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Opto-Electronics Review 27 (2019) 355–362

Contents lists available at ScienceDirect

Opto-Electronics Review

journal homepage: http://www.journals.elsevier.com/opto-electronics review

Full Length Article

Applications of light emitting diodes as sensors of their own emitted light

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A R T I C L E I N F O

Article history:
Received 13 May 2019
Received in revised form
27 September 2019
Accepted 25 November 2019
Available online 25 December 2019

Keywords:
Light emitting diode (LED)
Sensors
Image sensors
Distance sensors
Scanner

A B S T R A C T

In literature, it is known that a Light Emitting Diode (LED) could be used as a light sensor. It is also known that its emitted light spectrum and sensitivity spectrum can be partially overlapped. This work presents how commercial LEDs can be used as light emitters and simultaneously as sensors of the reflected portion of the light emitted by themselves. The realized devices present a unique characteristic: the transmitter and the receiver coincide spatially as they are the same device. This ensures the perfect overlapping between transmission and reception radiation lobes that could provide many benefits in several applications like as distance measurements or image sensors. Some simple electronic configurations that use LEDs as detectors of their own emitted light are presented. It has been also demonstrated how these $LEDs_{Tx-Rx}$ can work as image sensors by acquiring an image of a simple test object, and how they can realize distance sensors with respect to other known techniques. Further advantages can be obtained by realizing LED_{Tx-Rx} array in single integrated devices. With the realization of such devices, it will be also possible to experiment new constructive solutions for commonly used applications, without the need of using separate emitter and receiver.

1. Introduction

LEDs (Light Emitting Diodes LEDs) are semiconductor electronic components that have enormously developed in recent years. As widely known, these devices emit electromagnetic radiation from the near infrared range up to the ultraviolet. When their *pn* junctions are forward biased the current passing through the junction causes photon emission due to the passage of electrons from the conduction band to the valence band [1].

Usually, LEDs are used as light emitters and controlled in forward bias, but already in the late '70 Ozeki [2] had implemented an optical-data distribution system using alternatively a LED as source and as detector. Subsequently the interest for using LED as detector appeared to fade and it took up only later to characterize the dependence of junction temperature on the internal efficiency [3,4], to investigate the materials for LED construction [5–8,9] or to photometers application [10–13,14].

In recent times, the dual LEDs functioning is being largely analyzed and exploited for many other new and interesting applications [15–18,19–22,23,24] also in biomedical field [25–27].

In all these studies, LEDs are used as optical detectors in reverse bias conditions or in photovoltaic mode like a normal photodiode, and in several applications pairs of LEDSs can also be alternatively used as transmitters or receivers of an optical signal [28–30].

On the other hand, between the years 80 and 90, Mark Johnson demonstrated that a LED forward biased could be used as emitter and detector of its own radiation [31,32] realizing a prototype of proximity sensor of a rotating reflective encoder [31,33].

In our work, it is described how a LED forward biased (i.e., in the first quadrant (I) of the current-voltage I–V diagram) effectively works both as a light emitter and as a photo-detector and we propose possible applications in two operation areas: as images sensors (Scanner Operation Mode) and as distance meters (Distance Measurement Operation Mode).

In Fig. 1a) a typical I–V diagram of a LED is shown. The I(V) curve represents the characteristic curve in the absence of light radiation received from the junction, while the I'(V) represents the characteristic curve of the same semiconductor device when the junction is hit by a light radiation in the absorption spectrum of the device. As widely known, as a consequence of the irradiation, the characteristic curve moves downwards, because of the absorption of photons received from the junction.

However, the LED can detect an electromagnetic radiation coming from a different source, as a normal photodiode could do, or it can receive a fraction of the radiation emitted by the LED itself. In this case, it is necessary that emission band and absorption

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https://doi.org/10.1016/j.opelre.2019.11.008
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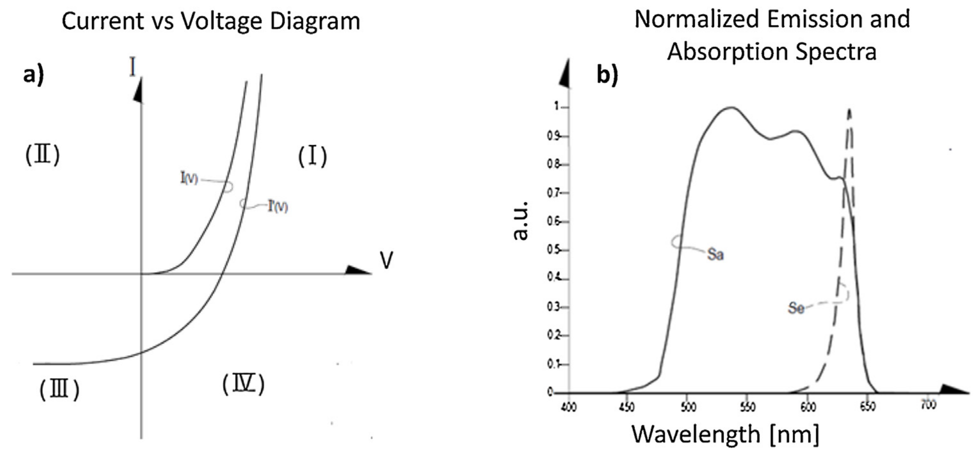

Fig. 1. In a) a schematic representation of the current-voltage I(V) curve of a generic LED is presented. I'(V) is the characteristic curve of the same semiconductor device when the junction is hit by a light radiation in the absorption spectrum of the device. In b) the absorption and emission spectra of the LR-H9GP LED [OSRAM Opto Semiconductors GmbH (Germany)] are shown.

band of the LED presents a partial overlapping at one use condition at least.

For example, in Fig. 1b) the absorption and emission spectra of a LED LR-H9GP (OSRAM Opto Semiconductors GmbH (Germany)) are shown. Its emission spectrum Se is centered on 632 nm and is partially superimposed with its absorption spectrum Sa, which results to be much wider due to the Stoke-Shift [7,8].

The spectra superimposition allows using LEDs simultaneously as emitters and receivers [33]. In fact, a LED that presents this characteristic can be forward biased, emitting a light beam towards a target that back-diffuses and/or at least reflects part of the light emitted by the LED itself. If this radiation is collected by the LED, it causes a deviation of the characteristic curve generating the characteristic named I'(V) of Fig. 1a). In order to operate the LED as emitter and receiver at the same time, the deviation of the I–V characteristic curve must be detected in the first quadrant simultaneously with the emission.

Many LEDs present this characteristic of partial overlapping of the emission and absorption spectra and can therefore be used profitably to detect a part of the radiation emitted by themselves.

At first this article explains the operating principle that allows LEDs, controlled in forward bias, to operate simultaneously by photoemitters and photodetectors.

Some simple circuit solutions will be briefly described to highlight the phenomenon and the operating conditions in which, at the same time, the LED also detects a part of the radiation emitted from itself will be defined.

2. Material and methods

As widely known, LEDs can be electrically driven in various ways. In general, LEDs driven anyway present some modifications in current and/or voltage as a function of the light absorbed [1,34–36].

To highlight the phenomenon it is possible to fix one electrical parameter and measure the variation of the other electrical parameter, induced by the absorbed light radiation. For example, the LED can be controlled by setting the voltage to highlight changes in current or by setting the current to highlight changes in voltage.

In Fig. 2a) a simple description of the behaviour of a LED controlled at fixed current is presented. In the absence of other photoelectric phenomena, and in particular in the absence of incident radiation on the LED in the wavelength range of the absorption spectrum, the voltage will assume a V_0 value depending on its characteristic curve. Otherwise, if an electromagnetic radiation in the absorption spectrum of the LED arrives to the junction, there will be a generation of a weak current, inverse to that applied by the control circuit. By fixing the current I_0 that flows through the LED, voltage necessarily increases up to V_1. It is therefore possible to detect the value of V_1 and determine the radiant flux captured by the LED.

Vice versa, if the LED is driven at a fixed voltage V_0, as shown in Fig. 2b), the light radiation collected by the LED alters the characteristic curve and causes a weak reduction of the current flowing through the LED from the value I_0 to the value I_1.

In both cases, the detected photoelectric phenomenon allows to use the LED in forward bias as an emitter and, simultaneously, as a light receiver.

In Fig. 2c) is shown a simple explanatory circuit of fixed current driving in which the LED is inserted in the feedback network of an operational amplifier ($I_0 = V_{REF} / R$). In Fig. 2d) a simple fixed voltage V_{REF} driving circuit is schematically shown. In both cases, the signal generated by the incident light can be amplified with suitable and well-known circuit configurations.

An additional solution involves combining the adopted LED (named $LED_{Tx\text{-}Rx}$) with a second reference nominally identical LED (called LED_{REF}) driven under the same conditions as the $LED_{Tx\text{-}Rx}$, but optically shielded so it cannot receive any light radiation. This circuit solution permits to subtract the forward bias contribution from the signal detected by $LED_{Tx\text{-}Rx}$, eliminating the common mode noise components. In practice, using one or more $LED_{Tx\text{-}Rx}$ as emitters and at the same time as radiation detectors by using a single reference LED_{REF}, it is possible to carry out differential measurements of the radiation received from any single $LED_{Tx\text{-}Rx}$. It is worth to note that, for the correct subtraction of the bias currents, between $LED_{Tx\text{-}Rx}$ and LED_{REF}, they should be identical and at the same temperature.

Figure 3 schematically shows a device composed of N $LED_{Tx\text{-}Rx}$ with fixed voltage driving circuit and a single obscured reference LED_{REF}.

The circuit presented essentially consists of N + 1 circuits each equal to that of Fig. 2d), where N differential amplifiers can be used to amplify the differences between the outputs of the N $LED_{Tx\text{-}Rx}$ and the single LED_{REF}.

The schemes described up to now show simple solutions based on one or more $LED_{Tx\text{-}Rx}$ able to operate simultaneously by emitter and detector of the light radiation which, as said above, can be a part of the radiation emitted by the $LED_{Tx\text{-}Rx}$ itself and reflected or spread by a target. As said above, the only requirement to satisfy these operating conditions is a partial overlap between the

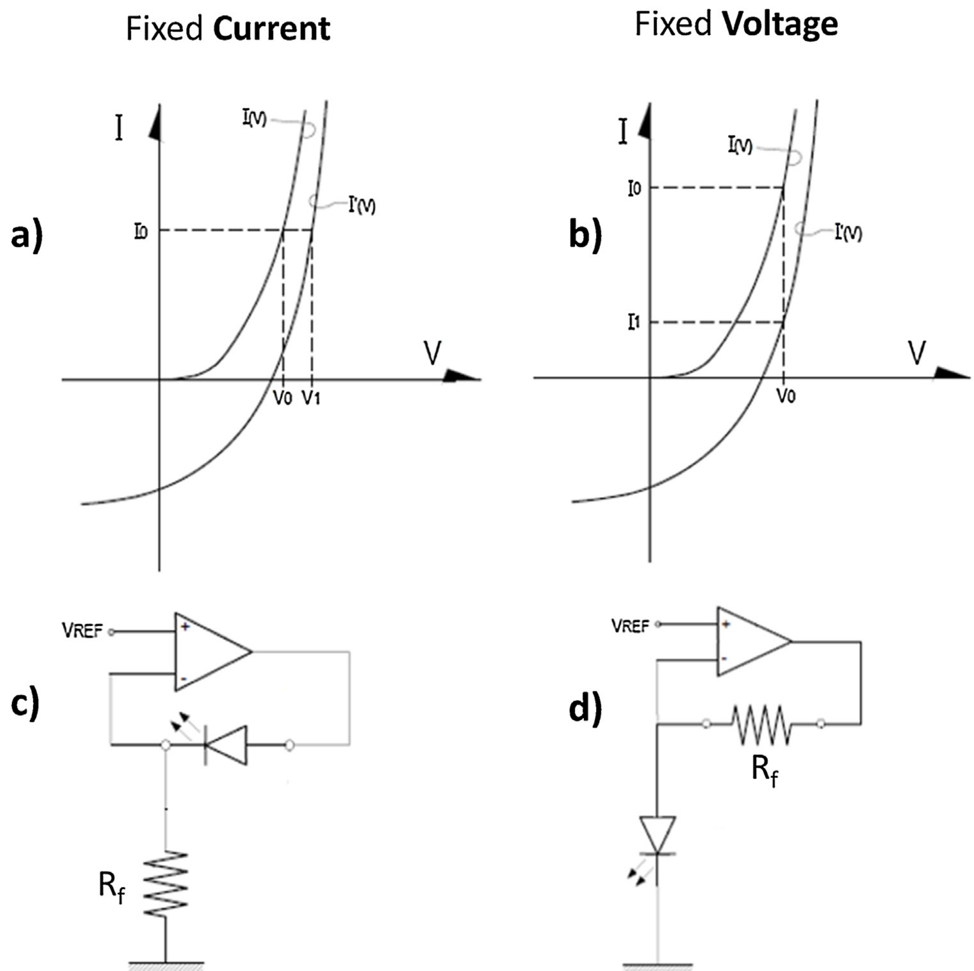

Fig. 2. Two modes are schematically presented in which the LED can be controlled with a fixed current a) or with a fixed voltage b). Two simple control circuits with a fixed current c) and a fixed voltage d) are also presented.

absorption and emission bands and fortunately it is verified for a large number of commercial LEDs in different technologies and wavelengths.

For this experiment it was decided to use a power LED SFH 4232 IR LED of the Platinum DRAGON® series (OSRAM Opto Semiconductors GmbH Leibnizstraße 4, D-93055 Regensburg). Indeed SFH4232 housing easily allows to minimize the temperature difference between the $LED_{Tx\text{-}Rx}$ and the LED_{REF}, simply by mounting them on the same heat sink. The LED has an active area of 1 mm^2 with a footprint on the smaller side of the case of 5.8 mm [Fig. 4]. The central wavelength of the emission is 860 nm while the absorption spectrum extends up to 700 nm [as it can be seen from the graph in Fig. 4].

It is worth to note the partial overlap between the two spectra shown in Fig. 4b which therefore corresponds to the operating spectral band of the $LED_{Tx\text{-}Rx}$ device.

Two different experimental setups have been prepared to evaluate two possible operation methods of the proposed technique. The first concerns an innovative use of these sensors as distance meters (Distance Measurement Operation Mode reported in Fig. 5) while the second evaluates the possibility of using $LED_{Tx\text{-}Rx}$ to reconstruct the image of an object (Scanner Operation Mode reported in Fig. 6).

2.1. Distance measurement operation mode

The proposed method can be used to perform distance measurements, thus creating a generic proximity sensor. Systems currently used for optical distance measurement by means of LED emitters, called LED Reflective Distance Sensors (LED-RDS), are constituted by a LED and a photodetector placed side by side [37,38]. LED-RDS are mass produced and used mainly in barcodes scanners or encoders. LED-RDS have also been used to provide low resolution distance measurement, for example in mobile robots [39]. The LED emits a light radiation according to its own radiation pattern and the photodetector receives, according to its receiving lobe, part of the retro-diffused radiation from a target placed in front of the LED/photodetector pair.

Some operating limits of this devices can be overcome by using LED as photoemitter and photodetector simultaneously, because in this case, the transmitter and receiver coincide spatially as they are the same device. This ensures the perfect sovrapposition between optical transmission and reception lobes.

In order to verify the operation as distance meter, the experimental setup presented in Fig. 5 has been realized. It was decided to compare the proposed method with the classical method of distance measurement with separate source and receiver. So, it was chosen to place side by side to the $LED_{Tx\text{-}Rx}$ a further LED SFH4232 (called LED_{Rx}) that acts as a radiation detector.

$LED_{Tx\text{-}Rx}$ and LED_{Rx} have been fixed to a mechanical support connected to a micrometric scanning system, controlled by PC. An aluminum mirror (30 mm X 30 mm) was placed on the XY plane and two scans along the Z axis (0–2 mm and 0–8 mm) have been performed.

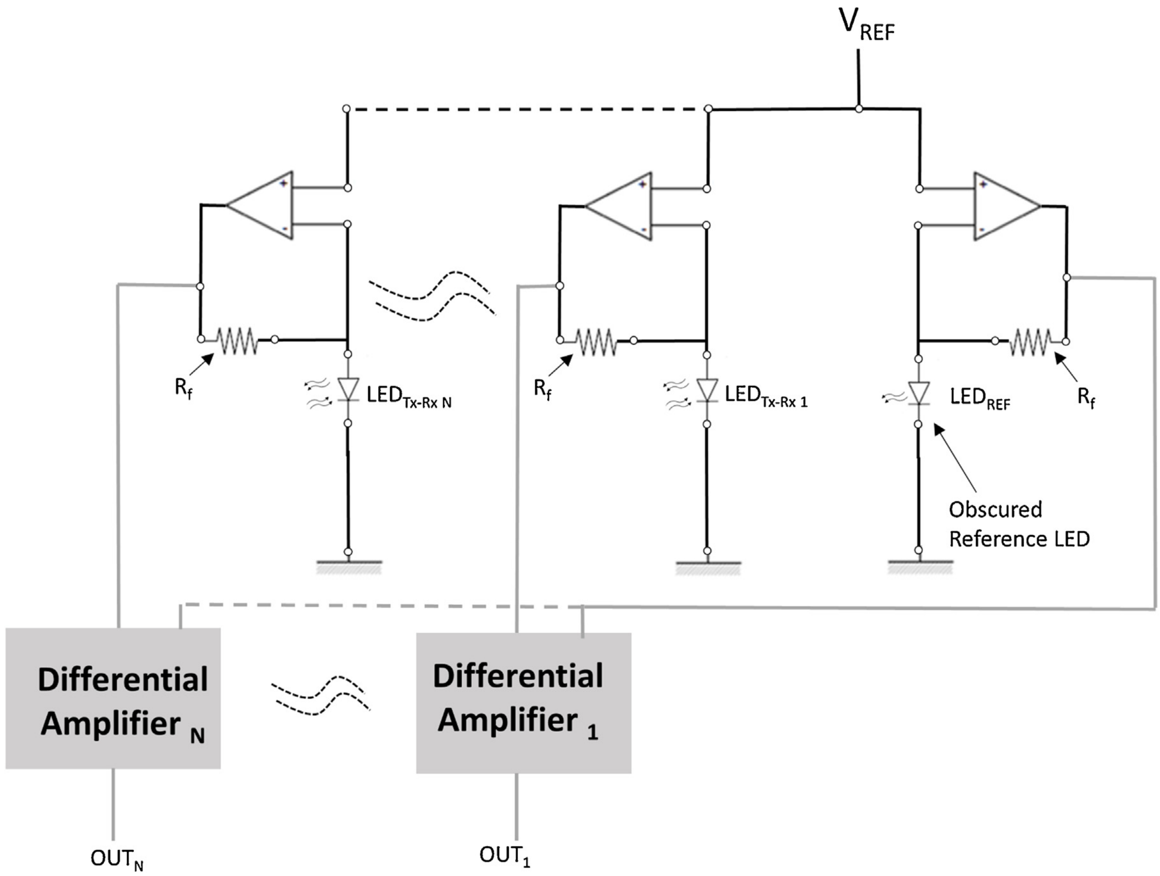

Fig. 3. The schematic diagram shows a device composed of N $LED_{Tx\text{-}Rx}$ with a fixed current driving circuit and one obscured reference LED_{REF}.

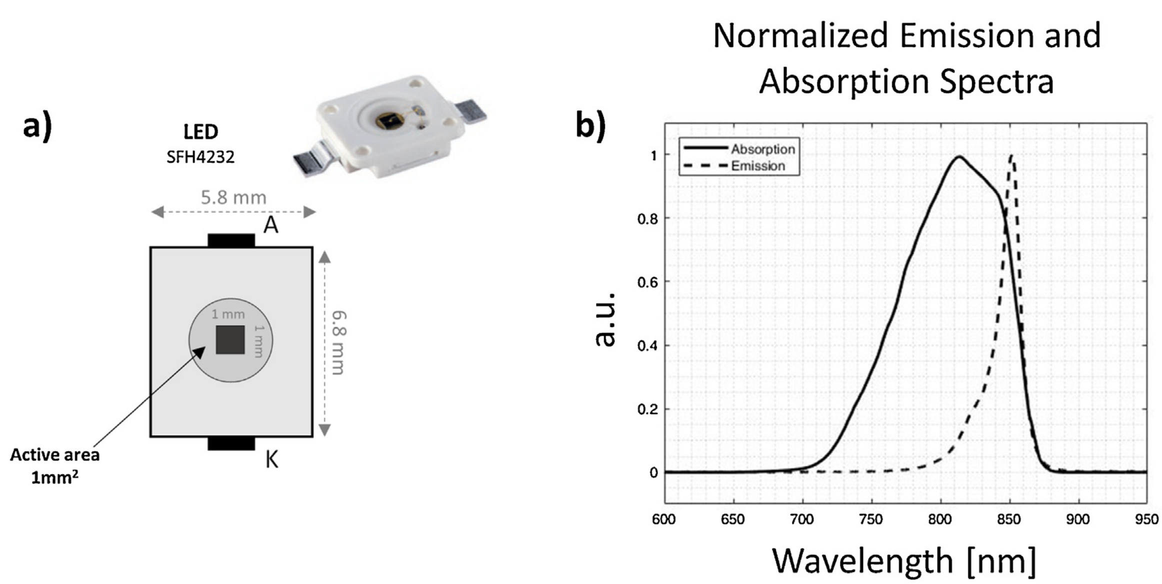

Fig. 4. In a) the SFH4232 LED used for experimentation is shown. In b) the relative spectral emission and spectral absorption of the SFH4232 LED is presented.

The $LED_{Tx\text{-}Rx}$ was driven according to the scheme described in Fig. 3. Within the block defined "Tx-Rx Electronics" a LED_{REF} SFH4232 identical to the $LED_{Tx\text{-}Rx}$ is present. LED_{Rx}, which is used only as a receiver and therefore works as a simple photodetector, is connected to a trans-impedance amplifier described as the "Rx Electronics" block in Fig. 5. A digital oscilloscope (TDS model, Tektronix Company, USA) has been employed to acquire both $LED_{Tx\text{-}Rx}$ and LED_{Rx} signals.

2.2. Scanner operation mode

A scanning system that includes this type of devices must be composed of a linear or bidimensional array. The $LED_{Tx\text{-}Rx}$ array illuminates a portion of the object and the light reflected from the surface of the object is collected by the same $LED_{Tx\text{-}Rx}$ that work simultaneously as detectors and light emitter. The image of the object is obtained through the signals generated by the part of light,

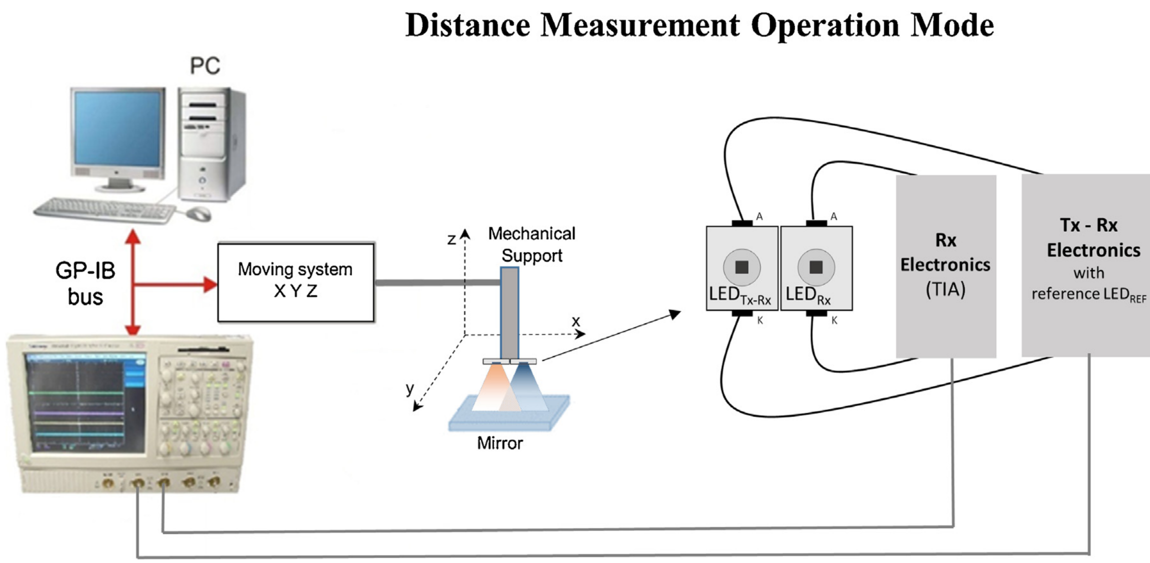

Fig. 5. Experimentation setup adopted for demonstration of LED$_{Tx-Rx}$ distance measurement operation.

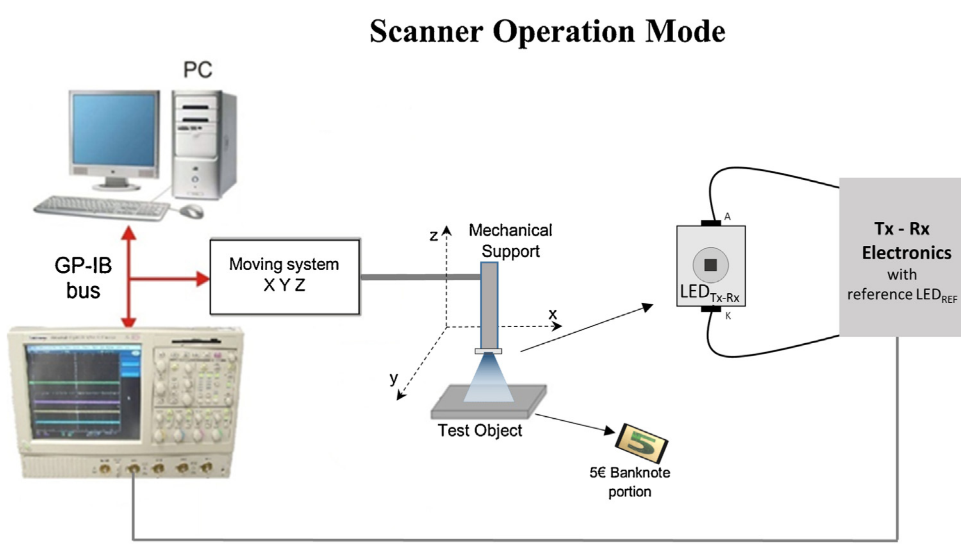

Fig. 6. Experimentation setup adopted for demonstration of LED$_{Tx-Rx}$ scanner operation.

emitted by the LED$_{Tx-Rx}$, reflected by the object and collected by the same LED$_{Tx-Rx}$.

In this work the operation described above was simulated by using a single LED$_{Tx-Rx}$ SFH 4232 to reconstruct an image of the emerald number portion of a €5 Europa Series banknote.

A 11 mm X 14 mm scan, with step of 100 μm, was carried out by holding the banknote on the X–Y plane and moving the LED$_{Tx-Rx}$. The LED was placed in contact with the banknote and driven according to the scheme described in Fig. 3. A digital oscilloscope (TDS model, Tektronix Company, USA) was employed to acquire the signal coming from the “Tx –Rx Electronics” block.

3. Results

Figure 7 shows the results related to the study of the method as distance meter performed with the system described in Fig. 5.

Figure 7a) shows the values of the signals received by LED$_{Tx-Rx}$(in blue) and LED$_{Rx}$(in red) in the operating range 0–8 mm subtracted from the respective offsets. In Fig. 7b) the values obtained are presented by repeating the measurement closer to the LEDs (range 0–2 mm) in order to highlight the different operating areas of the two techniques.

Figure 8 shows the result concerning the simulation of the scanner operation mode carried out with the system described in Fig. 6. The acquisition obtained is compared with the original image of the emerald number of the € 5 banknote used for the experimentation.

In Fig. 8a) the original image acquired with a commercial camera is presented, while in Fig. 8b) the reconstructed image received by the LED$_{Tx-Rx}$ is shown in grayscale.

4. Discussion

Our experimentation confirms that a forward biased LED can be simultaneously used as emitter and receiver and has proven that its functioning can be optimized and employed for useful applications.

The LED can detect an electromagnetic radiation coming from a different source with respect to it or it can be sensitive to a portion of the radiation emitted by the LED itself. For this last use, fundamental requirement is the partial overlap between the LED absorption and emission bands. On the market, there are many LEDs that present this feature, allowing special applications of these

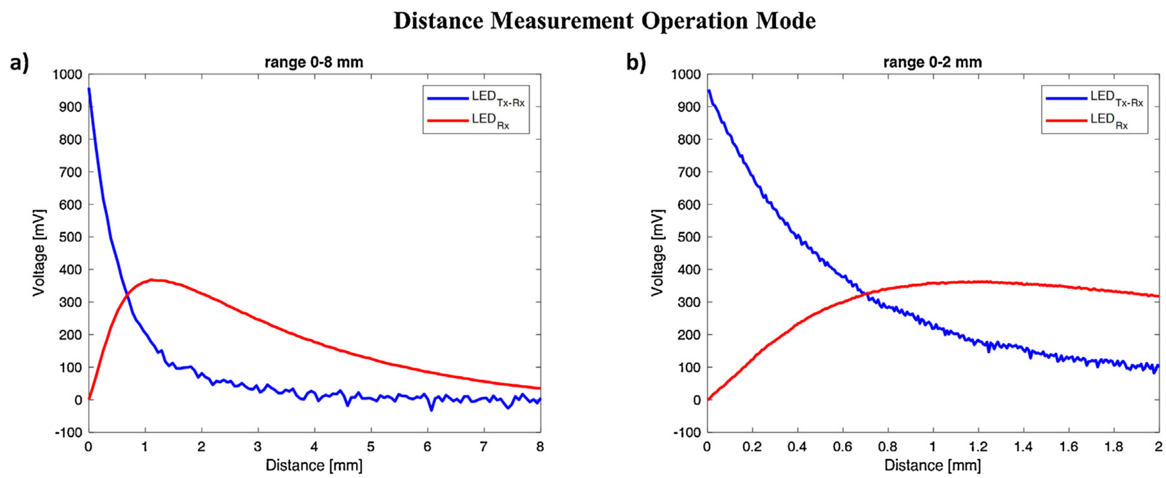

Fig. 7. Distance Measurement Operation Mode. Results obtained using the setup shown in Fig. 5. In a) the results of $LED_{Tx\text{-}Rx}$ (in blue) and by LED_{Rx} (in red) are shown in the operating range between 0 and 8 mm. In b) the measurements in an operating zone closer to the LEDs (range 0–2 mm) are presented.

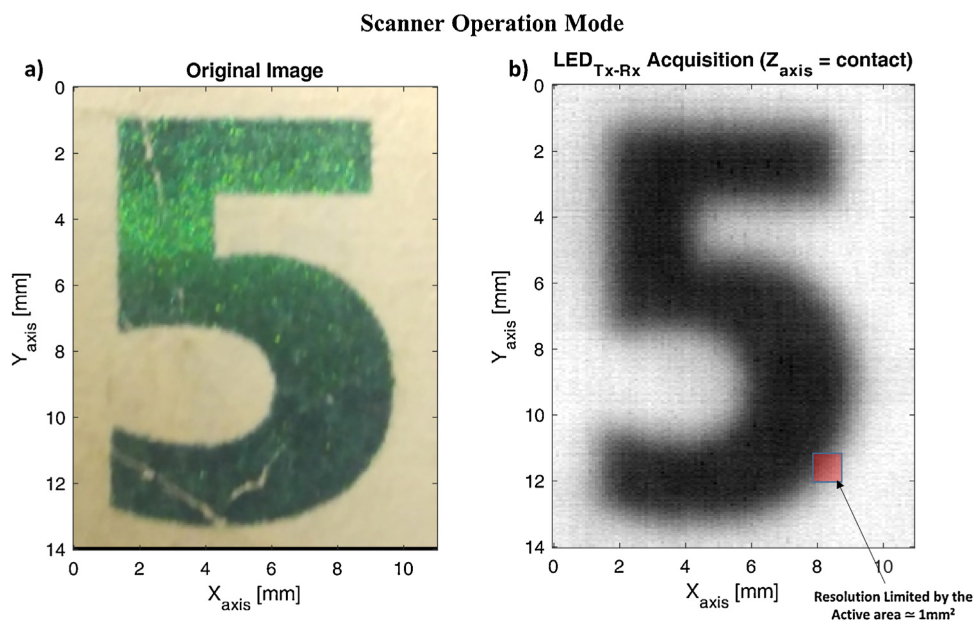

Fig. 8. Scanner Operation Mode. Results obtained using the setup shown in Fig. 6. In a) the original image of the emerald number of a € 5 banknote of common course (Europa series) is shown. In b) the same image reconstructed by the $LED_{Tx\text{-}Rx}$ in scanner operation mode is presented in grayscale.

devices. In particular, in this article the commercial LED SFH4232 was used. It is fundamental to point out that the overlapped band between emission and absorption spectra presented in Fig. 4b) corresponds to the effective operating band of the LED that simultaneously works as emitter and receiver of a part of its transmitted light.

In this article two specific operating modes are presented:

1) Distance Measurement Operation Mode
2) Scanner Operation Mode

For both operating modes, it was decided to use simple driving and reception circuits with a single LED (called $LED_{Tx\text{-}Rx}$) and a reference obscured LED (called LED_{REF}), as described in Fig. 3. The presence of the LED_{REF} is very useful as it allows to carry out differential measurements.

Let's now analyze the "Distance Measurement Operation Mode". Similar to the LED-RDS commercial distance meters, it assumes that there is a law that binds the amount of light received by the LED and the distance of the target. In this article the proposed technique was compared with a usual LED-RDS technique as shown in the setup presented in Fig. 5.

Figure 7 shows the signal received by the LED_{Rx} (in red) as a function of the distance (shown in abscissa). Similarly to the operation of the commercial LED-RDS devices [37] the received signal presents at first an increasing area and the measurement becomes suitable only after a certain distance (about 1 mm) from the active area of the photodetector, since the two transmitting and receiving lobes are at first completely distinct. Many solutions are known in the literature and on the market for minimizing or increasing this minimum operating value, while remaining undoubtedly separate the spatial positions between source and photodetector. Instead, by using the single-LED distance measurement technique, source and detector are physically the same object and therefore are inevitably in the same position.

The results presented in Fig. 7b) show how this technique could be particularly useful and sensitive in the case of small distance measurements (<2 mm). The intensity of the flux could be interpreted as an approximation function of the square of the distance and presents its own maximum value when the distance between the $LED_{Tx\text{-}Rx}$ and the target is equal to zero (contact measurement).

The proposed technique could therefore be useful when it is necessary to detect small distances and reduce the size of the realized device. In these conditions it could also be easy to shield the device from ambient light.

Let's now analyze the "Scanner Operation Mode". In Fig. 8 it was obtained, for the first time in the literature up to our knowledge, an image of an object using a single LED in simultaneous operation as transmitter and receiver. It can be seen in Fig. 8b) the emerald number 5 of a €5 banknote has been correctly acquired through the use of a $LED_{Tx\text{-}Rx}$ SFH4232.

The image reconstruction highlights the possibility of realizing scanners based on the proposed technique. In sake of simplicity, it was decided not to use specific optics, thus limiting ourselves to the evaluation of the technique as contact sensor. In this particular situation the resolution obtained in Fig. 8b) is therefore due exclusively to the size of the active area ($1\,mm^2$) of the adopted $LED_{Tx\text{-}Rx}$. These features can be significantly improved with the use of dedicated optics, designed according to application needs.

Further advantages can be obtained by realizing $LED_{Tx\text{-}Rx}$ array in single integrated devices. Two-dimensional arrays can be used in monochromatic or multispectral confocal imaging acquisition systems, particularly useful in the medical field to perform, for example, dermatoscopes or endoscopes in which the radiation emitted by the LEDs is conveyed into an optical fiber bundle to reach a point inside the human body.

With the realization of such devices, it will be also possible to experiment new constructive solutions for commonly used applications, such as optical switches, optical mouses or fingerprint detectors, without the need of using separate emitter and receiver.

Generally, the proposed technique can provide innovative solutions for all those applications where it is important to perform extreme miniaturization or when it could be significantly advantageous to exploit the coincidence between emitted and reflected light paths.

5. Conclusions

This article demonstrates that the use of LED as emitter and a receiver of its own light can be effectively exploited in two important application modes, when the optical emission band and the absorption band of the LED are partially overlapped.

In this way, it is possible to realize a plurality of innovative devices, with many different functions.

For example, it has been demonstrated how LEDs can be used to acquire images. A scanning system that includes this type of devices must be composed of a linear or a bidimensional array. Innovative distance meter has also been proposed and verified. The technical solution presented in this work can be considered alternative and / or complementary to solutions with separated illuminator and sensor.

CRediT authorship contribution statement

Enrico Vannacci: Conceptualization, Methodology, Software, Validation, Investigation, Resources, Writing - original draft, Writing - review & editing. **Simona Granchi:** Formal analysis, Data curation, Investigation, Writing - original draft, Writing - review & editing, Visualization. **Marco Calzolai:** Conceptualization, Validation, Investigation, Resources, Writing - review & editing. **Elena Biagi:** Supervision, Project administration.

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