, OLEDs have a planar structure of several tens to hundreds of nanometers thickness. This forms a high capacitance which limits bandwidth drastically\textsuperscript{14,15}, with few reports exceeding 10 MHz\textsuperscript{16}. A striking consequence of this is the highest reported data rate for an OLED optical data link is 51.6 Mbps by Chen et al.\textsuperscript{17}, whereas GaN LEDs have achieved visible light communication (VLC) data links of several Gbps\textsuperscript{18-20}

OLEDs with high electrical bandwidth (of hundreds of MHz or above) could enable a wide range of new applications of organic electronics. For example, OLEDs are an attractive light source for low cost integration in lab-on-a-chip formats for disposable point of care diagnostics\textsuperscript{21}; fast intensity modulation would enable time-resolved fluorescence measurements of biomarkers\textsuperscript{22}, broadening the scope for diagnostic tests with high specificity. Visible light communications is a promising approach to address the rapidly increasing global demand for wireless communications bandwidth\textsuperscript{23-25}; fast OLED transmitters could play a role in data links with smart phones, smart label sensors or secure contactless communications between credit cards and ATMs. Fast modulation of OLED arrays and displays could also enable new approaches to fluorescence lifetime imaging\textsuperscript{26-28}, optical detection\textsuperscript{29} and ranging\textsuperscript{30,31}, and structured light imaging\textsuperscript{32,33}.

Here, we report a significant breakthrough in speeds of OLEDs. To achieve this, we carefully investigated the factors limiting the bandwidth of OLEDs and how to overcome them. We explored the effect of active area size, electrode design, and the emitting material. By simultaneously optimizing all three of these aspects, we fabricated OLEDs that show a significant improvement in bandwidth. We illustrate one area of possible application of these very fast OLEDs by showing that they can be used as a transmitter for a free space communication link at a rate of 1.13 Gbps over a distance of 2 m. To the best of our knowledge, this constitutes an improvement of a factor of 20 over previously reported OLED VLC data rates\textsuperscript{17}, and is achieved over a much larger distance. We believe that these results will pave the way for efficient, low-cost, and high-speed organic optoelectronics, with potential applications in secure communications, point of care diagnostics, and optical imaging and ranging.

Results Overview. Three generations of OLED devices were developed and a combination of optoelectronic and photophysical measurements made to identify the key factors limiting their modulation bandwidth and overcome them. Each OLED generation was then characterized in a data transmission measurement to assess their capacity to usefully exploit their modulation bandwidth. An orthogonal frequency division multiplexing (OFDM) modulation scheme was used, which permits adaptive allocation of data and energy in different frequency bands to optimally utilize the available bandwidth (see Methods section for further details)\textsuperscript{18,34,35}.

First generation OLEDs with p-i-n structure and fluorescent emitter. The first generation of OLEDs were designed with a p-i-n structure\textsuperscript{36} with doped charge transport layers, based on an established blue fluorescent emitter, 2,5,8,11-tetra-tert-butylperylene (TBPe)\textsuperscript{37-39} (hereafter termed “G1-OLEDs”, see Fig. 1 for details). This fluorescent emitter was chosen over more efficient phosphorescent and thermally activated delayed fluorescent emitters due to its substantially shorter luminescence lifetime\textsuperscript{40} (4.4 ns for TBPe doped into 2-methyl-9,10-bis(naphthalen-2-yl) anthracene (MADN) (hereafter termed “TBPe film”, see Supplementary Fig. 1a) A p-i-n structure with doped transport layers\textsuperscript{36} was selected to achieve good charge injection from the contacts and high conductivity. This reduced heating of the device and hence enabled operation at high current and high brightness (Supplementary Fig. 2a).

To assess the bandwidth of the G1-OLEDs, the frequency response of the system was determined (see Methods section). The overall optical link exhibits a low-pass characteristic whose bandwidth is significantly determined by the OLED. Figure 2a displays the bandwidth of the link (the frequency at which the power gain of a VLC link, |H|^2, decreases 6 dB from its maximum value) as a function of the voltage applied to the G1-OLEDs. We observed an increase of the bandwidth with increasing voltage. This may be attributed to a reduction in device resistance as the voltage was increased, leading to a reduction of the electrical time constant of the OLEDs\textsuperscript{41} (see Supplementary Note 2). We note that the maximum voltage for the G1-OLED was limited to around 5 V by device breakdown. The details and the limiting factors of the G1-OLEDs are discussed further in the next section.

A free-space data link using the G1-OLED as transmitter was next evaluated by locating a receiver 2 m away and driving the OLED with a data stream using an implementation of direct current (DC)-biased optical orthogonal frequency division multiplexing (DCO-OFDM) (see Supplementary Note 3 for the details of data transmission optimization). Figure 2b shows the data rate at a bit error ratio (BER) of 3.8 \times 10^{-5}, which corresponds to the 7% forward error correction limit (7% FEC limit\textsuperscript{42}) as a function of voltage for the G1-OLEDs. A maximum data rate of 140 Mbps (average of 4 OLED samples, Supplementary Table 1) was achieved for an applied DC voltage of 5 V.

Second generation OLEDs of different active area with thermal management and top emission geometry. To further improve the OLED bandwidth, it is necessary to reduce the electrical time constant. To achieve this, the device design was modified to reduce both the wiring resistance, which is the resistance between the contact pads and the active area of the OLED, and the capacitance of the OLED. These steps reduced the RC time constant, and also enabled the device to operate at higher voltage. The indium tin oxide (ITO) layer (90 nm; \(42 \Omega/\text{sq.}\)) was replaced with a thin silver layer (30 nm; \(<3 \Omega/\text{sq.}\)), thereby reducing the resistance of the transparent electrode. Smaller OLED areas can achieve higher bandwidth\textsuperscript{44} due to reduced capacitance, but this comes with a penalty of lower light output, potentially limiting the signal to noise ratio (SNR) of a data link. We therefore fabricated an improved set of OLEDs with the same organic stack but in a range of different sizes to test this trade-off and find an optimized area to maximize the communication performance. We used thermal evaporation of crossed electrodes.
to define the device area rather than introducing insulators with photolithography, which would cause parasitic capacitance. Finally, we note that for the first generation OLEDs, both their bandwidth and data rate increased with applied voltage, but were limited to a maximum value by the temperature rise of the device, which led to device breakdown. To suppress this temperature rise, the second generation OLEDs were fabricated on silicon substrates, which offer high thermal conductivity. These second generation OLEDs (hereafter termed “G2-OLEDs”) were fabricated with three different device areas: G2-S-OLEDs (1.2 × 10⁻³ cm²), G2-M-OLEDs (1.1 × 10⁻² cm²), and G2-L-OLEDs (9 × 10⁻² cm²).

Figure 2a shows the results of bandwidth measurements of a link using G2-OLEDs as a function of voltage. The bandwidth is higher for G2-OLEDs with smaller device area—for example at 8 V the bandwidths of G2-L-OLED, G2-M-OLED, and G2-S-OLED are 24, 37, and 81 MHz, respectively. It can also be seen that the bandwidth increases with increasing voltage. Both observations are substantially due to a reduction in electrical time constant. This arises from the change in device area and (as diodes have nonlinear current–voltage characteristics) a reduction in resistance as voltage is increased. The results show that reducing device size and increasing operating voltage are helpful to realize high bandwidth. The data rate of these devices is shown in Fig. 2b. For all second generation OLEDs, the data rate increases with voltage, with the G2-S-OLEDs giving the highest data rate of 610 Mbps at 9 V (average of three OLED samples).

Third generation OLEDs with improved device configuration and faster emitter. The potential ways of increasing the modulation bandwidth of the G2-S-OLEDs are to reduce further the electrical time constant, decrease the charge transit time, and shorten the emission lifetime. These points were addressed in the third generation OLEDs (G3-OLEDs). The electrical time constant could be reduced further by reducing the device area, increasing the number of contact pads for the more resistive transparent electrode (as resistance decreases by connecting two resistors in parallel), and by increasing the thickness of the aluminum (Al) bottom electrode to reduce wiring resistance.
G3-OLEDs were therefore designed with similar stack structure to the G2-OLEDs, but with the device area slightly reduced to $9.2 \times 10^{-4} \text{cm}^2$, and a different electrode configuration. The cathode was re-designed with two contact pads, while the thickness of the Al anode was increased from 80 to 200 nm (see Fig. 1b).

Since the bandwidth of the G2-S-OLED is comparable to the emission lifetime of the TBPe film, OLEDs with an alternative emitter of shorter photoluminescence (PL) lifetime, 4,4'-bis[4-(diphenylamino)styryl]biphenyl (BDAVBi), were fabricated as well (G3-“fast-emission-molecule” (FEM)-OLEDs). The lifetime of BDAVBi films doped into MADN was measured to be 1.1 ns (see Supplementary Fig. 1a).

Figure 2a shows our initial measurements of the link’s bandwidth with the G3-OLED and G3-FEM-OLEDs as a function of applied voltage. Higher bandwidth was observed with the G3-OLED than with the G2-S-OLED. The bandwidth of the fastest OLEDs was then studied in more detail using a photodiode with flatter frequency response (Thorlabs, APD430A2/M) and the wiring resistance at all operating voltages. In this scenario, the effect of the change in device resistance is minor, and the main effect is the reduction of charge transit time. In combination with the short emission lifetime, this leads to the very high bandwidth of the emitting molecules, especially for the G3-OLED which uses TBPe as an emitter. This suggests there are additional processes in the device, such as singlet-triplet annihilation, which shorten the emission lifetime.

There are two main factors that contribute to the increase of bandwidth with increasing voltage. One is that the higher electric field leads to a shorter charge transit time. The other is that the reduction in resistance reduces the electrical time constant. In the G3-FEM-OLED the resistance of the device is large compared with the wiring resistance at all operating voltages. In this scenario, the effect of the change in device resistance is minor, and the main effect is the reduction of charge transit time. In combination with the short emission lifetime, this leads to the very high bandwidth for an organic semiconductor device of 245 MHz. We note that this measurement was made with a detector with a resonance around 100 MHz (Supplementary Fig. 6).

Finally, the VLC performance of the G3- and G3-FEM-OLEDs was investigated. Figure 2b and Supplementary Table 1 show the data rate at the 7% FEC limit of the OLEDs in a 2 m data link. Both G3-OLEDs achieved data rates exceeding 1 Gbps. The highest data rate was for the G3-FEM-OLED which exhibited a modulation bandwidth of 165 MHz.

Like other OLED-VLC work we used a lens at the transmitter and receiver, and this allows us to compare our results with
increasing separation distance, we achieved our value in a link. OLEDs could potentially be applied to shorter contact-point alignment of the transmitter and receiver, the fast lens-coupled 2 m data link demonstrated here requires point-to-point alignment. We have illustrated this by making a 20-fold improvement in the data rate. Organic optoelectronic devices working much faster than previously thought possible. Moreover, our results suggest that OLEDs may be suitable for a range of potential applications where fast modulation is required, spanning secure communications, point of care diagnostics, and optical imaging and ranging. The principles developed here may also prove useful for making other organic electronic devices faster than previously thought possible.

**Methods**

Fabrication of OLEDs and films of emission layers of OLEDs. The OLEDs were fabricated as follows: metals and organic materials were thermally evaporated through a shadow mask in a vacuum chamber at a base pressure of 10⁻⁷ mbar (Angstrom Engineering Inc., EvoVac). The OLED layer stack consisted of 40 nm N,N'-di-2-naphthyl-N,N'-diphenyl-1,4-phenylenebis-benzimidazole (TCNQ) (4 wt%) as a hole transport layer (HTL), 10 nm N,N'-diphenylbenzidine (NPB) as an electron blocking layer (EBL), 20 nm emission layer (EML, detailed below), 10 nm bis-(2-methyl-8-quinolinolato)-(4-phenyl-pheno-1,2-)phenylalanine (BDPhen) as an n-doped electron transport layer (ETL). Calibrated quartz crystal microbalances were used to control deposition rates and the thickness of the EML. All materials were purchased from commercial suppliers and used without further purification. All OLEDs were encapsulated under nitrogen atmosphere using a 1.1 mm thick glass lid (Shanghai Amerina Optoelectronic Co., Ltd.), epoxy resin (Norland Products Inc., Norland Optical Adhesive 68), and an additional moisture getter (Dyonic Corporation, HD-071210T-505). A similar procedure was used to make films of the emission layers of the OLEDs although films for PL quantum yield were not encapsulated.

The G1-OLED was fabricated onto 1.1 mm thick glass substrates coated with a 90 nm thick pre-patterned indium tin oxide (ITO) anode (Thin Film Devices Inc.). The device stack was capped with a 100 nm thick aluminum cathode. The EML consisted of the fluorescent emitter 2,5,8,11-tetra-tert-butylphenylene (TBP), which was doped with 1.5 wt% in the host 2-methyl-9,10-bis(naphthalen-2-yl)anthracene (MADN). The active area of these G1-OLEDs was 16.1 mm².

The G2- and G3-OLEDs were fabricated on silicon substrates with a thickness of 675 μm coated with a 300 nm silicon dioxide (SiO₂) layer on both sides to prevent electrical leakage through the substrate. Aluminum anodes were evaporated onto the SiO₂ layer through a shadow mask with different aperture sizes. The organic material stack was subsequently evaporated as detailed above. The EML of the G2- and G3-OLEDs consisted of TBP, which was doped at 1.5 wt % in MADN. The EML of G3-FEM-OLEDs consisted of 4.4-bis-[4-(diphenylamino) styryl]biphenyl (BDAVBi) doped at 3 wt% in MADN. A 30 nm silver layer was evaporated onto a transparent metal cathode and the stack was finished with a 50 nm thick NbP capping layer. Shadow masks were changed without breaking vacuum. A single layer of aluminum was used as a bottom electrode instead of the commonly used multi-layer of aluminum and silver as this was found to give higher device fabricability yield and more stable operation. The active areas were measured from electroeluminescence (EL) images of the operating OLEDs under a microscope (ZEISS, Axio Lab A1, (see Fig. 1d)).

**OLED characterization.** Current density-voltage-radiance characteristics were measured using a source meter (Keithley Instruments, Inc., 2400 SourceMeter), and a multimeter (Keithley Instruments, Inc., 2000 Multimeter) with a calibrated Si photodiode. Emission spectra from the OLEDs under constant current operation at 6 mA/cm² were recorded by a CCD spectrometer (Andor Technology Ltd., DV420-BV), and used to calculate the radiance. The external EL quantum efficiency (EQE) of the OLEDs was estimated assuming a Lambertian emission pattern. The frequency response of G2-, G3-, and G3-FEM-OLEDs was measured using a photodiode with a linear frequency response (Thorlabs, APD430A2/M, −3 dB bandwidth at 500 MHz). The OLEDs and the receiver were connected to a network analyser (Keysight, E5061B) and the measurement knowledge (KBN) measurement was conducted to estimate the frequency response of the OLEDs at different DC bias voltages and at frequencies in the range 0.1–500 MHz. Results are shown up to 400 MHz due to low SNR above this frequency. The frequency response of all the emission layers in a similar way but with excitation by a laser at 405 nm (US-Lasers Inc., D405-20) connected to the network analyser through a diode driver (Thorlabs, LDC210C) and with a long-pass filter (Comar Optics Ltd, 510 IY 50) inserted between the lenses. The frequency response of the laser was measured and the frequency response of the films was estimated by dividing the measured frequency response of the films by the frequency response of the laser.

**VLC link set-up.** In all the data transmission experiments, orthogonal frequency division multiplexing (OFDM) was used. It is a well-known and widely applied modulation scheme in visible light communication. OFDM was selected because it is adaptive to communication systems properties, and permits adaptive allocation of data and energy at different frequency bands. It further offers advantages such as cost-effective equalization with single-tap equalizers and an easy way to avoid low-frequency interference cause by ambient light. Supplementary Fig. 8 shows a schematic illustration of the set-up for VLC measurement. The OLEDs were mounted in tailor-made device holders. All communication experiments were conducted under typical office illumination levels. This included natural light from windows in combination with artificial light from fluorescent lamps. The link followed a typical setup for a VLC experiment. For the G2-, G3- and G3-FEM-OLEDs, a heat sink with a fan was used to dissipate Joule heating at high driving powers. The modulated digital signal was passed onto...
an arbitrary waveform generator (AWG, Agilent, 81180A) with analog output. The maximum peak-to-peak voltage ($V_{pp}$) available from the AWG was 2 V so a broadband amplifier (Mini-Circuits, ZHL-6A-S+) was used for higher voltages. To measure the $V_{pp}$ produced by the amplifier, we applied a 120 MHz sine wave with the same $V_{pp}$ from the AWG as during VLC measurement to the amplifier. The output voltage of the amplifier was then measured using a bias tee (Mini-Circuits, ZFBT-4R2GW) and oscilloscope (Agilent, MSO7104B). $V_{pp}$ was adjusted to maximize data rate at each bias voltage. During VLC measurement, the signal created by the AWG was combined with a DC bias voltage ($V_{bias}$) from a power supply (Keithley Instruments, Inc., 2400 SourceMeter) through the bias tee and used to drive the OLEDs. Aspheric condenser lenses (Thorlabs, ACLS0832U-A) with numerical aperture of 0.76 and focal length of 32 mm were used to collimate and focus the light onto the receiver circuit. The length of the communications link (distance between the lenses) was 2 m. The custom-made receiver circuit for the OLEDs comprised a silicon avalanche photodiode (Hamamatsu, S8664-10K) with an active area of 0.78 mm$^2$ and the cutoff-frequency of 530 MHz and a transimpedance amplifier with an operational amplifier (Texas Instruments, OPA847). The output from the receiver circuit was captured by the oscilloscope through a low pass filter (Mini-Circuits, SLP-150+), and then processed using a laptop computer. The VLC link used an implementation of DCO-OFDM. An adaptive bit loading and power loading algorithm based on the work by Kaltenbrunner, M. et al. Ultrathin and lightweight organic solar cells with high flexibility. Nat. Commun. [https://doi.org/10.1038/ncomms1772] (2012).

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Author contributions
H.H., I.D.W.S., and G.A.T. conceived of the project and supervised the research. K.Y. and P.P.M. planned the project, guided by H.H., I.D.W.S., and G.A.T. C.M. designed the G1 OLEDs which were fabricated by her and K.Y. under the supervision of M.C.G. and I.D.W.S. K.Y. was responsible for the design, development and fabrication of G2 and G3 OLEDs. P.P.M. built the apparatus for measuring the frequency response of the OLEDs and films, and performed the measurements with K.Y. Z.C. and R.B. measured the frequency response of the VLC channel and its BER. K.Y., C.M., P.P.M., H.H., I.D.W.S., and G.A.T. wrote the manuscript, which was then reviewed by all authors.

Competing interests
H.H. is founder, director and a shareholder in PureLiFi, a company developing LiFi technology. The other authors declare no competing interests.

Additional information
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