Modulation of LED Photo-Luminescence for Underwater Optical Communications

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***Abstract*—An optical wireless communication approach that exploits the photo-luminescent radiation of LEDs is presented. In this approach the photo-luminescence of an array of LEDs is modulated by varying the impedance connected to the LEDs. The LEDs are also employed to harvest radiant energy making possible fully passive optical communications tags. Possible applications of this approach include short-range underwater communications. Initial experimental results suggest that communication speeds of few kilobits per second can be achieved.**

I. Introduction

Underwater wireless communication (UWC) refers to a set of technologies that enable the transmission of data in unguided underwater environments using wireless carriers [1]. UWC makes possible a number of applications such as ocean exploration, pollution and environmental monitoring, offshore exploration, disaster early warning systems, military operations, construction, underwater inspection, mining activities, diver communications, climate recording, and oceanographic data collection among others [1]–[5]. The wireless carriers that support UWC are acoustic waves, radio frequency (RF) waves and optical waves.

Historically, acoustic communications has been the dominant underwater wireless technology due to its long communication range of several tens of kilometers [6]. However, it also has drawbacks such as relatively low data rates (in the order of kbps), severe communication latency (in seconds) due to the slow speed of sound in water, susceptibility to turbulence and temperature gradients, and its need for costly, bulky and power hungry acoustic transceivers [1,7]. RF underwater communications are less sensitive to turbulence and temperature gradients, but have to overcome the high level of attenuation that RF waves experience in water, especially in seawater. At 125 kHz, for instance, the penetration depth for RF in seawater is 71 cm and at 13 MHz it drops to 68 mm [8]. Longer ranges can be achieved at extremely low frequencies (30 to 300 Hz) but at the cost of extremely low data rates and very large antenna sizes. Optical underwater communications do not require large antennas, in fact optical transceivers can be very compact and power efficient. Moreover, very high data rates and low latencies are possible with light. However, light propagation underwater experiences strong scattering and absorption due to suspended particulates. Nevertheless, data rates of 9.6 Gbps and 1.2 Mbps have been achieved using high-power lasers (at 8 m) and LEDs (at 30 m), respectively [9,10]. Underwater optical communication is most effective in the blue-green wavelength range (400 to 550 nm), which is where the optical absorption of water is the lowest.

This work explores the modulation of photo-luminescent emissions of green light-emitting diodes (LEDs) for underwater communications. The phenomenon of light emission upon electrical stimulation is known as electro-luminescence (EL). By design, LEDs are very efficient electro-luminescent devices. However, LEDs are also very good photo-luminescent devices. That is, LEDs emit light when stimulated by a light source with shorter emission wavelength than their emission wavelength.

Modulation of the photo-luminescence (PL) of GaAs solar cells has been reported in [11]–[14] in a concept dubbed Optical Frequency Identification (OFID). In OFID, a solar cell is employed for three different functions: energy harvesting, data reception and data transmission (via PL or EL modulation). The PL or EL radiation emitted by GaAs solar cells lies in the 800 to 900 nm range. Unfortunately, this wavelength range does not coincide with the blue-green window that is most effective for underwater communications. In this work, the OFID concept is extended to underwater communications using LEDs (instead of solar cells) to develop opto-electronic devices that are able to: 1) harvest radiant energy by operating the LEDs as photo-voltaic cells, 2) receive information encoded optically and 3) transmit information optically by modulating the PL emissions of the LEDs. These LED-based OFID devices will work together with an optical reader, which is equipped with a high-power light source to illuminate the LEDs (in order to stimulate a PL response and to transmit power) and an optical receiver to receive the modulated PL emissions from the LEDs.

The proposed OFID device has some similarities with radio frequency identification (RFID) technology. For instance, both RFID and OFID devices can be fully passive, being energized by a nearby reader, and can both send and receive data to and from a reader wirelessly. Similar to RFID devices, OFID devices can be used for underwater applications such as fish tracking, pipeline and underwater infrastructure monitoring,

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underwater navigation and environmental monitoring [8]. An advantage of OFID over RFID for underwater applications is that light can be readily collimated or concentrated using low-cost optics. Hence, especially in seawater, light has the potential for longer communication ranges than radio waves.

II. Background

LEDs are made out of semiconductor materials with an energy bandgap, E_g, that is tuned to the wavelength of the light emitted by the LED. When an electric current is applied to an LED, the injected electrons in the conduction band transition to the valence band with high probability and in the process loose their excess energy in the form of a photon of energy $h\nu_e$, where $\nu_e = c/\lambda_e$, c is the speed of light and λ_e is the wavelength of the emitted photon. The emission of light through this process is called electro-luminescence (EL) and is illustrated qualitatively in Fig. 1.

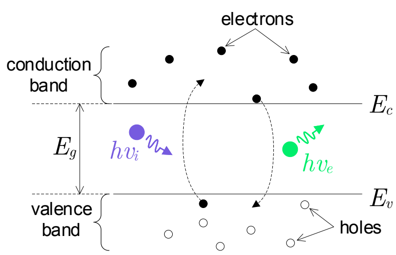

Fig. 1: Qualitative diagram of the energy band structure of an LED and possible electron transitions between the conduction and the valence bands.

Another possible transition is when an electron in the valence band gains energy from an absorbed photon of energy $h\nu_i > E_g$ and moves to the conduction band. Once in the conduction band, this electron could leave the LED as an electric current or could transition back to the valence band releasing a photon of energy $h\nu_e$. The process of absorbing a photon of energy $h\nu_i$ and releasing a photon of energy $h\nu_e < h\nu_i$ is called photo-luminescence (PL).

The electric current through an LED is a function of the voltage applied to it and the photon flux illuminating it. Fig. 2a) shows a setup employed to measure the current-voltage (IV) relationship of an LED. A source meter (Keithley 2400) was used to sweep the voltage across the LED (V_D) and measure the current through the LED (I_D). A blue/violet laser pointer with a 405 nm emission wavelength illuminated the LED. Fig. 2b) shows measured IV curves of a green LED (LXZ1-PM01 from Lumileds) when it is illuminated and when it is not illuminated (dark) by the laser pointer.

When the LED is illuminated, three different regions can be observed: reverse biased, photo-voltaic and forward biased. In the reverse and forward bias regions, the LED dissipates power. However, in the photo-voltaic region the LED generates power (positive V_D and positive I_D coming out of the LED's anode). Hence, LEDs can work as small solar cells generating power when illuminated. Unlike solar cells, however, LEDs have a much narrower absorption spectrum. Thus, they have

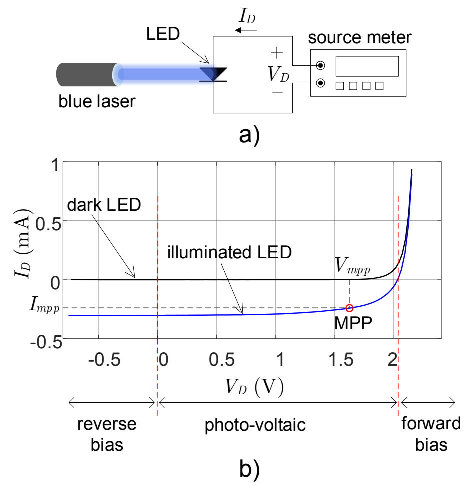

Fig. 2: Current-vs-voltage response of an LED. a) Measurement setup; b) IV curves of a dark and an illuminated LED.

to be illuminated by light with a suitable wavelength. The point at which the LED generates the maximum power (MPP) is marked in the figure. V_{mpp} and I_{mpp} are the LED voltage and current at the MPP, respectively. If the LED is loaded with a resistor $R_{mpp} = V_{mpp}/I_{mpp}$, then the maximum amount of power is transfered to the load.

Fig. 3 shows an experiment in which a green LED (LXZ1-PM01 from Lumileds) is illuminated with a blue/violet laser pointer with wavelength of 405 nm. A camera outfitted with an optical bandpass filter (550 nm center wavelength) captured images of the LED (shown on the right side of Fig. 3).

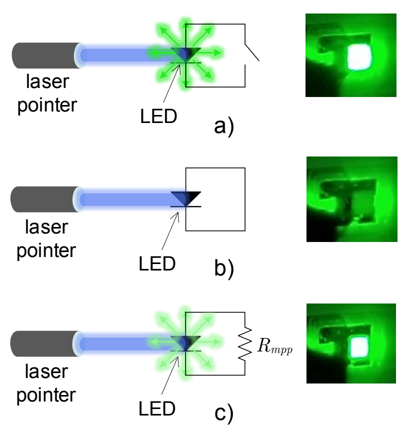

Fig. 3: Experimental demonstration of LED PL modulation as LED is illuminated with a 405 nm laser pointer. a) open circuit PL; b) short circuit PL; c) PL at the maximum power point.

Fig. 3a) shows that when the LED is kept in open circuit (OC), the LED lights up emitting green light. This emission is called open circuit photo-luminescence (OC PL) and occurs when electrons move to the conduction band after absorbing energy from blue photons and since they cannot leave the LED, they transition back to the valence band emitting green photons. On the other hand, if the terminals of the LED are short circuited (Fig. 3b), the electrons in the conduction band have a path to leave the LED, hence they do not transition back to the valence band and no light is emitted. Fig. 3c) shows the case in which the LED is biased at the MPP by connecting the load R_{mpp} to it. At the MPP, the PL of the LED is neither maximum nor zero. This experiment shows that the PL of an LED can be modulated by operating the LED at the OC, the MPP or the short circuit (SC) operating points. For instance, binary modulation could be accomplished by switching the LED between OC and SC or between OC and the MPP according to the transmitted binary symbols. OC-SC binary modulation results in the highest signal-to-noise ratio while OC-MPP modulation allows harvesting energy while transmitting binary symbols.

The PL and photo-voltaic properties of an LED can be exploited to develop an OFID wireless device that uses LEDs for three different functions: 1) energy harvesting if the LEDs are operated in the photo-voltaic region, 2) optical data reception by taking advantage of the photo-transduction property of LEDs and 3) optical data transmission by modulating the PL or EL emissions of LEDs. Fig. 4 shows a conceptual diagram of an OFID communication system. It consists of a reader and a tag. The tag uses a 2D array of green LEDs, instead of a GaAs solar cell as the luminescent device, to align with the blue-green window that is most suitable for underwater communications. An array of LEDs is need to increase the area for light collection and light emission (since typical LEDs have small sizes).

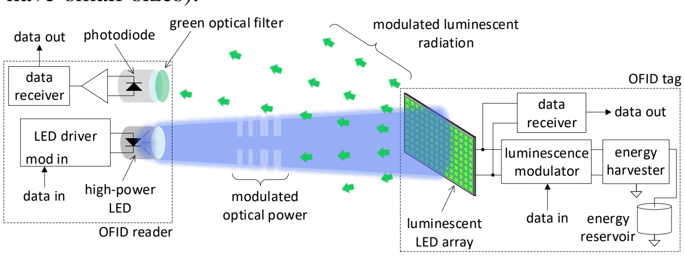

Fig. 4: Conceptual diagram of an OFID communication system. The system consists of a reader and an OFID tag. The tag includes an array of green LEDs, a data receiver, a luminescence modulator, an energy harvesting circuit and an energy reservoir.

Other components of the OFID tag are a data receiver, a luminescent modulator, an energy harvesting circuit and an energy reservoir, which could be a battery or a super-capacitor. The reader consists of a high-power blue LED, an LED driver with a modulation input (mod in), a photo-diode with its corresponding trans-impedance amplifier and a data receiver to recover the information transmitted by the tag. The transmission of data from the reader to the tag is referred to as downlink and from the tag to the reader as uplink.

III. Experimental Setup and Results

As a proof of concept, the experimental setup shown in Fig. 5 was built to test validity of the proposed energy harvesting and communication approach.

The setup includes of a 2D array of 72 green LEDs (LXZ1-PM01 from Lumileds) connected in parallel. The setup also includes a high-power blue/violet LED with a 415 nm center wavelength (M415LP1 from Thorlabs), an LED driver, a dichroic mirror (DMLP490R from Thorlabs), a photodiode (BPW34), a trans-impedance amplifier (TIA), a water tank and an optical power sensor (S120C from Thorlabs). The dichroic mirror reflects the light from the high-power LED towards the plano-convex lens, which focuses it onto the LED array. The PL light from the LED array travels back through the water tank, gets focused by the plano-convex lens, passes through the dichroic mirror and is detected by the photo-diode. The water tank was filled with tap water.

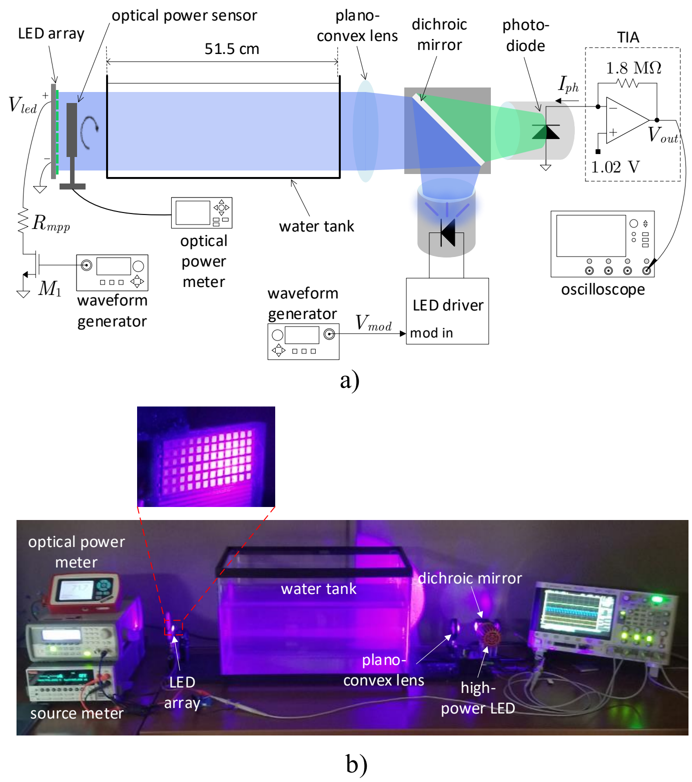

Fig. 5: Experimental setup employed to validate the proposed energy harvesting and optical communication approach. a) Schematic diagram showing component arrangement and connections; b) photograph of the experimental setup.

The IV curve of the LED array was measured with a source meter (Keithley 2401) with and without the water tank present. The power-vs-voltage (PV) curves were calculated from the IV curves and are shown in Fig. 6. The maximum power generated by the LED array is 920.9 μW when the water tank is not present and 154.9 μW when the water tank is present. The optical power measured by the optical power sensor is 19.2 mW and 2.99 mW without and with the water tank. Considering that the active area of each green LED is 0.86 mm^2 and that the active area of the optical power sensor is 94.1 mm^2, the power conversion efficiency of the LED array is 7.8%.

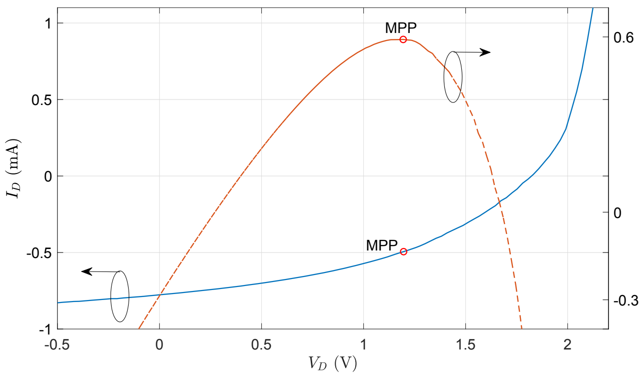

Fig. 6: Measured IV and PV curves from the green LED array through air (top) and through water tank (bottom).

OC-MPP binary modulation of the LED array PL was accomplished using MOSEFT M_1 (NTS4409) and resistor R_{mpp} as shown in Fig. 5. When M_1 is on, the R_{mpp} resistor is connected to the LED array biasing it at the MPP. When M_1 is off, the LED array is left in OC. For OC-SC modulation, R_{mpp} is shorted. The modulating input (V_{mod}) and the output of the TIA (V_{tia}) for OC-MPP modulation are presented in Fig. 7 for the cases when the water tank was not present (top) and when it was present (bottom). Likewise, V_{mod} and V_{tia} for OC-SC modulation are presented in Fig. 8 for the cases when the water tank was not present (top) and when it was present (bottom). The modulation frequency was set to 2.5 kHz. Notably, the water greatly attenuates the modulated PL signal. However, it is still detectable and with further amplification it could be used to decode binary information. Above a frequency of about 10 kHz, the received modulated PL signal is undetectable (below the noise floor of the experimental setup).

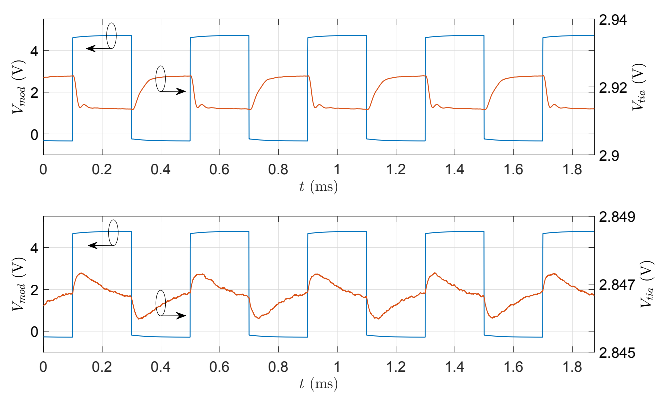

Fig. 7: OC-MPP binary modulation of PL without (top) and with (bottom) the water tank.

These waveforms also show that OC-SC modulation barely increases the signal swing at the receiver beyond that of OC-MPP modulation. However, the OC-SC scheme does not allow energy harvesting during PL modulation. With OC-MPP modulation, energy harvesting is still possible, albeit at a lower level. If the duty cycle of the modulation signal is set to $D\%$, then the maximum power that could be harvest from the LED array would be $D\%$ of the MPP.

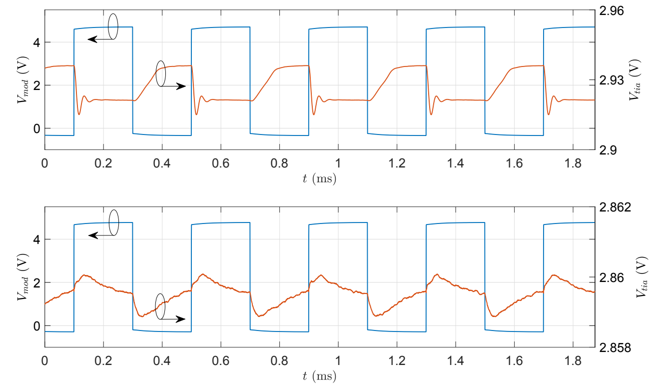

Fig. 8: OC-SC binary modulation of PL without (top) and with (bottom) the water tank.

A final test was carried out to demonstrate the downlink communication direction. To this end, the LED array was loaded with an R_{mpp} resistor and the output power of the high-power LED was modulated with a square wave of 2.5 kHz. The voltage waveform at the positive terminal (LED anodes) of the LED array, V_{led}, is shown in Fig. 9 for the cases when the water tank was not present (top) and when it was present (bottom). Notably, the received signal (V_{led}) has a much larger swing than the received signal in Figs. 7 and 8 indicating that longer communication ranges are possible in the downlink direction than in the uplink direction.

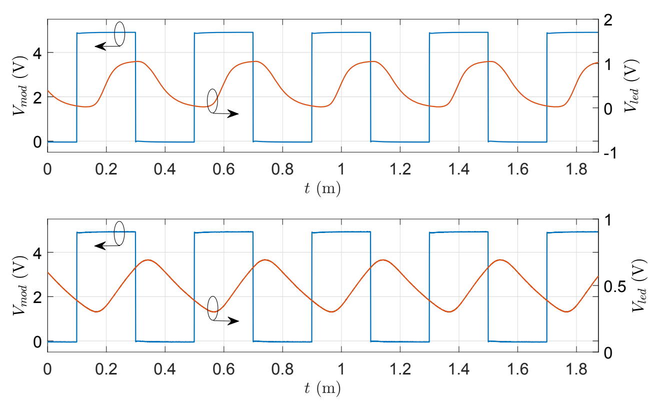

Fig. 9: Modulating and received waveforms for the downlink direction.

IV. Conclusion

An optical wireless communication approach that modulates the photo-luminescent radiation of LEDs has been presented. This approach also allows energy to be harvested by the LEDs. Hence, a fully passive optical communications tag can be realized. Possible applications of this approach include short-range underwater communications. Initial tests suggest that communication speeds of few kbps per second can be achieved.

Acknowledgment

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