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METHOD ARTICLE

REVISED Fiber-coupled light-emitting diodes (LEDs) as safe and convenient light sources for the characterization of optoelectronic devices

[version 2; peer review: 2 approved]

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Abstract

Optoelectronic device characterization requires to probe the electrical transport changes upon illumination with light of different incident powers, wavelengths, and modulation frequencies. This task is typically performed using laser-based or lamp + monochromator-based light sources, that result complex to use and costly to implement. Here, we describe the use of multimode fiber-coupled light-emitting diodes (LEDs) as a simple, low-cost alternative to more conventional light sources, and demonstrate their capabilities by extracting the main figures of merit of optoelectronic devices based on monolayer MoS_2, i.e. optical absorption edge, photoresponsivity, response time and detectivity. The described light sources represent an excellent alternative for performing optoelectronic characterization experiments on a limited budget.

Keywords

Optoelectronics, Photocurrent spectroscopy, 2D materials

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REVISED **Amendments from Version 1**

The main text and supplementary information have been updated according to the referee's advice as follows:
1. Added additional references to earlier works using the illumination setup presented here
2. Added a comment regarding the safety of these light sources compared to free-space configurations
3. Added extended discussion on the limitations of the light sources
4. Added a new dataset to the supp. info. showing the full recovery of the OFF state of the device
5. Included comparison between the led performance and a lamp+monochromator system of similar price (in the Supp. Info.)
6. New Supp. Info. figure showing the FFT of the dark trace
7. Corrected error in the calculation of detectivity

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Plain language summary

In this work we present a low-cost light source based on light-emitting diodes (LEDs) for its use in measurement systems for characterization of photodetectors. The reduced cost and ease of use of the proposed light source makes it ideal for device characterization experiments on a limited budget.

Introduction

The scientific activity on optoelectronics has grown steadily over the last decades thanks to the discovery of novel promising materials such as two-dimensional transition metal dichalcogenides[1–7], perovskites[8–14], etc. Indeed, according to the Dimensions database, the number of scientific publications in this field has grown from roughly 4000 articles per year in 1990 to more than 60000 in 2020.

To characterize the main figures of merit of optoelectronic devices accurately and quantitatively, it is necessary to probe the electrical transport changes upon illumination with light of different incident powers, wavelengths, and modulation frequencies, which typically require the use of specialized light sources. In most laboratories, free-space laser sources are commonly used to characterize the response to light of the fabricated devices. While these light sources present several advantages (e.g., they are very bright, and have very well-defined wavelengths) they also have some shortcomings (high cost, safety issues, speckle, and restringing mounting conditions amongst others). Moreover, to achieve the required functionality, laser-based or lamp + monochromator-based testing setups usually must be combined with additional optical elements, such as neutral density filters to change the intensity of the incident light or mechanical choppers to modulate the incident signal in time, adding to their prize and complexity of usage. Therefore, an alternative cost-efficient light source, fiber-coupled, without speckle and with a fully voltage-based adjustment of the illumination intensity and modulation frequency would be highly desirable.

In our laboratory we started seven years ago to employ multi-mode fiber-coupled light emitting diode (LED) sources to test optoelectronic devices and they have proven to be a very convenient alternative to the commonly used free-space laser or lamp based light sources[15–22]. In fact, we have found that these light sources are very simple to operate and can be readily used to extract figures-of-merit of 2D based photodetectors, without presenting the safety issues associated to the use of free-space high power collimated laser beams. During this time, we have also seen that their use is not widely spread, at least in the community working on 2D materials based optoelectronic devices, motivating us to write this paper.

In this work, we thoroughly describe the use of fiber-coupled LED light sources to extract the different figures of merit of photodetector devices. We illustrate their use by characterizing a single-layer MoS_2 photodetector and show how one can easily extract relevant optoelectronic parameters such as the response time, photocurrent power dependence, responsivity and detectivity. The capability of the system to accurately extract these parameters at different wavelengths allows us to accurately characterize the responsivity spectrum of the device, even when using other lights sources with a non-constant spectral power density.

The presented fiber-coupled LEDs are rather inexpensive, if compared with laser systems, and are modular, making it possible to improve the system little by little. While these light sources cannot compete with lasers in terms of spectral narrowness and output power, their improved safety, as well as their capability to modulate the light power and/or switch it ON/OFF with an external voltage, without the need of neutral density filters nor mechanical choppers, make them very flexible light sources, suitable for characterization techniques where a large output power and extremely narrow bandwidth are not a must.

We hope that this Method article can be of interest of the researchers that are setting up their laboratories, especially those running under a tight budget.

Methods

Fiber-coupled LED light sources

Our LED light sources are based on the Thorlabs MXXXF fiber-coupled LEDs, the Thorlabs LEDD1 controller and a programmable bench power supply (TENMA 72-2705). Figure 1a shows a picture of several LEDs sources with their controllers, mounted on dedicated breadboards that can be moved around the laboratory. Table 1 summarizes the different components used for the assembly of our fiber-coupled LEDs based light sources. Note that one can decide the number of different LED modules to add, with an average total cost of ~800€ per LED with different wavelengths. This cost could be reduced even further by replacing the individual controllers connected to each LED with a single controller connected to a switch box or even by connecting the LEDs directly to the benchtop programmable power supply that we use to modulate the power. This would reduce the cost from ~800€ to ~450€ per wavelength at the expense of losing the capability to use several LEDs simultaneously. To illuminate our devices, a multimode optical fiber is attached to the LED source of the desired wavelength and the other end of the fiber is attached to a lens system placed above the optoelectronic device under study. By placing the core of the fiber at the image plane of the lens

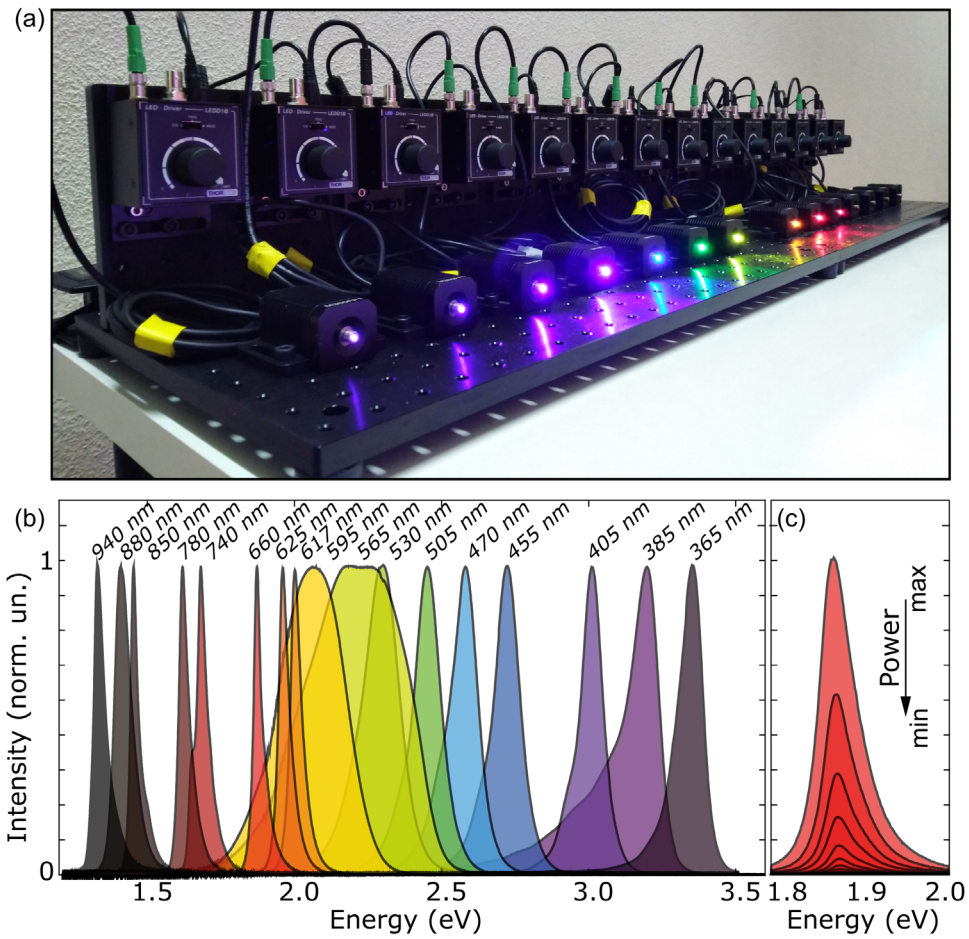


Figure 1. Bench with an assemble of fiber-coupled light-emitting diodes (LEDs). (**a**) Picture of an illumination system implemented with 14 different fiber-coupled LEDs with their power supplies. (**b**) Spectra of 17 different LED light sources used in our laboratory. (**c**) Spectra of a 660 nm LED source at different biasing conditions to control the intensity of the out-coming light.

Table 1. List of required components for the assembly of the fiber-coupled light emitting diodes (LEDs) based light sources.

	Code	Description	Unitary price	Units	Total price
UV to BLUE bench	MB3060/M	Aluminum Breadboard, 300 mm x 600 mm x 12.7 mm, M6 Taps	248.11 €	1	248.11 €
	MB1560/M	Aluminum Breadboard, 150 mm x 600 mm x 12.7 mm, M6 Taps	143.25 €	1	143.25 €
	AP90L/M	Large Right-Angle Mounting Plate, M6 x 1.0 Compatible	149.46 €	1	149.46 €
	RDF1	Rubber Damping Feet, Set of 4	4.92 €	1	4.92 €
	M365FP1	365 nm, 9.8 mW (Min) Fiber-Coupled LED, 1400 mA, SMA	601.99 €	1	601.99 €
	M385FP1	385 nm, 18 mW (Min) Fiber-Coupled LED, 1400 mA, SMA	601.99 €	1	601.99 €
	M405FP1	405 nm, 19.3 mW (Min) Fiber-Coupled LED, 1400 mA, SMA	601.99	1	601.99
	M420F2	Violet (420 nm) Fiber-Coupled LED, SMA, 1000 mA, 8.90 mW (Min)	394,20 €	1	394,20 €
	M455F1	455 nm, 17 mW (Min) Fiber-Coupled LED, 1000 mA, SMA	388,55 €	1	388.55 €
	KPS101	15 V, 2.4 A Power Supply Unit with 3.5 mm Jack Connector for One K- or T-Cube	32.14 €	5	160.70 €
	LEDD1B	T-Cube LED Driver, 1200 mA Max Drive Current (Power Supply Not Included)	294.11 €	5	1 764.66 €

	Code	Description	Unitary price	Units	Total price
BLUE to RED bench	MB3060/M	Aluminum Breadboard, 300 mm x 600 mm x 12.7 mm, M6 Taps	248.11 €	1	248.11 €
	MB1560/M	Aluminum Breadboard, 150 mm x 600 mm x 12.7 mm, M6 Taps	143.25 €	1	143.25 €
	AP90L/M	Large Right-Angle Mounting Plate, M6 x 1.0 Compatible	149.46 €	1	149.46 €
	RDF1	Rubber Damping Feet, Set of 4	4.92 €	1	4.92 €
	M470F1	Blue (470 nm) Fiber-Coupled LED, SMA, 1000 mA, 8.0 mW (Min)	339,30 €	1	339.30 €
	M505F1	Cyan (505 nm) Fiber-Coupled LED, SMA, 1000 mA, 7.0 mW (Min)	339,30 €	1	339.30 €
	M530F2	530 nm, 6.8 mW (Min) Fiber-Coupled LED, 1000 mA, SMA	371,82 €	1	371.82 €
	M565F3	565 nm, 9.9 mW (Min) Fiber-Coupled LED, 700 mA, SMA	410.09 €	1	410.09 €
	M595F2	595 nm, 8.7 mW (Min) Fiber-Coupled LED, 1000 mA, SMA	360,99 €	1	360.99 €
	M617F2	617 nm, 10.2 mW (Min) Fiber-Coupled LED, 1000 mA, SMA	371,82 €	1	371.82 €
	M625F2	625 nm, 13.2 mW (Min) Fiber-Coupled LED, 1000 mA, SMA	360.99 €	1	360.99 €
	KPS101	15 V, 2.4 A Power Supply Unit with 3.5 mm Jack Connector for One K- or T-Cube	32.14 €	7	224.98 €
	LEDD1B	T-Cube LED Driver, 1200 mA Max Drive Current (Power Supply Not Included)	294.11 €	7	2 058.77 €

	Code	Description	Unitary price	Units	Total price
RED to NIR bench	MB3060/M	Aluminum Breadboard, 300 mm x 600 mm x 12.7 mm, M6 Taps	248.11 €	1	248.11 €
	MB1560/M	Aluminum Breadboard, 150 mm x 600 mm x 12.7 mm, M6 Taps	143.25 €	1	143.25 €
	AP90L/M	Large Right-Angle Mounting Plate, M6 x 1.0 Compatible	149.46 €	1	149.46 €
	RDF1	Rubber Damping Feet, Set of 4	4.92 €	1	4.92 €
	M660F1	Deep Red (660 nm) Fiber-Coupled LED, SMA, 1000 mA, 13.0 mW (Min)	339,30 €	1	339.30 €
	M740F2	740 nm, 4.1 mW (Min) Fiber-Coupled LED, 800 mA, SMA	426,88 €	1	426.88 €
	M780F2	780 nm, 5.5 mW (Min) Fiber-Coupled LED, 800 mA, SMA	378,70 €	1	378.70 €
	M850F2	IR (850 nm) Fiber-Coupled LED, SMA, 1000 mA, 10.5 mW (Min)	339,30 €	1	339.30 €
	M880F2	IR (880 nm) Fiber-Coupled LED, SMA, 1000 mA, 10.5 mW (Min)	378,70 €	1	378.70 €
	M940F3	940 nm, 10 mW (Min) Fiber-Coupled LED, 1000 mA, SMA	363.60 €	1	363.60 €
	M1050F1	1050 nm, 1.1 mW (Min) Fiber-Coupled LED, 700 mA, SMA	426,88 €	1	426.88 €
	KPS101	15 V, 2.4 A Power Supply Unit with 3.5 mm Jack Connector for One K- or T-Cube	32.14 €	7	224.98 €
	LEDD1B	T-Cube LED Driver, 1200 mA Max Drive Current (Power Supply Not Included)	294.11 €	7	2 058.77 €

system we project an image of the core onto the device under study. Unlike with focused free-space laser sources, this method yields circular spots with homogeneous power density and (because of the use of incoherent sources) speckle-free[23]. This is highly desirable to facilitate the calculation of the incident power and thus to accurately determine the figures of merit of photodetectors.

Figure 1b shows the individual spectra of the 17 LED sources, spanning the spectral range from 365 nm to 940 nm. Each of the LEDs emits light at a different, narrow, spectral window, with full-width-at-half-maximum ranging from ~10 nm to ~100 nm (depending on the wavelength, the typical value is ~30 nm). The intensity of the emitted light can be tuned, either manually or via an external voltage input. Figure 1c shows the spectral emission profile of an individual LED at different operation powers. While the spectral profile slightly changes with the power, the emission peak remains stable within a 5 meV range. It is worth noting that for the LED sources with nominal wavelengths of 595 and 565 nm,

the emission bandwidth is much larger than for the rest of the sources. This will be a limitation when probing a system with sharp spectral features around those wavelengths. In that case one could mitigate this limitation by coupling narrow band-pass filters at the output of the optical fiber to reduce the FWHM to ~10 nm. Such filters can be obtained at typical costs of around 200 €.

Results

Device fabrication and optoelectronic response

In the following, we demonstrate the capabilities of the LED light sources by performing a step-by-step characterization of a single-layer (1L) MoS_2 phototransistor. The device is fabricated by standard mechanical exfoliation of monolayer MoS_2 crystals with Nitto SPV-224PR-MJ tape and Gel-Film WF X4 (by Gelpak) tape, and ulterior transfer onto a SiO_2/Si substrate with prepatterned Ti/Au electrodes, following the deterministic transfer technique described in references[24–26]. The resulting device is showed in the inset of Figure 2a[27]. The main panel in Figure 2a shows two current *vs.* voltage (*I-V* hereafter) characteristics of the 1L-MoS_2 device, acquired in the dark (black) and under homogeneous illumination with λ = 660 nm, a power density P_D = 5.2 mW mm^{-2} and a spot of 375 µm in diameter (red). The *I-V* curves are nonlinear due to the presence of Schottky barriers at the Au/MoS_2 interfaces. Upon illumination, the drain-source current I increases by an amount I_{PC} due to photoconductivity.

Figure 2b shows the time evolution of the drain-source current, registered while turning the illumination on and off with a computer by using the external modulation port of the LEDD1 controller and the TENMA Programmable Bench

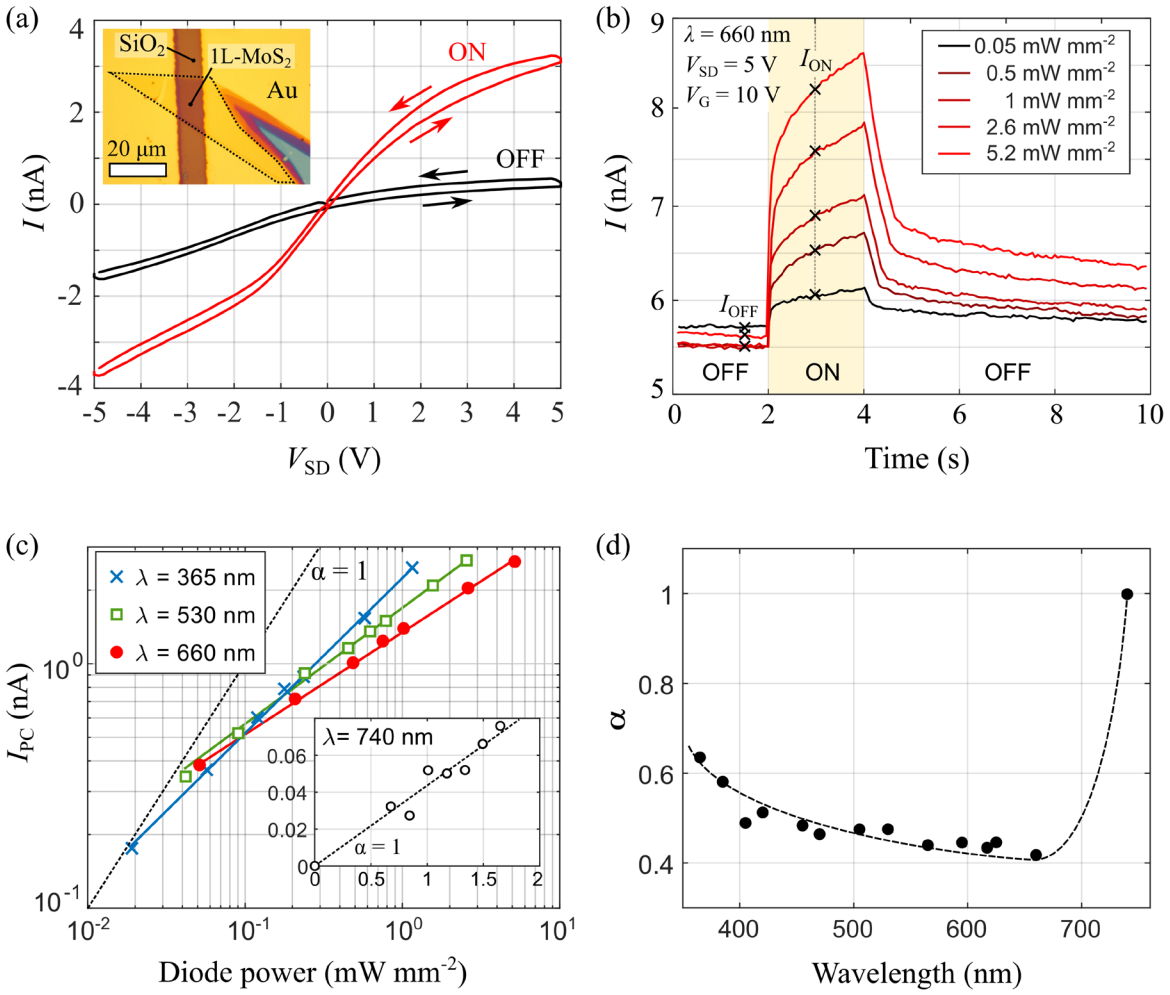


Figure 2. Optoelectronic response of the 1L-MoS_2 transistor. (**a**) *I-V* characteristics of the device at V_g = 0 V, measured in the dark (black) and upon illumination with λ = 660 nm and P_D = 5.2 mW mm^{-2}. Arrows indicate the voltage ramping direction. Inset: Optical image of the device. (**b**) Drain-source current I measured at V_{SD} = 5 V and V_G = 10 V while switching the illumination on and off at different light power densities. (**c**) Power dependence of the photocurrent I_{PC} at three different illumination wavelengths. I_{PC} is measured as the difference between the drain-source current one second after (I_{ON}) and immediately before (I_{OFF}) turning on the illumination. Solid lines are fittings to equation $I_{PC} \propto P^{\alpha}$. For reference, the slope corresponding to α = 1 is showed as a black, dashed line. (**d**) Wavelength dependence of the α parameter, extracted from the fittings to Equation 1. The dashed line is a smoothed interpolation of the experimental data.

Power Supply to turn on and off the LED source. As further discussed below, the optoelectronic response of the device is dominated by photogating, resulting in a slow photoresponse, which takes several seconds to stabilize after the light is switched on. The different curves shown in the figure correspond to consecutive measurements acquired for increasing illumination power densities. For completeness, we provide the Matlab script used to acquire these measurements on Zenodo[28]. For each measurement, the sample is exposed to light for 2 seconds and then kept in the dark for 30 seconds to recover the original "off" current I_{OFF}. The photocurrent I_{PC} is then calculated as the difference between the current I_{ON}, registered 1 second after the light is turned on, and I_{OFF}, measured immediately before exposure to light.

The measurements from Figure 2b allow us to estimate the response time of the device, as discussed in Supplementary Note 3 in the extended data[29]. For our 1L-MoS_2 device we get a rise time of $t_R = 2.1$ s and a much longer fall time $t_F = 20.2$ s.

Note that the possibility of adjusting the power density of the incident light with a software makes it possible to quickly measure the power dependence of the photogenerated current at many different wavelengths. This task can be very tedious for systems requiring the use of a manually-operated neutral density filter wheel to modify the incident power density.

In monolayer MoS_2 phototransistors, photoconductivity typically originates from two main mechanisms: photogating and photoconductive effect. These two mechanisms can be distinguished by their different dependence on the illumination power density[30–32]. The typical procedure consists on fitting the measured photocurrent to the phenomenological equation

$$I_{PC} = R_0 \times P^{\alpha}, \tag{1}$$

Where R_0 and α are fitting parameters. As a general rule, $\alpha = 1$ in devices which photoresponse is dominated by the photoconductive effect, and $\alpha < 1$ for photogating[30,32–35]. Figure 2c shows the power dependence of I_{PC} for different illumination wavelengths, λ. The resulting values of α are presented in Figure 2d as a function of λ. For illumination wavelengths lower than 700 nm (i.e. for photon energies larger than the optical bandgap of 1L-MoS_2) I_{PC} depends sublinearly on the illumination power, and we get $\alpha \approx 0.5$. For $\lambda > 700$ nm the photoresponse decreases abruptly and the power dependence of I_{PC} becomes linear, suggesting a different photoresponse mechanism for sub-bandgap energy photons.

Responsivity spectrum

The capability of the LED light sources to provide a spectrum of α as a function of wavelength (Figure 2d) can also be exploited to correct the spectra measured with other light sources with non-flat spectral power density. Figure 3a shows a photocurrent spectrum of the 1L-MoS_2 device, obtained using a wavelength-tunable Xenon light source (Bentham TLS120Xe). As also showed in the Figure, the spectral density of the light source, $P_{lamp}(\lambda)$, is not homogeneous throughout the whole spectral range, which introduces distortions in the measured spectral profile of I_{PC}. For linear optoelectronic devices, where $\alpha = 1$ (see Equation 1), one can trivially obtain the wavelength-dependent responsivity $R(\lambda)$ from photocurrent spectra such as the one from Figure 3a by simply dividing I_{PC} by the spectral density of the lamp $P_{lamp}(\lambda)$ for each given wavelength. However, the situation is more complex for $\alpha \neq 1$, as in this case the responsivity depends nonlinearly on the illumination power:

$$R(\lambda, P) = \frac{I_{PC}(\lambda)}{P} = R_0(\lambda) \times P^{\alpha(\lambda)-1}. \tag{2}$$

Thus, after measuring I_{PC} as a function of λ, one also needs to know the wavelength dependence of the power α, which can be easily done using the presented LED light sources. Then, the device responsivity (at a given power P) can be obtained as

$$R(\lambda, P) = \frac{I_{PC}(\lambda)}{P}\left(\frac{P}{P_{lamp}(\lambda)}\right)^{\alpha(\lambda)}. \tag{3}$$

Figure 3b shows the resulting responsivity spectra for four different illumination power densities $P = 0.1$, 0.25, 0.5 and

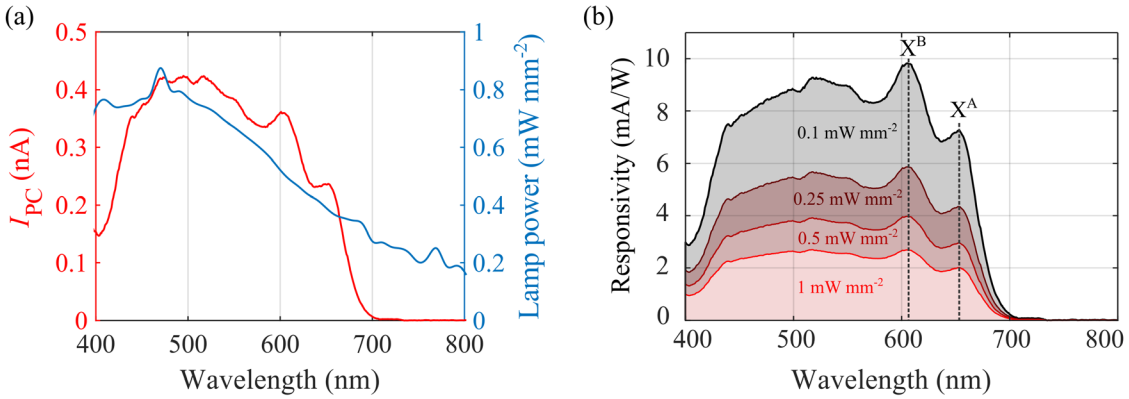


Figure 3. Responsivity spectra of the 1L-MoS_2 device. (**a**) Spectral dependence of I_{PC} (red line, left axis) and P_{lamp}(blue line, right axis) (**b**) Responsivity spectra calculated by inserting the experimentally measured values of $I_{PC}(\lambda)$, $P_{lamp}(\lambda)$ and $\alpha(\lambda)$ into Equation 3 for four different values of the power density P.

1 mW mm^{-2}. Note that, since in our device we get $\alpha < 1$, the responsivity is larger for smaller values of P.

Note that the fiber-coupled LEDs can also be used as a standalone light source to characterize the basic spectral behavior of a given material/device. As an example, Figure 4 shows the wavelength dependence of the photocurrent in the 1L-MoS_2 device, measured using the different LEDs at a fixed power density of 1 mW mm^{-1}. The resulting pseudospectrum could be used, for example, to estimate the absorption edge of 1L-MoS_2 within ~ 30 nm accuracy.

Characterization of device detectivity

Apart from the responsivity, another figure-of-merit widely used in the characterization of photodetectors is the specific detectivity D^*[34,36,37]. This quantity characterizes the performances of a photodetector in detecting small signals. Figure 5a shows a schematic of the experimental setup used to assess this figure-of-merit. We connect a function generator to a LED source and modulate the light intensity through a square wave, effectively turning on and off the illumination at a certain frequency ν (typically 1 Hz). We then shine the light onto the device under test and use a set of ND filters (from OD

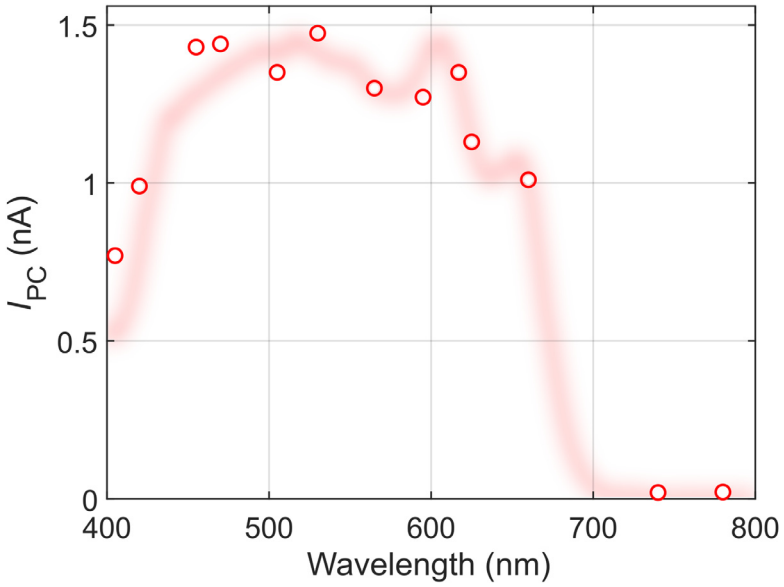


Figure 4. Photocurrent pseudospectrum of the 1L-MoS_2 device, measured using the LED light sources at a fixed power density of 1 mW mm^{-2}, as a function of their nominal wavelength. The shaded red line shows the full photocurrent spectrum as a guide to the eye.

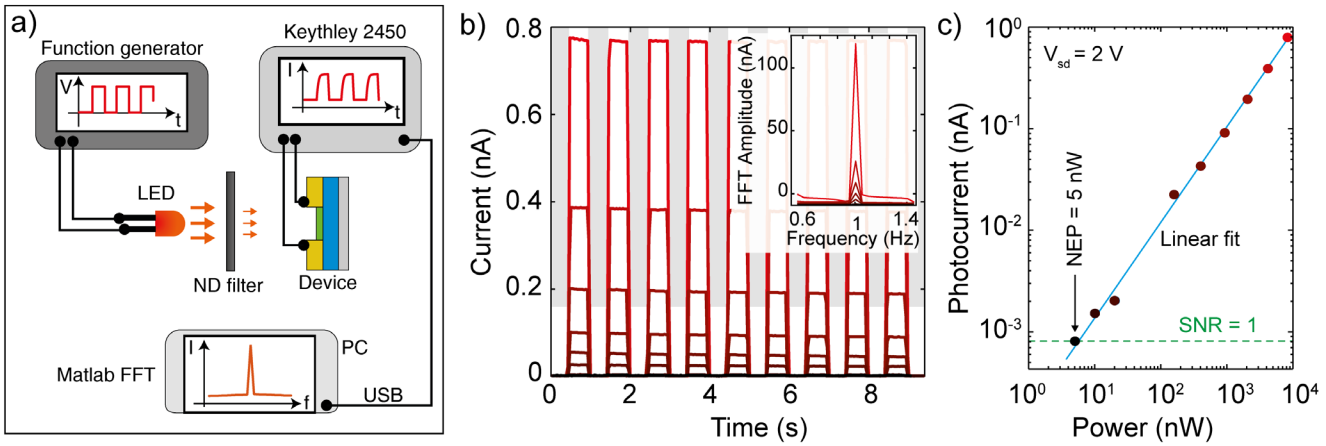


Figure 5. (**a**) Schematic of the experimental configuration to extract the detectivity of a device. (**b**) Current versus time traces recorded on a Au-InSe-Au photodetector at a source drain voltage of 2 V while applying a 660 nm square wave modulated illumination with frequency 1 Hz. The different colors represent different illumination powers (achieved by reducing the intensity of the excitation using ND filters. Inset: fast fourier transform (FFT) of the current vs time traces. (**c**) Photocurrent of the device (extracted from the amplitude of the FFT at 1 Hz) as a function of illumination power. The blue line is a linear fit to the data and the green dashed line indicates the noise level of the setup, which correspond to a signal-to-noise ratio (SNR) equal to 1.

0.3 to OD 4.0) to vary the intensity of the light. We record a set of current vs time traces, one for each illumination power. By computing the fast fourier transform (FFT) of each trace in Matlab, we can extract the response of the device at that power by extracting the amplitude of the FFT at the frequency ν. From this one can find the noise equivalent power of the device (*NEP*), which can then used to calculate the specific detectivity $D^* = \frac{\sqrt{Af}}{NEP}$, where A is the area of the device and f is the bandwidth.

Figure 5b shows a set of current vs time traces recorded on a back-to-back Schottky diode realized by transferring an InSe multilayer flake bridging two gold electrodes deposited onto a SiO_2 –Si substrate (see Supporting Note 4 for a picture of the device). The curves have been measured by applying a source drain voltage of 2 V while turning on and off the 660 nm illumination with a frequency of 1 Hz and different illumination powers (from 10 μW, red curve, to 5 nW, black curve). The fourier transforms of these traces, shown in the inset of Figure 5b, present a series of peaks at the odd harmonics of the fundamental frequency of 1 Hz. By extracting the area of the 1 Hz peak and plotting it as a function of the illumination power we can extract the NEP of our device. Figure 5c shows the photocurrent amplitude extracted from the FFT transforms in Figure 5b as a function of illumination power in a double logarithmic plot. The data follow a linear trend indicating that the photocurrent and the power are related by a power law dependency. The dashed line indicates the photocurrent intensity at which the signal to noise ratio (SNR) becomes equal to 1, which in our measurement corresponds to approximately 0.8 pA. The intersection between the linear fit and the line of unitary SNR happens at the power corresponding to the NEP of our device, which in this case is 5 nW. By applying the formula for the detectivity and using an area A = 1800 μm^2 and a bandwidth of 1 Hz, we find $D^* = 10^7$ Jones.

Conclusions

In all, the LED-based light sources described here represent a low-cost, modular, and easy to use alternative to the commonly used free-space light sources. While the achievable spectral resolution of these light sources is limited, they still allow to extract the essential figures of merit of photodetector devices such as response time, responsivity, optical absorption edge and detectivity. The stability, homogeneous power density and absence of speckle makes these light sources especially well-suited for characterizing the power dependence of photoresponse in optoelectronic devices. Furthermore, they can even be used in combination with low-cost power sources for automated measurement. Thus, we believe that these light sources are an excellent alternative for performing optoelectronic characterization experiments on a limited budget.

Data availability

Underlying data

Zenodo: Fiber-coupled LEDs as safe and convenient light sources for the characterization of optoelectronic devices. https://doi.org/10.5281/zenodo.5153604[27].

Extended data

Zenodo: Supplementary Information to: Fiber-coupled LEDs as safe and convenient light sources for the characterization of optoelectronic devices. https://doi.org/10.5281/zenodo.5166973[29].

This project contains the following extended data:

- AlphaSpectroscopy_SuppInfo_v7.pdf (Supplementary Notes 1–4)

Data are available under the terms of the Creative Commons Attribution 4.0 International license (CC-BY 4.0).

Analysis code

Analysis code for the ON-OFF measurements presented in Figure 2b available at: https://github.com/JorgeQuereda/Fiber-coupled-LEDs-as-safe-and-convenient-light-sources-for-the-characterization-of-optoelectronic-d/tree/v1.0

Archived analysis code as at time of publication: https://doi.org/10.5281/zenodo.5153596[28].

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Publisher Full Text

Open Peer Review

Current Peer Review Status: ✔ ✔

Version 2

Reviewer Report 29 July 2022

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✔ **Marcel Claro**
Universidade de Santiago de Compostela, Santiago de Compostela, Spain

The manuscript "Fiber-coupled light-emitting diodes (LEDs) as safe and convenient light sources for the characterization of optoelectronic devices " demonstrates the use of a combination of LEDs with different wavelengths for optoelectronic characterization of photodetectors and/or photoresponsive materials, in substitution of conventional white light+monochromator setup or lasers. It gives some application examples for 2D material photodetectors. It presents a very practical, robust and relatively cheap setup which I would recommend for this application. All my questions in the 1st version were answered and I recommend for indexing as it is.

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Molecular beam epitaxy, III-V, II-VIs, and 2D materials, optoelectronic device fabrication and characterization, mid-infrared.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Version 1

Reviewer Report 05 November 2021

https://doi.org/10.21956/openreseurope.15106.r27993

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Marcel Claro
[1] Universidade de Santiago de Compostela, Santiago de Compostela, Spain
[2] Universidade de Santiago de Compostela, Santiago de Compostela, Spain

The manuscript "Fiber-coupled light-emitting diodes (LEDs) as safe and convenient light sources for the characterization of optoelectronic devices " demonstrates the use of a combination of LEDs with different wavelengths for optoelectronic characterization of photodetectors and/or photoresponsive materials, in substitution of conventional white light+monochromator setup or lasers. It gives some application examples for 2D material photodetectors. The paper is well written and presents valuable information.

Here are my comments.

1. Considering the price for LED+controller and the number of LEDs required, it would not be much cheaper than lamp + monochromator kit. The practicality is an obvious aspect, but I would also expect some gain in the light intensity in specific wavelengths (where filtered white light is usually weak). Then it would be great to have some comments on:
   a) Table with specifications (resolution, intensity at some wavelengths, wavelength range) and direct comparison with setup with lamp+monochromator in a similar price range, compare price.
   b) The necessity of dedicated LED controllers for each LED, the possibility of using a switching matrix or other solution to multiplex the LEDs, and use one controller to further reduce the price.

2. There are several unclear points in the detectivity section. It does not show any particularity of the light source system and could be removed. Some of the unclear points are:
   a)The bandwidth of 1Hz. Is it related to the FFT? sample rate (and then integration time)?
   b)What is the contribution of amplifier noise? Noise floor level?
   c)It would be great to have a full FFT spectrum in the SI, then comment on 1/f noise, especially at 1Hz.
   d)10^4 Jones is extremely low for photodetectors (especially for visible wavelengths). Is it right? any comment on why it is so low?

I recommend the paper for indexing after solving these issues.

Is the rationale for developing the new method (or application) clearly explained?
Yes

Is the description of the method technically sound?
Partly

Are sufficient details provided to allow replication of the method development and its use by others?
Yes

If any results are presented, are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions about the method and its performance adequately supported by the findings presented in the article?
Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Molecular beam epitaxy, III-V, II-VIs, and 2D materials, optoelectronic device fabrication and characterization, mid-infrared.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 19 May 2022

Jorge Quereda

Marcel Claro: Referee #2 Referee #2 (Reviewer comments in italics):

The manuscript "Fiber-coupled light-emitting diodes (LEDs) as safe and convenient light sources for the characterization of optoelectronic devices " demonstrates the use of a combination of LEDs with different wavelengths for optoelectronic characterization of photodetectors and/or photoresponsive materials, in substitution of conventional white light+monochromator setup or lasers. It gives some application examples for 2D material photodetectors. The paper is well written and presents valuable information. Here are my comments. Q1. Considering the price for LED+controller and the number of LEDs required, it would not be much cheaper than lamp + monochromator kit. The practicality is an obvious aspect, but I would also expect some gain in the light intensity in specific wavelengths (where filtered white light is usually weak). Then it would be great to have some comments on:
1.a) Table with specifications (resolution, intensity at some wavelengths, wavelength range) and direct comparison with setup with lamp+monochromator in a similar price range, compare price.

Response: This is a good point. Regarding the price, as stated in your point 1b, the cost could be reduced drastically (see below). Regarding the point about the higher intensity of the LEDs with respect to lamp+monochromator systems, we have now compared the power intensity out of a 400 μm core multimode fiber (NA 0.39) when using the LEDs and when using a xenon lamp + monochromator system of the same price range (~15 k€) and similar linewidth output (Bentham TLS120Xe; average FWHM of ~12 nm). We have included this comparison in the Supporting Information.

1.b) The necessity of dedicated LED controllers for each LED, the possibility of using a switching matrix or other solution to multiplex the LEDs, and use one controller to further reduce the price.
Response: This is an excellent point that we didn't discuss in the original manuscript. That is completely feasible, one could easily control all the LEDs using a unique controller and a switch box or even connecting the LEDs directly to the benchtop programmable power supply that we use to modulate the power (TENMA 72-2705). This would reduce the cost from ~800€ to ~450€ per wavelength. In the revised version of the text, we now comment

on this possibility to make the system more affordable.

Q2. There are several unclear points in the detectivity section. It does not show any particularity of the light source system and could be removed. Some of the unclear points.
Response: We wanted to demonstrate that this simple illumination system could be used to directly determine experimentally the detectivity, as in the literature of 2D materials it is very common to use indirect methods to determine the detectivity, which in some cases could lead to a gross overestimation of the detectivity. We have seen in other groups that quite sophisticated setups with dedicated acquisition electronics are used to measure the detectivity and thus we believed that it might provide valuable information to show how this measurement can also be done at a lower price tag with the LED sources.

2.a) The bandwidth of 1Hz. Is it related to the FFT? sample rate (and then integration time)?
Response: The sampling rate of the measurement is 50 Hz (integration time of 20 ms), while the square wave modulated light illumination frequency is 1 Hz, according to the definition of the detectivity (see, for example, https://www.nature.com/articles/s41566-018-0288-z or https://www.thorlabs.com/images/TabImages/Noise_Equivalent_Power_White_Paper.pdf).

2.b) What is the contribution of amplifier noise? Noise floor level?
Response: The data acquisition electronics (including current to voltage amplifiers) can contribute to the measurement of detectivity through their noise floor level, i.e. the total noise of the system (device + amplifier) is determined by the sum of the squares of the various noise components. For our Keithley 2450 at a current range of 10 nA, the current noise level in the 1 Hz frequency region is smaller than 0.2 pA. Thus, the noise floor observed in the experiment is due mostly to the device noise. In the experiment, the illumination power at which one reaches the level of SNR = 1 gives the noise-equivalent-power of the system, allowing to determine the corresponding detectivity.

2.c) It would be great to have a full FFT spectrum in the SI, then comment on 1/f noise, especially at 1Hz.
Response: We now present the FFT of the dark trace (shutter closed and LED still modulated at 1 Hz) in the Supplementary Information. We find a low frequency region with power law exponent of -0.5 and a higher frequency component of -2.5 indicating that there are other noise generating mechanisms that go beyond the 1/f noise.

2.d) 104 Jones is extremely low for photodetectors (especially for visible wavelengths). Is it right? any comment on why it is so low?
Response: Using the commonly used formula of the detectivity based on the assumption of a shot noise limited photodetector we find a detectivity of 109 Jones. The value that we give in the main text is a lower boundary of the detectivity since we did not measured directly the bandwidth and used the lowest value of 1 Hz. Note that the value that we previously reported was also low because of an error in the calculation, the area value used was in meters squared instead of centimeters squared. The correct value is 107 Jones. We thank the reviewer for highlighting this error, which has been corrected in the revised manuscript.

Competing Interests: No competing interests were disclosed.

Reviewer Report 11 October 2021

https://doi.org/10.21956/openreseurope.15106.r27466

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Antonio Rossi
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The manuscript "Fiber-coupled light-emitting diodes (LEDs) as safe and convenient light sources for the characterization of optoelectronic devices " describe a cost-effective and portable setup for multi-wavelength device characterization. The setup is built using a modular selection of light-emitting diodes and it is presented as an alternative to conventional and more expensive light source. The authors report on the optoelectronic characterization of a photodetector made from transition metal dichalcogenide MoS2. The paper is well written and offers detailed guidelines for reproducing the results shown.

Here below, my comments to the paper are reported.

1. In the introduction the authors state that they have been using such a setup for 7 years. Is there any peer reviewed work that has been published with the support of such a setup? If yes, I would suggest to report on that in the introduction.

2. At the end of the introduction the authors claim that the presented fiber-coupled LEDs are rather inexpensive if compared to more sophisticated laser systems, underlining the modular capability of the setup. Is this the only advantage with respect a traditional light source? What is the downside of not using a coherent laser? What are the types of characterization you cannot perform? For users approaching this technique for the first time, it would be useful to understand what they can but also what they cannot do.

3. In the methods section the authors write that the spectral line F-W-H-M of the single light source can range from 10 to 100 nm. Figure 1B also supports this claim, where the 595 and 565 nm lights seem to be very broad, together also with the 385 nm one. In a number of measurements the authors show wavelength dependent results. In particular when discussing photocurrent, responsivity but also detectivity of the device. How reliable is a source with a FWHM of 100 nm when extracting this figures of merit?

4. In Figure 2(b) the authors show the drain source current I measured on a ON-OFF cycle. The authors identify the photogating effect as the main cause of the long rump-up till saturation and the slow recovery of the dark state. Would it be possible to provide at least one single

curve that shows the system completely recovering the OFF state? Can the authors comment on what is causing the photogating?

In conclusion, I recommend the paper for indexing after addressing my comments above.

Is the rationale for developing the new method (or application) clearly explained?
Yes

Is the description of the method technically sound?
Partly

Are sufficient details provided to allow replication of the method development and its use by others?
Yes

If any results are presented, are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions about the method and its performance adequately supported by the findings presented in the article?
Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: My area of expertise is on 2D materials, x-ray photoemission and optical spectroscopy, nano-fabrication and scanning probe microscopy.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Author Response 19 May 2022

Jorge Quereda

We would like to thank the Referees Antonio Rossi and Marcel Claro for providing constructive comments and suggestions and for their positive appraisal of our work. We have accordingly modified the manuscript adding the changes noted.

Antonio Rossi: Referee #1 Referee #1 (Reviewer comments in italics): *The manuscript "Fiber-coupled light-emitting diodes (LEDs) as safe and convenient light sources for the characterization of optoelectronic devices " describe a cost-effective and portable setup for multi-wavelength device characterization. The setup is built using a modular selection of light-emitting diodes and it is presented as an alternative to conventional and more expensive light source. The authors report on the optoelectronic characterization of a photodetector made from transition metal dichalcogenide MoS2. The paper is well written and offers detailed guidelines for reproducing the results shown.*
Here below, my comments to the paper are reported Q1. In the introduction the authors state

that they have been using such a setup for 7 years. Is there any peer reviewed work that has been published with the support of such a setup? If yes, I would suggest to report on that in the introduction.
Response: Thank you for raising this point. As a matter of fact, we have used different versions of this setup along the last years in some of our peer-reviewed works. We now include references to those works.

Q2. At the end of the introduction the authors claim that the presented fiber-coupled LEDs are rather inexpensive if compared to more sophisticated laser systems, underlining the modular capability of the setup. 2.a) Is this the only advantage with respect a traditional light source?
Response: Apart from the low cost and the modular design, we believe that fiber-coupled LEDs have other advantages. In particular, as now stressed in the revised manuscript, their improved safety in comparison with free-space laser systems, as well as their capability to modulate the light power and/or switch it ON/OFF with an external voltage, without need of neutral density filters nor mechanical choppers.

2.b) What is the downside of not using a coherent laser?
Response: Free-space laser sources typically have higher intensity and narrower linewidths.

2.c) What are the types of characterization you cannot perform?
Response: These light sources are not adequate for fine spectroscopic measurements requiring an exquisite energy/wavelength resolution (e.g. photocurrent spectroscopy of samples with narrow features like excitonic peaks).

2.d) For users approaching this technique for the first time, it would be useful to understand what they can but also what they cannot do.
Response: We agree with this point and in the revised version of the manuscript we now discuss the limitations of this setup in line with what has been discussed above: “The presented fiber-coupled LEDs are rather inexpensive, if compared with laser systems, and are modular, making it possible to improve the system little by little. While these light sources cannot compete with lasers in terms of spectral narrowness and output power, their improved safety, as well as their capability to modulate the light power and/or switch it ON/OFF with an external voltage, without the need of neutral density filters nor mechanical choppers, make them very flexible light sources, suitable for characterization techniques where a large output power and extremely narrow bandwidth are not a must.”

Q3. In the methods section the authors write that the spectral line F-W-H-M of the single light source can range from 10 to 100 nm. Figure 1B also supports this claim, where the 595 and 565 nm lights seem to be very broad, together also with the 385 nm one. In a number of measurements the authors show wavelength dependent results. In particular when discussing photocurrent, responsivity but also detectivity of the device. How reliable is a source with a FWHM of 100 nm when extracting this figures of merit?
Response: It is true that some of the LEDs have a much wider spectral line and it means that the spectral features and the figures of merit extracted with those LEDs will be averaged over a wider wavelength/energy range. This will be a limitation when probing a system with sharp spectral features around those wavelengths. In that case one could mitigate this limitation by coupling narrow band-pass filters at the output of the optical

fiber to reduce the FWHM to 10 nm. In the revised version of the manuscript we now comment on this limitation and the possible way to tackle it.

Q4. In Figure 2(b) the authors show the drain source current I measured on a ON-OFF cycle. The authors identify the photogating effect as the main cause of the long rump-up till saturation and the slow recovery of the dark state. Would it be possible to provide at least one single curve that shows the system completely recovering the OFF state? Can the authors comment on what is causing the photogating?
Response: We now include a dataset in the Supporting Information that shows a full recovery to the OFF state that takes more than 30 s.

Q5. In conclusion, I recommend the paper for indexing after addressing my comments above.
Response: Thank you for the appreciation, we tried to address the points raised as thoroughly as possible.

Competing Interests: No competing interests were disclosed.