NIR to Visible Light Upconversion Devices Comprising an NIR Charge Generation Layer and a Perovskite Emitter

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NIR to Visible Light Up-conversion Devices Comprising an NIR Charge Generation Layer and a Perovskite Emitter

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Near infrared (NIR) to visible light up-conversion is of significant importance in many applications including thermal imaging, bio-imaging, night vision and wellness monitoring. In this work, we report our effort to develop a high performing NIR to saturated green light up-conversion device comprising a front solution processable organic bulk heterojunction NIR charge generation layer (CGL) and an upper CsPbBr₃ perovskite light-emitting diode (LED) unit. The NIR CGL, based on a blend of the NIR sensitive donor polymer and a nonfullerene acceptor, enables an efficient hole injection in the CsPbBr₃ LED in the presence of the NIR light and also serves as an optical out-coupling layer to enhance the visible light emission by the CsPbBr₃ LED. The CsPbBr₃-based perovskite LED has a narrow emission spectrum with a peak wavelength of 520 nm, corresponding to the wavelengths near the peak response of the human eye, and has the advantage in imaging applications. Based on the up-conversion process, a pixel-less NIR to visible light imaging device was demonstrated, which can be operated at a low voltage of 3 V. The results are very encouraging,
revealing a high performing solution processable up-conversion device for application in NIR light imaging.

**Key words**: NIR to visible light up-conversion, nonfullerene acceptor, perovskite LED, NIR imaging

**Introduction**

Up-conversion is a process where photons with a low energy are absorbed leading to the emission of photons with a high energy\(^1,2\). Specially, transferring near infrared (NIR) into visible light during the up-conversion process is of significant importance in different applications, including bio-imaging\(^3-6\), solar harvesting\(^7,8\) and long wavelength light detecting\(^9\). The NIR to visible light up-conversion process provides a real-time image for the human eye enabling vivo investigation and diagnose. In bio-imaging applications, the up-conversion from NIR to visible light was achieved by targeting delicately designed nano-particles in the tissues or organs\(^10,11\). These particles enable a nonlinear optical process via anti-stokes shift\(^11\), where NIR photons are transferred to photons of visible light. However, this imaging technique often involves the use of the toxic elements in the tissues or organs\(^12\). The NIR to visible light up-conversion can also be realized using an up-conversion devices to convert the incoming NIR photons to that of the visible light\(^13-17\). These up-conversion devices usually consist of an NIR charge generation layer (CGL), serving as a charge injection layer, and an integrated light-emitting diode (LED) unit that emits the visible light\(^6,13,14,16,18\). The efficient charge injection in the LEDs is enabled by the NIR CGL in the presence of the NIR light. The efficient electroluminescence (EL), taking place in area where the efficient charge injection was enabled by the NIR CGL, occurs in the LEDs, producing the visible light image. The flexible and large area up-conversion devices that can be made by solution fabrication processes are particularly attractive for use in pixel-less NIR imaging applications. The pixel-less imaging process avoids the complicated design...
of NIR detector arrays and complex external circuits for data processing required in the traditional NIR imaging techniques\cite{15}.

Inorganic semiconductors are often employed for the up-conversion devices\cite{15,19}. However, the inherent process difficulty with regarding to the lattice mismatch, brittle and rigid characteristics of inorganic materials, limit their uses for application in large area and flexible devices. Monolithic integration of solution processable organic photodetector with organic light-emitting diode (OLED) provides significant process flexibility, cost benefit, as well as the functional superiority for a broad range of applications, e.g., high contrast OLEDs \cite{20}, and organic optical sensors \cite{21}. Therefore, the vertical integration of organic NIR photodetector with LED for up-conversion devices have attracted increasing attentions due to the advantage of solution fabrication capabilities, attaining large area NIR image devices\cite{6,14,18}, creating a pixel-less NIR imaging technology platform\cite{6,14,15,18} for application, e.g. wellness monitoring\cite{6}. Up-conversion devices with an OLED unit have a relatively broadband light emission spectrum\cite{14,15,17,22}. The emerging perovskite LEDs are very attractive for use in the NIR to visible light conversion devices. The perovskite LEDs exhibit saturated and tunable emission spectra by tuning the component composition\cite{23–25}, and can be prepared by both vacuum sublimation and solution fabrication processes. The inorganic CsPbBr$_3$ perovskite LEDs with a maximum external quantum efficiency ($EQE$) of 1.55\% and emission spectrum with a full width at half maximum of <20 nm have been reported \cite{26}, enable a greater color gamut for full-color imaging applications. The CsPbBr$_3$-based perovskite solar cells also demonstrate a promising power conversion efficiency of >11\% \cite{27}, revealing the inorganic CsPbBr$_3$-based perovskite semiconductor materials have excellent optoelectronic properties and processabilities for a variety of device applications. In this work, the solution processable CsPbBr$_3$ perovskite LEDs, having a narrow EL emission with a peak wavelength of 520 nm, were used for the up-conversion devices, due to the advantages of saturated green EL
emission and excellent air stability\textsuperscript{[28]}, simple device architecture\textsuperscript{[25,29]} and the flexible device fabrication processes\textsuperscript{[30]}.

For the NIR sensitive media, solution based organic materials show promising characteristics due to their high sensitivity to the NIR light. The donor/acceptor bulk heterojunction (BHJ) type active media is a wildly accepted strategy for efficient photon absorption and charge generation. Compared to fullerene based acceptors with absorption mainly in the UV-visible region, the development of nonfullerene based molecules with excellent long wavelength sensitivity has drawn increasing attentions\textsuperscript{[31–34]}. High efficiency nonfullerene acceptor based BHJ solar cells, with the absorption extended in the NIR region, have been reported\textsuperscript{[32,33]}. The NIR sensitive nonfullerene acceptors also are attractive for NIR detection applications.

In this work, high performance NIR to visible light up-conversion devices were obtained by integrating a CsPbBr\textsubscript{3} perovskite LED unit and a solution-processed high efficiency NIR CGL, based on the NIR sensitive polymer donor/nonfullerene acceptor BHJ. The hole injection in the upper CsPbBr\textsubscript{3} LED unit in the up-conversion devices is enabled by the NIR CGL in the presence of the NIR light. In such a process, the visible light emission can be seen clearly corresponding to the area where the effective hole injection occurs, enabled by the NIR CGL in the presence of the NIR light, such that the objects reflecting or illuminating of the NIR light can be displayed by the visible light, realizing the NIR imaging. The effect of the BHJ NIR CGL on the performance of the up-conversion devices was investigated.

**Results and discussion**

The schematic illustration of the cross-sectional view of the up-conversion device is shown in **Figure 1a**. A front NIR photodiode unit was monolithically integrated with an upper LED unit. These two functional units were stacked vertically forming an NIR to visible light up-conversion device. In
the NIR photodiode unit, the BHJ, made with diketopyrrolopyrrole-dithienylthieno[3,2-b]thiophene polymer (DPP-DTT): [6,6]-Phenyl C_{71} butyric acid methyl ester (PC_{70}BM) or DPP-DTT: CO_{8}DFIC\textsuperscript{[32,33]} blend layer, serves as an NIR CGL where NIR photon induced charge generation occurs. The molecular structures of the NIR absorbing polymer DPP-DTT, fullerene acceptor of PC_{70}BM and nonfullerene acceptor of CO_{8}DFIC are shown in Figure 1b. The corresponding normalized absorbance spectra of DPP-DTT\textsuperscript{[37,38]} and the acceptors are shown in Figure 1c. Compared to the fullerene acceptor PC_{70}BM, the nonfullerene acceptor CO_{8}DFIC has a relatively weaker absorption in the UV-visible region, but a stronger absorption in the NIR region with a peak absorption located at 850 nm. The perovskite CsPbBr\textsubscript{3} LED was selected due to its solution processability and a narrow EL emission spectrum with a saturated green light (520 nm). The performance of the CsPbBr\textsubscript{3}-based LEDs in this work was optimized by controlling the thickness and morphology of the CsPbBr\textsubscript{3} light-emitting layer.

The current density−voltage (J−V) and luminance−voltage (L−V) characteristics of the NIR-to-visible up-conversion devices were measured in the presence and the absence of the NIR light illumination. It shows that the performance of the up-conversion devices is dependent on the type of the BHJ NIR CGLs and their layer thickness. J−V and L−V characteristics measured for the up-conversion devices made with different DPP-DTT:PC_{70}BM NIR CGL thicknesses of 46 nm, 65 nm and 85 nm are presented in Figures 2a-2c. The corresponding luminance On/Off ratios, defined as the ratio of the luminance of the up-conversion device in the presence of the NIR light to that measured for the devices in the absence of the NIR light, as a function of the voltage are plotted in Figure 2d. The intensity of the NIR light (850 nm) of 5 mW/cm\textsuperscript{2} was used in the measurement. In the absence of the NIR light, the threshold voltage of the visible light emission in the up-conversion devices increases with the increase in the thickness of the NIR CGL, which is related to the gradual decrease in the
efficiency of the hole injection in the CsPbBr$_3$ LED unit, caused by the increase in the CGL thickness. While in the presence of the NIR light, the visible light emission of the up-conversion devices increases significantly as compared to the ones measured in the absence of the NIR illumination. This is due to the increase in the hole injection and improved hole-electron current balance the LED unit, enabled by the NIR CGL in the presence of the NIR light. The visible light emission of the up-conversion devices in the absence of the NIR light, observed for the devices operated under a large bias, can be considered as a background noise, therefore a high luminance On/Off ratio is desired for application in high performing NIR to visible light conversion. A relatively higher current density and a higher luminance in the up-conversion devices with a thinner NIR CGL were observed in the absence of the NIR light, resulting in a much lower On/Off ratio, due to the relatively lower responses of the thinner CGL to the NIR light. With increase in the thickness of the NIR CGL to 65 nm in the up-conversion devices, a gradual increase in the difference between current density and visible light luminance, observed in the presence and the absence of the NIR light, was observed, along with an increase in the visible light luminance On/Off ratio due to an enhanced response of the CGL to the NIR light. However, further increase in the thickness of the NIR CGL in the up-conversion devices leads to an obvious decrease in the luminance On/Off ratio, caused by a poor visible light out-coupling in the devices due to the absorption by the thick BHJ CGL. The results, shown in Figure 2d, clearly indicate the effect of the thickness of the NIR CGL on the luminance On/Off ratio of the DPP-DTT:PC$_{70}$BM CGL based up-conversion devices. The strong absorption of the visible light by the PC$_{70}$BM acceptor in the BHJ CGL limits the luminance On/Off ratio of DPP-DTT:PC$_{70}$BM CGL based up-conversion devices.

$J$–$V$ and $L$–$V$ characteristics measured for the up-conversion devices, made with different DPP-DTT:CO$_{8}$DFIC CGL thicknesses of 45 nm, 67 nm and 91 nm, are plotted in Figures 3a–3c. The luminance On/Off ratios of the corresponding up-conversion devices as a function of the operating
voltage are shown in Figure 3d. The effect of the NIR CGL thickness on light emission threshold voltage, luminance On/Off ratio of the DPP-DTT:CO\textsubscript{8}DFIC CGL based up-conversion devices is very similar to that of the DPP-DTT:PC\textsubscript{70}BM based up-conversion devices. The increase in the thickness of the NIR CGL layer also leads to an increase in the luminance On/Off ratio, and followed by a drop. This is attributed to the trade-off between the NIR absorption and the visible light out-coupling in the CGL. However, compared to the DPP-DTT:PC\textsubscript{70}BM CGL, DPP-DTT:CO\textsubscript{8}DFIC CGL has a much lower absorption in the visible light region, therefore, an obvious enhancement in the luminance On/Off ratio was realized in the DPP-DTT:CO\textsubscript{8}DFIC based up-conversion devices. The results show that the luminance On/Off ratio obtained from the optimized DPP-DTT:CO\textsubscript{8}DFIC based up-conversion devices is two orders of magnitude higher as compared to that measured from the optimized DPP-DTT:PC\textsubscript{70}BM based up-conversion devices. Apparently, a combination of a high efficiency NIR light response and an improved light out-coupling in the DPP-DTT:CO\textsubscript{8}DFIC based up-conversion devices is favorable for achieving a high luminance On/Off ratio.

The current efficiency–voltage characteristics ($\eta$–$V$) measured for the up-conversion devices made with DPP-DTT:PC\textsubscript{70}BM and DPP-DTT:CO\textsubscript{8}DFIC NIR CGLs are shown in Figures 4a and 4b. It shows that the increase in the current efficiency of the up-conversion devices in the presence of the NIR light as compared to that of the devices in the absence of the NIR light is closely associated with the properties of the NIR CGL, which plays a critical role in efficient hole injection in the perovskite LED unit. The NIR CGL-assisted hole injection, obtained in the presence of the NIR light, helps to improve the hole-electron current balance in the LED, thereby improving the current efficiency. In the meantime, compared to the DPP-DTT:PC\textsubscript{70}BM CGL, a weak visible light absorption in the DPP-DTT:CO\textsubscript{8}DFIC NIR CGL, also is favorable for attaining a high current efficiency due to the improved optical out-coupling efficiency in the visible light range. The up-conversion efficiency, defined as the
ratio of the number of visible light photons emitted by the up-conversion devices in the presence of the NIR light to the number of incident NIR photons, as a function of the operating voltage, measured for the DPP-DTT:PC_{70}BM and DPP-DTT:CO_{8}DFIC based up-conversion devices are presented in Figure 4c and 4d. A high NIR photon to visible light photon up-conversion efficiency of 1.9% was achieved for the optimized DPP-DTT:CO_{8}DFIC based up-conversion devices operated at 6V, which is comparable to that of the reported up-conversion devices made with the organic small molecules\textsuperscript{[16,18]}. The high NIR photon to visible light photon up-conversion efficiency is mainly originated from the simultaneously high NIR sensitivity of the donor and nonfullerene acceptor in the DPP-DTT:CO_{8}DFIC BHJ.

To further unravel the properties of the BHJ NIR CGLs, two types of photodiodes made with a 65 nm thick DPP-DTT:PC_{70}BM active layer and a 67 nm thick DPP-DTT:CO_{8}DFIC active layer were fabricated. The schematic cross-sectional view of the NIR photodiode having a device configuration of ITO/zinc oxide (ZnO)/NIR CGL/poly(3,4-ethylenedioxythiophene)-poly(styrenesulfonate) (PEDOT:PSS)/Au is shown in Figure 5a. The normalized absorption spectra measured for the DPP-DTT:PC_{70}BM and DPP-DTT:CO_{8}DFIC CGLs, the spectrum of the 850 nm NIR LED light source used in the measurement, and the EL spectrum of the CsPbBr_{3} LED are presented in Figure 5b. DPP-DTT:CO_{8}DFIC BHJ layer shows a much higher absorption in the NIR region and a lower absorption in the visible region. On the contrary, the DPP-DTT:PC_{70}BM based CGL has a large absorption in the visible region, covering the EL spectrum emitted by the perovskite LED unit, due to the fullerene acceptor PC_{70}BM which is sensitive to the UV-visible light. The normalized EQE spectra measured for the NIR photodiodes having a DPP-DTT:PC_{70}BM NIR CGL and a DPP-DTT:CO_{8}DFIC BHJ NIR CGL are presented in Figure 5c. Consisting with the absorption characteristics, the DPP-DTT:CO_{8}DFIC based NIR photodiode showed a much higher EQE in the NIR region and a lower
EQE at the EL spectrum of the perovskite LED. This indicates a higher NIR sensitivity and a higher green light out-coupling for the DPP-DTT:CO8DFIC CGL based up-conversion device, agreeing with the above discussions with regarding to the high efficient up-conversion processes. The photocurrent–voltage characteristics of the NIR photodiodes were also investigated. The DPP-DTT:CO8DFIC CGL based NIR photodiodes exhibit a much profound photocurrent generation in the presence of the NIR light as a function of the light intensity, as shown in Figure 5d. This is correlated with the CGL absorption profiles and the photodiode EQE results.

The schematic operation mechanism of the up-conversion device is illustrated in Figure 6. The BHJ serves as an NIR CGL, assisting the hole injection in the LED in the presence of the NIR light. As shown in Figure 6a, the hole injection to the perovskite LED is efficiently suppressed in the absence of the NIR light, due to the large hole injection barrier in the CsPbBr3 LED. Although the injection of the electrons can be achieved through the Al electrode side, the light emission in the upper perovskite LED unit is suppressed and only limited emission can be attained by the injection of the holes under a large forward bias. In the presence of the NIR light, the generation of the charge carriers in the NIR CGL facilitates the hole injection in the CsPbBr3 LED, enabling an efficient emission of the visible light. The visible light emitted from the perovskite LED passes the NIR CGL before escaping the substrate, as shown in Figure 6b. In such a case, the DPP-DTT:CO8DFIC NIR CGL with a weak absorption in the visible light region is preferred as compared to the DPP-DTT:PC70BM NIR CGL, which is one of the reasons that is responsible for the improved up-conversion performances as compared to that of DPP-DTT:PC70BM CGL based up-conversion devices.

The transient response as a function of the NIR signal is critical for imaging applications. In this work, the transient NIR response characteristics of the up-conversion devices were studied. A 2 kHz frequency modulated NIR light source (780 nm) was used for analyzing the current responses of the
up-conversion devices with a 65 nm thick DPP-DTT:PC₇₀BM CGL and a 67 nm thick DPP-DTT:CO₈DFIC CGL. The results were shown in Figure 7a. The clear comparison of the typical responses of the up-conversion devices, the duty cycle of the NIR signal used in the measurement are plotted in Figure 7b. The rising time of the up-conversion devices with a 65 nm thick DPP-DTT:PC₇₀BM CGL and a 67 nm thick DPP-DTT:CO₈DFIC CGL were estimated to be 95 µs and 76 µs respectively, which are fast enough for imaging applications.

The quality of the visible light emitter also is an important factor in visualizing the NIR light. In this study, the inorganic CsPbBr₃ perovskite light emitter was selected due to its solution processibility, high air stability and saturated green light emission with a peak EL at 520 nm, which is very close to the wavelengths near the peak response of the human eye. J–V and L–V characteristics measured for a control CsPbBr₃ LED are plotted in Figure 8a. The schematic cross-sectional view of the control CsPbBr₃ LED configuration is presented as an inset in Figure 8a. η–V characteristics measured for the control CsPbBr₃ LED are shown in Figure 8b. A control standalone CsPbBr₃ LED is capable of emitting a uniform green light (522 nm) at a forward bias of > 2 V, achieving a high luminance of 7730 cd/m² and a current efficiency of 1.23 cd/A at 10 V. No obvious difference in the EL emissions among all up-conversion devices was observed. The EL spectra of the up-conversion devices are the same as that observed for the control CsPbBr₃ LED. The typical EL emission spectra, measured for an up-conversion device having a 67 nm thick DPP-DTT:CO₈DFIC NIR CGL at different driving voltages under the NIR irradiation of 5 mW/cm² are plotted in Figure 8c. The peak position of the EL spectra measured for the up-conversion device at different driving voltages is very stable. The CIE coordinates of the EL spectrum measured for the up-conversion device, the CIE coordinates of the EL spectra of other up-conversion devices reported in the literatures also are presented in the CIE chromaticity diagram for comparison, as shown in Figure 8d. With CIE coordinates of (0.09, 0.77), the EL emission...
from our up-conversion devices produced a very good saturated green light, offering a promising device option for application in NIR to visible light imaging with a large color gamut.

Visualizing the NIR light was demonstrated using an NIR to visible light up-conversion device with a layer configuration of ITO/ZnO/DPP-DTT:COi8DFIC NIR CGL (67 nm)/PEDOT:PSS/CsPbBr (30 nm)/2,2',2"-(1,3,5-Benzinetriyl)-tris(1-phenyl-1-H-benzimidazole) (TPBi)/Li/Al, as shown in Figure. 9. The device can be operated at a very low driving voltage of 3 V. A photo picture taken for the up-conversion device is shown in Figure 9a, illustrating that there was no visible light emission in the absence of the NIR light, operated at 3 V. The photo picture taken for the same up-conversion device in the presence of the NIR light of 1 mW/cm², operated at 3V, is shown in Figure 9b. Bright green light emission over the whole up-conversion area of 0.1 cm² is clearly observed in the presence of the NIR illumination, revealing the NIR to visible light up-conversion. The photo pictures taken for the up-conversion device operated using the dot, vertical stripe and lateral strip shaped NIR light sources (1 mW/cm²) are shown in Figures 9c-9e. The up-conversion device displayed clearly the same shapes of the NIR light sources and produced a saturated green light emission, demonstrating the pixel-less imaging capabilities of the up-conversion from NIR to visible light. A video about visualizing the NIR light using different shaped NIR light sources is given in the Supporting Information. The NIR to visible light up-conversion technique demonstrated in this work would provide significant cost benefits as well as the functional superiority for a broad range of NIR imaging applications.

Conclusion

The performance of the solution processable NIR to visible light up-conversion devices were studied. Our results reveal that the blend of NIR sensitive polymer DPP-DPP with a nonfullerene acceptor COi8DFIC is a suitable NIR CGL for the up-conversion processes, due to its unique combination of strong NIR absorption and weak visible light absorption. The high performing NIR to
visible light up-conversion devices were demonstrated using a solution processable CsPbBr$_3$-based perovskite LED, producing a saturated 520 nm green light EL emission in the presence of an 850 nm NIR light source. The use of the perovskite LED unit that produces a highly saturated green light, corresponding to the wavelengths near the peak response of the human eye, is favorable for imaging applications. The device concept of the up-conversion devices provides a platform for vivo observation of the NIR light, suitable for applications in bio imaging, disease diagnose and wellness monitoring.

**Experimental Section**

**Material preparation.** The CsPbBr$_3$ solution was formulated by dissolving 0.314 M CsBr (Sigma Aldrich) and 0.18 M PbBr$_2$ (Sigma Aldrich) in DMSO (Sigma Aldrich) with excess CsBr in the solution. The precursor solution was then stirred overnight before use. The NIR absorbing donor material DPP-DTT (Ossila) was blended with the fullerene acceptor PC$_{70}$BM (Sigma Aldrich) and nonfullerene acceptor CO$_8$DFIC$^{[32,33]}$ in a weight ratio of 1:1. The mixtures were then dissolved in 1,2-Dichlorobenzene (Sigma Aldrich) at a concentration 6 mg/mL. The polymer/acceptor solutions were kept at 60 °C and stirred for 24 h. ZnO precursor solution was prepared$^{[39,40]}$ with different concentrations of 0.05 M and 0.5 M. The ZnO precursor solutions were stirred overnight before use. All materials were used as received.

**Device fabrication.** Pre-patterned ITO (180 nm)/glass substrates were cleaned by ultrasonication sequentially with diluted detergent, deionized water, acetone and isopropanol each for 20 min. The ITO/glass substrates were dried in oven and treated with the UV-Ozone plasma prior to the device fabrication. The ZnO film was formed from a sol-gel method. 0.05 M precursor solution was spin-coated on the top of ITO and annealed at 200 °C for 10 min, as the seed layer. A 0.5 M ZnO precursor solution was casted to the ZnO seed layer and annealed at 200 °C for 10 min to form a 50 nm thick ZnO electron transporting layer. The BHJ based NIR CGLs were prepared by spin coating the blend
solutions using different rotation speeds in glovebox followed by annealing at 90 °C for 10 min. The hydrophobic BHJ surface was modified by the Argon plasma, producing a hydrophilic surface for deposition of a 40 nm PEDOT:PSS hole transporting layer. The samples were post-annealed at 100 °C for drying. The CsPbBr$_3$ light emission layer was formed on the surface of the PEDOT:PSS hole transporting layer by spin-coating and post-annealed at 70 °C for 10 min. The samples were then transferred to a vacuum chamber for deposition of a 100 nm thick TPBi (Sigma Aldrich) electron transporting layer, 1 nm thick electron injection layer LiF (Sigma Aldrich) and a 100 nm thick Al top contact using thermal evaporation. The finished devices were encapsulated in N$_2$ environment before taking out for measurements.

**Device characterization.** The luminance–current density–voltage ($L$–$J$–$V$) of the up-conversion devices were characterized using a luminance colorimeter, an electro meter and control software. The steady NIR irradiation was supplied by an NIR LED light source (Zolix) with a peak wavelength at 850 nm. In the transient NIR response measurements, the NIR signal was provided by a 780 nm LED (THORLABS), which was controlled by a function generator at a fixed driving voltage of 3 V and a frequency of 2 kHz. All measurements were carried out in air.

**Supporting Information**

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

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References


Figure 1. (a) Schematic diagram illustrating the cross-sectional view of an NIR to visible light upconversion device, with an NIR photodiode and a CsPbBr₃ perovskite-based visible light LED, (b) molecular structures of DPP-DTT, PC₇₀BM and CO₈DFIC, and (c) their corresponding normalized absorbance spectra.
Figure 2. $J-V$ and $L-V$ characteristics measured for the NIR to visible light up-conversion devices made with different DPP-DTT:PC$_{70}$BM-based NIR CGL thicknesses of (a) 46 nm, (b) 65 nm and (c) 85 nm. (d) The luminance On/Off ratio, defined as the ratio of the luminance of the up-conversion device in the presence of the NIR light to that measured for the device in the absence of the NIR light, as a function of the voltage. The NIR light intensity is 5 mW/cm$^2$. 
Figure 3. $J-V$ and $L-V$ characteristics measured for the NIR to visible light up-conversion devices made with different DPP-DTT:CO$_2$8DFIC-based NIR CGL thicknesses of (a) 45 nm, (b) 67 nm and (c) 91 nm. (d) The luminance On/Off ratio as a function of the voltage. The NIR light intensity is 5 mW/cm$^2$. 
Figure 4. $\eta$–$V$ characteristics measured for the NIR to visible light up-conversion devices made with different NIR CGLs of (a) DPP-DTT:PC$_{70}$BM and (b) DPP-DTT:CO$_8$DFIC. The up-conversion efficiency, defined as the ratio of the number of visible light photons emitted by the up-conversion devices in the presence of the NIR light to the number of incident NIR photons, as a function of the operating voltage measured for (c) DPP-DTT:PC$_{70}$BM- and (d) DPP-DTT:CO$_8$DFIC-based up-conversion devices.
Figure 5. (a) The schematic cross-sectional view of the NIR photodiode, (b) the normalized absorption spectra measured for the DPP-DTT:PC\textsubscript{70}BM and DPP-DTT:CO\textsubscript{8}DFIC BHJs used in the NIR photodiode, the spectrum of an NIR LED used in the measurement, and the EL spectrum of a CsPbBr\textsubscript{3} LED. (c) The normalized $EQE$ spectra measured for the photodiodes having DPP-DTT:PC\textsubscript{70}BM (65 nm thick) and DPP-DTT:CO\textsubscript{8}DFIC BHJ (67 nm thick) NIR CGLs. (d) The NIR photoresponse, photocurrent–voltage characteristics measured for the photodiodes under different intensities of NIR irradiations.
Figure 6. Schematic diagrams showing the energy levels of the functional materials used in the up-conversion devices, and the processes of (a) hindering hole injection in the absence of the NIR light, and (b) facilitating the hole injection in CsPbBr₃-based perovskite LED to allow light emission in the presence of the NIR Light.
Figure 7. (a) The transient photocurrent responses measured for the DPP-DTT:PC\textsubscript{70}BM (65 nm thick)- and DPP-DTT:CO\textsubscript{8}DFIC (67 nm thick) based up-conversion devices using a 2 kHz frequency modulated NIR source. (b) Comparison of the typical responses of the corresponding up-conversion devices, the duty cycle of the NIR signal also is plotted for reference. The rising time of the up-conversion devices with different NIR CGLs of DPP-DTT:PC\textsubscript{70}BM and DPP-DTT:CO\textsubscript{8}DFIC are about 95 μs and 76 μs respectively.
Figure 8. (a) $J$–$V$ and $L$–$V$ characteristics measured for a control CsPbBr$_3$ LED. The inset: the schematic cross-sectional view of the control LED. (b) $\eta$–$V$ characteristics measured for the control CsPbBr$_3$ LED. (c) EL emission spectra measured for an up-conversion device, having a 67 nm thick DPP-DTT:CO$_8$DFIC NIR CGL, at different driving voltages using a steady state NIR irradiation of 5 mW/cm$^2$. (d) The CIE coordinates of EL spectrum measured for the DPP-DTT:CO$_8$DFIC (67 nm) CGL based up-conversion device, the CIE coordinates of the EL for other up-conversion devices reported in the literatures also are presented in the CIE chromaticity diagram for comparison.
Figure 9. Photo picture of an up-conversion device having a 67 nm thick DPP-DTT:CO₃8DFIC NIR CGL, (a) in the absence of the NIR light, (b) in the presence of the NIR light. The photo pictures taken for the same up-conversion device operated using (c) dot, (d) vertical stripe and (e) lateral strip shaped NIR light sources. The NIR light sources with a wavelength of 850 nm and an intensity of 1 mW/cm² were used in the measurements. All the devices were operated at 3V.