ACTA IMEKO
ISSN: 2221-870X
December 2021, Volume 10, Number 4, 80 - 89

LED-to-LED wireless communication between divers

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ABSTRACT
For military divers, having a robust, secure, and undetectable wireless communication system available is a fundamental element. Wireless intercoms using acoustic waves are currently used. These systems, even if reliable, have the defect of being easily identifiable and detectable. Visible light can pass through sea water. Therefore, light can be used to develop short-range wireless communication systems. To realize secure close-range underwater wireless communication, the Underwater Optical Wireless Communication (UOWC) can be a valid alternative to acoustic wireless communication. UOWC is not a new idea, but the problem of the presence of sunlight and the possibility of using near-ultraviolet radiation (near-UV) has not been adequately addressed in the literature yet. In military applications, the possibility of using invisible optical radiation can be of great interest. In this paper, a feasibility study is carried out to demonstrate that UOWC can be performed using near-ultraviolet radiation. The proposed system can be useful for wireless voice communications between military divers as well as amateur divers.

Section: RESEARCH PAPER

Keywords: underwater communication; visible light communications; optical wireless communication, bidirectional communication; LED; photo detector

Citation: Fabio Leccese, Giuseppe Schirripa Spagnolo, LED-to-LED wireless communication between divers, Acta IMEKO, vol. 10, no. 4, article 15, December 2021, identifier: IMEKO-ACTA-10 (2021)-04-15

Section Editor: Francesco Lamonaca, University of Calabria, Italy

Received October 4, 2020; **In final form** December 6, 2021; **Published** December 2021

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1. INTRODUCTION

Currently, the use of wireless communications is very common in a wide range of terrestrial devices. In the underwater world, wireless information transfer is of great interest to the military. It plays an important role in military raids carried out by a team of divers. For safety and to coordinate actions, a secure and reliable bidirectional communication system is useful. Nowadays, underwater wireless communications are implemented almost exclusively via acoustic waves due to their relatively low attenuation [1], [2].

Communication by measuring light waves (Visible Light Communication - VLC) is a technology that employments light spectra from 400 to 700 nm as data carriers. VLC techniques transmit data wirelessly by pulsing visible light. This new technology, called Li-Fi, can replace the Wi-Fi connection, based on radio frequency waves [3]-[6].

Beer's law is usually utilized to correlate the absorption of diffuse light to the properties of the medium through which the light is traveling. From a mathematical point of view, we can write [7], [8]:

$$P(\lambda, r) = P_0 \cdot \mathrm{e}^{-K_\mathrm{d}(\lambda) \cdot r}\,, \tag{1}$$

where P_0 is the initial transmitted power, $P(\lambda, r)$ is the residual power after the light beam with wavelength λ has traveled the distance r through the medium with Diffuse Attenuation Coefficient $K_\mathrm{d}(\lambda)$. Figure 1 shows the attenuation coefficient of three typical ocean waters I, II and III and five coastal waters 1, 3, 5, 7 and 9; the lower numbers correspond to clearer waters. The classification corresponding of Jerlov water types [9]-[11].

Light with longer wavelengths is absorbed more quickly than that with shorter wavelengths. Because of this, the higher energy light with short wavelengths, such as blue-green, is able to penetrate more deeply. In open ocean, below 100 m depth, only blue-green radiation is present [12]. However, the blue component of sunlight can also reach depths of up to 1000 m; although the quantity is so low that photosynthesis is not allowed [12]. Figure 1 shows that the minimal absorption is between 460 nm and 580 nm; depending on the type of water. Therefore, VLC technology is extensively studied as an alternative solution for short range underwater communication links [13]-[28].

Really, underwater optical wireless communication (UOWC) is not a new idea. After the pioneering works of the 1980s [29]-[31], in 2009, Doniec et al. [32] have developed a 5-meter

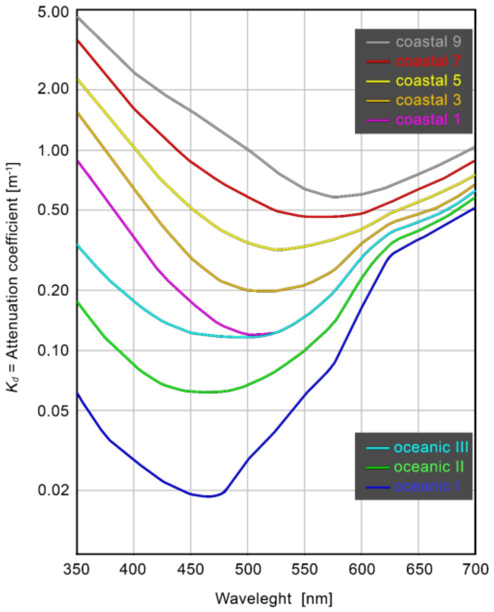

Figure 1. Diffuse attenuation coefficient $K_d(\lambda)$ for several oceanic and coastal water types according Jerlov classification. Curves obtained from the data present in [9]-[11].

underwater wireless optical communication link (called AquaOptical) with a 1 Mbps data rate. Later in 2015, Rust et al. [33] have implemented an UOWC system for use in remote controlled vehicles (ROVs) used for the inspection of nuclear power plants. In addition, some systems are currently commercially available [34]-[37]. Unfortunately, the performance of UOWC is currently limited to short range [38]. However, in some specific situations, short-range communication is more than enough. On the other hand, there are circumstances where short range communication is needed without the need for large bandwidth. A typical example is the communication between divers.

For communication between divers, the most common form is through hand signals [39], and underwater writing slates [40], [41]. Figure 2 shows two example of standard diver hand signals and a dive slate.

The dialect of the diver's hand signals includes only plain and precise gestures easily identifiable. This allows only simple communications and require extensive memorization. On the

Figure 2. Examples of Standard Diver Hand Signals and of a Dive Slate.

Figure 3. Examples of Standard Diver Hand Signals and of a Dive Slate.

other hand, slates do not allow communication in real time; it takes time to write and to attract the attention of the underwater partners.

Recently, full face diving masks with snorkels have been introduced that allow the diver to breathe and speak normally inside the mask [42], [43]. For this type of masks, reliable underwater intercoms have been developed to allow divers to talk each other underwater [44], [45]. A transducer is attached to the diver's face mask. This transducer converts the voice into an ultrasonic signal. Each diver of the team has an ultrasonic receiver, which accepts the signal and converts it back to a sound that the divers can hear, enabling communication. This type of communication system can be used by amateur or professional divers. Figure 3 shows two commercially available systems of underwater intercoms.

During military raids with divers, it is very important that the various components of the command can communicate with each other. Unluckily, hand signs do not allow for complex information to be communicated, and the use of dive slate can be incompatible with the times. An audio communication is essential for complex communications needed in military actions.

Another key problem in military communications is that they must be secure and undetectable. Unfortunately, the acoustic waves that travel in water are easily detectable. Therefore, their use is not convenient during critical military missions. In this scenario, UOWC is a good alternative to acoustic communication [46]. It has the advantage that it cannot be intercepted. This specific application does not require long range and high band communications. Therefore, the usable systems can be simple, small, lightweight and with low power. Figure 4 shows a typical UOWC between divers. The information could be transmitted through a special torch and be captured by sensors positioned on the diving suit.

Unfortunately, communications with visible light suffer from noise generated by solar background noise or artificial light sources. Special precautions must be taken to minimize this noise [47]. It would be convenient to implement UOWC systems that use optical radiation different from that normal present in water.

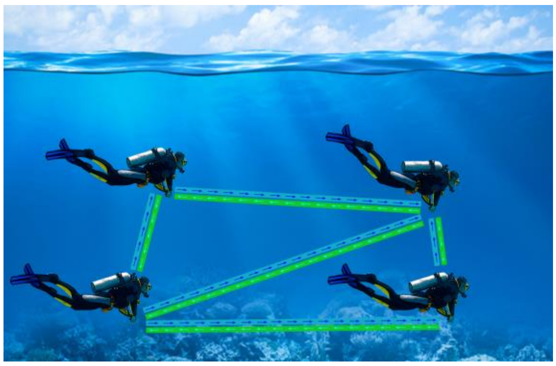

Figure 4. Optical communication between divers.

In addition, during communications between the military divers it would be useful to use light not visible from normal video surveillance systems.

The main purpose of the paper is to verify the feasibility of a communication system that can be used by the military divers. The system must be simple, robust, consuming few energy and not affected by ambient light, and, above all, difficult to detect and/or intercept by video surveillance systems sensitive to visible radiation. To obtain these performances it is necessary to avoid the use of blue-green radiation, present in the solar radiation that penetrates into the water. In addition, visible radiation must be avoided, which is easily detectable at night by underwater video surveillance systems.

In this paper, an underwater near-ultraviolet light communication is proposed. The proposed system uses as emitter (Tx) an UV LED with peak wavelength λ = 385 nm and half width $\Delta\lambda$ = 15 nm. Instead, a photodiode, made with an LED like the one used as a transmitter, is used as a receiver (Rx). This system is intrinsically low sensitive to ambient light and produces an invisible communication channel. Since there are video surveillance systems that have good sensitivity in the blue-green spectral band [48], the use of radiation in the near UV allows having a relatively good penetration of the radiation into the water and at the same time to be invisible to these video surveillance systems.

The system works well in short range communications where large bandwidth is not required. For example, if we are only interested to speech transmission, a bandwidth of 32 kbps is generally acceptable. With this type of communication, it is possible to create simple, small, light, robust and energy efficient systems.

2. UNDERWATER COMMUNICATIONS BY UV-A RADIATION

A part of the solar radiation spectrum overlaps with the radiation commonly used for the Visible Light Communication (VLC) [49]. Therefore, it is very difficult to attenuate the effects of sunlight without loss of useful signal. In the presence of sunlight, the receivers see very high white noise and can often go into saturation. To try to solve the problems deriving from solar radiation (in general of the ambient lights present), it is possible to use near-ultraviolet radiation for the communication channel.

Generally, solar intensity decreases with depth. By examining how light is absorbed in water (see Figure 1), we see that the best wavelengths to use in UOWC are 450 nm – 500 nm for clear waters and 570 nm – 600 nm for coastal waters. This same attenuation is also true for the solar spectrum [50]. In any case, at a depth of a few meters, the solar radiation in the near ultraviolet is practically absent. Furthermore, in relatively clear waters this radiation is relatively poorly attenuated especially in ocean waters but less in coastal waters (according to Figure 1). For these reasons, submarine communication systems, which use UV-A band communication channels, are extremely interesting.

We must also observe two other important characteristics of optical communication that uses the near ultraviolet. This communication channel is difficult to detect and intercept, particularly attractive feature for military applications. Furthermore, the use of ultraviolet radiation allows wireless connections to be made without requiring perfect alignment between transmitter and receiver (NLOS UV scattering communication) [51], [52]. Very useful characteristic for wireless transmission between moving objects.

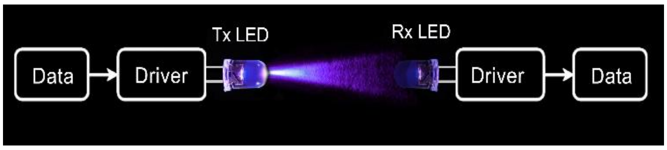

Figure 5. Basic LED used as light emitter and receiver.

3. LED USABLE AS LIGHT DETECTOR

In addition to emitting light, LEDs can be employed also as light sensor/detector [53]-[60]. Figure 5 schematically, shows this application In addition, the LED can also be used as a temperature sensor [61].

To verify the possibility of underwater communication through UV radiation, we have chosen to use a reverse-polarized LED as a detector. The choice was made to have an inexpensive photodetector that is not very sensitive to the light radiations present in the environment; without the need for filters that cut visible radiation. LED can be also used as Avalanche PhotoDiode (APD) [62], [63].

Unlike normal photodiodes, LEDs can detect a narrow band of wavelengths, they are spectrally selective detectors. In contrast, normal photodiodes have a wide spectral response and require costly filters to detect a specific wavelength. Both LEDs and photodiodes have sensitivity stable over time. However, the filters have a limited life.

In a p-n diode, inside the junction, there are free charges generated by thermal energy. When a p-n junction diode is reverse biased, these charges are accelerated. This movement of charges produces the reverse current of the diode. If the reverse polarization potential is increased, the free charges can acquire enough energy to ionize some atoms of the crystal lattice. This ionization produces additional free charges. Moreover, these additional charges are accelerated by the polarization potential. This creates an avalanche effect, producing a large reverse current (breakdown current). The polarization voltage at which this arises is called Zener potential [64].

If you want to use an LED as light detector, generally, the photocurrents generated are linear but very small. In UOWC applications, we have currents in the range of nano amps. Therefore, for their correct subsequent signal processing, it is necessary to transform the detect current into a suitable voltage. For this operation, transimpedance amplifiers are commonly used [65]. The amplitude of the signal received by the LED, and subsequently amplified by transimpedance amplifiers, depends on many external parameters. For this reason, the transmitted optical signal must be suitably digitized and modulated. Our system uses a modulation format based on pulse width modulation (PWM).

4. UV LED-TO-LED COMMUNICATION SYSTEM

In underwater optical wireless transmission, the signal reaching the receiver has low intensity. For this reason, extensive studies are underway to use very sensitive detectors such as Avalanche PhotoDiode (APD) or Single Photon Avalanche Diode [66]-[75]. With the use of very responsive photosensors, the problem of the presence of ambient light is very important [76].

With the use of a LED-to-LED transmission system that uses UV LEDs, it is possible to implement an underwater

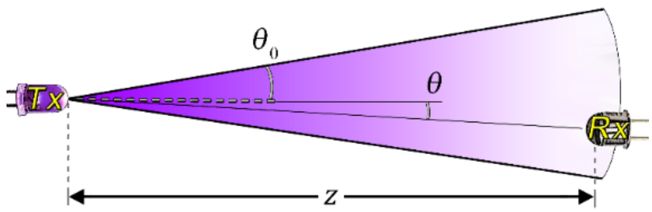

Figure 6. Seawater light transmission model.

communication system with invisible radiation that is not very sensitive to ambient light.

LED-to-LED communication systems are characterized by low cost, low complexity and, above all, low energy consumption. On the other hand, they can be used only when the exchange of messages occurs at a small distance without the need for large bandwidth [76], [77].

As already mentioned, underwater, practically, ultraviolet radiation is absent. Therefore, using UV LED as light emitter and a UV LED, used as APD, as receiver allows to have a system that is not very sensitive to environment light; an LED can detect radiation with a wavelength slightly shorter than or equal to that emitted (Internal photoelectric effect) [56], [57], [78].

The same type of LED can be used as a receiver and as a transmitter. The use of the same type of LED is useful in half duplex communication systems; the same LED can be used as a transmitter or as a receiver. In this work, we have used a Bivar UV5TZ-385-30 LED as a transmitter and receiver [79]. This LED has viewing angle of 30° and an aperture area of $25 \cdot 10^{-6}$ m².

Seawater light transmission model is shown in Figure 6.
The optical power on the receiver can be written as [80]-[83]:

$$P_{\mathrm{Rx}} = P_{\mathrm{Tx}} \cdot \eta_{\mathrm{Tx}} \cdot \eta_{Rx} \cdot \exp\left[-\frac{K_{\mathrm{d}}(\lambda) \cdot z}{\cos\theta}\right] \cdot \frac{A_{\mathrm{R_x}} \cdot \cos\theta}{2\pi \cdot z^2 (1 - \cos\theta_0)}, \quad (2)$$

where P_{Tx} is the transmitted power, η_{Tx} and η_{Rx} are the optical efficiencies of the Tx and Rx correspondingly, $K_{\mathrm{d}}(\lambda)$ is the attenuation coefficient, z is the perpendicular distance between the Tx plane and the Rx plane, θ_0 is the Tx beam divergence angle, θ is the angle between the perpendicular to the Rx plane and the Tx- Rx trajectory, and $A_{\mathrm{R_x}}$ is the receiver aperture area.

In our system, they experimentally verified that the received signal is correctly reconstructed if the misalignment is $\theta < 20°$.

The transmitter LED was driven with 25 mA by means of a pulse generator. While the current generated by the LED used as a receiver, reverse biased with a voltage of 15 V, was read through a transimpedance amplifier. Two Ultralow Noise Precision High Speed Op Amps [84] were used to implement the transimpedance amplifier. The amplifier, as shown in Figure 7, is made in two states. This is to be able to obtain a passband greater than 100 kHz.

The Rx and Tx LEDs, together with the relative control electronics, were inserted in a tank filled with real seawater (water taken from the Tyrrhenian coast - Anzio - Italy). The LEDs are placed at 50 cm and facing one towards the other.

Figure 8 shows the experimental setup used for the tests. The experimental tests were carried out in the laboratory and outdoors in different configurations of ambient brightness. Figure 8(a) shows the system working in laboratory. Figure 8(b) shows the system working outdoors in full sun. All the tests carried out confirmed that the system is practically insensitive to ambient light (both artificial and natural).

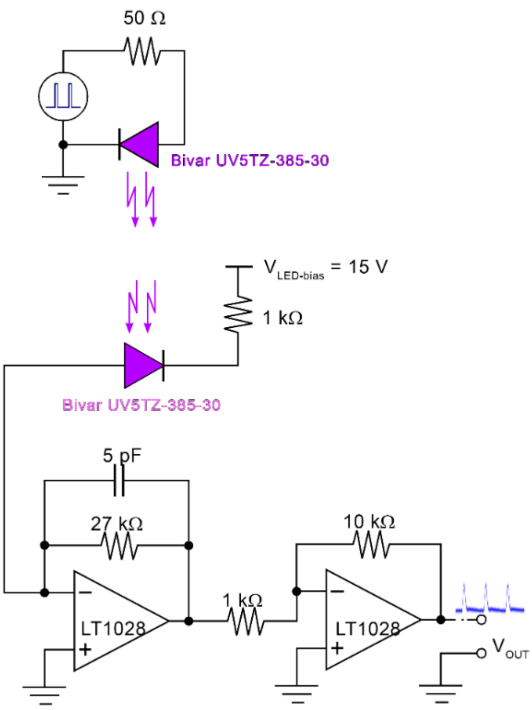

Figure 7. Rx and Tx LED driver circuit.

The experimental setup is realized to be able to obtain three different lengths of the optical channel. The different lengths of the optical path are obtained by means of mirrors, as shown in Figure 9.

The Figure 10 show the signal used to drive the Tx LED (cyan trace) and the corresponding output signal (V_{out}) from the Rx circuit (yellow trace).

The implemented system uses only one LED as a transmitter and another as a receiver. In our application, there are no restrictions on using a LED cluster to transmit information. As well as it can be useful to use LED array to receive the signal. By using many diodes as Tx, as well as Rx, systems with better performance can be obtained. We used the simplest possible configuration as the aim was to demonstrate the possibility of

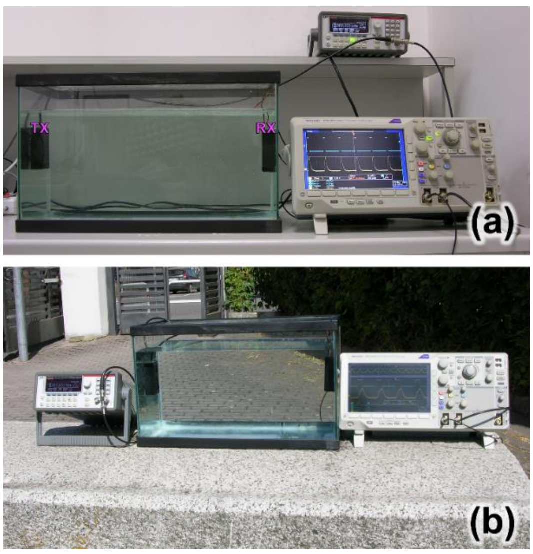

Figure 8. Experimental setup used for the tests: (a) system working in laboratory; (b) system working outdoors.

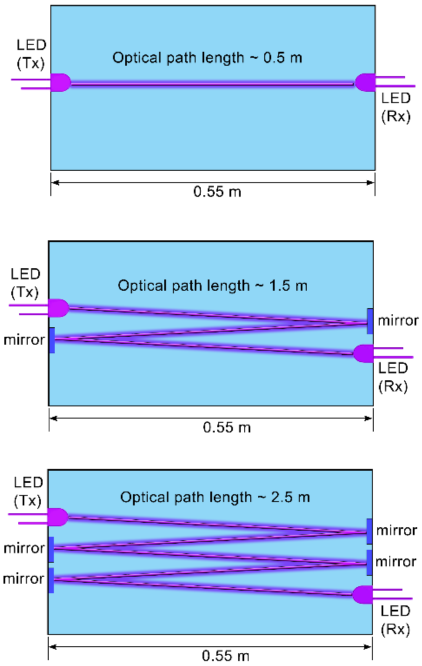

Figure 9. Schematic of the water canal. The different optical path is obtained with the help of mirrors.

implementing an underwater LED-to-LED transmission using near ultraviolet radiation.

5. SYSTEM DESCRIPTION

In any reliable communication system, data must be suitably modulated. Modulation consists in varying one or more properties of a relatively high frequency signal (carrier).

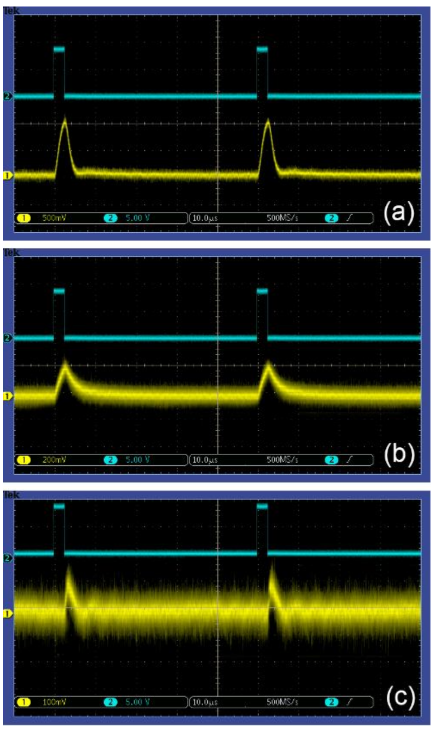

Figure 10. The cyan line represents the signal used to drive the Tx LED. The yellow line represents the corresponding Rx output signal. (a) Distance between transmitter and receiver 0.5 m. (b) Distance between transmitter and receiver 1.5 m. (c) Distance between transmitter and receiver 2.5 m.

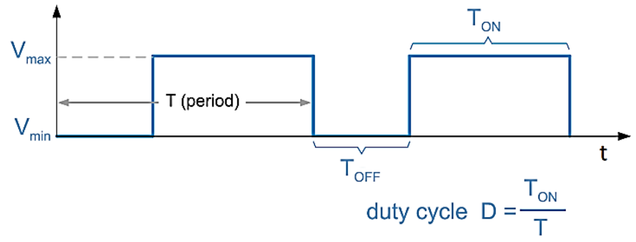

Figure 11. PWM signal. Square wave with constant frequency and amplitude by variable duty cycle.

We used PWM modulation to implement our system. Furthermore, considering that high sound quality is not required for audio communication between divers, this type of modulation is more than enough to test the feasibility of wireless audio communication via UV-A optical channel. Obviously, more performing, and more robust modulation systems with respect to noise can be used.

The PWM consists of the information signal (in our case the audio signal) that causes the modification of the time duration of the pulse carrier. This pulse signal turns the transmitter LED on and off at the rate of the carrier's frequency. In other word, with PWM technique we change the duty cycle of a square wave with constant frequency and amplitude; as shown in Figure 11.

The average value of a PWM signal, period by period, can be expressed as:

$$V_{\text{average}} = \frac{1}{T}\left(\int_{0}^{D\cdot T} V_{\max} \cdot dt + \int_{D\cdot T}^{T} V_{\min} \cdot dt \right). \quad (3)$$

If $V_{\min} = 0$, the Equation (3), can be simplified as:

$$V_{\text{average}} = D \cdot V_{\max} \,. \quad (4)$$

Equation (4) indicates that if the amplitude of the carrier is constant (along a period), the average value of the PWM signal is directly proportional to the duty cycle. If the duty cycle is proportional to the information to be transmitted, it can be extracted through a simple averaging operation on the PWM signal. Average is easily obtainable through opportune low pass filtering.

To verify the real possibility of realizing an audio communication, we have respectively coupled a modulator and a demodulator to the LED transmitter and to the LED receiver [85]-[87].

The block diagram of our audio modulator and LED driver is shown in Figure 12. This LED driver has a restricted baud rate. The main reason is the limited switching speed of silicon devices. A maximum data rate of 100 kbps can be achieved with this driver. In any case, this speed of data transmission is more than enough to implement an excellent audio connection. The PWM is achieved by means of a timing circuits NE555 [88] and a comparator LT1011 [89]. Our circuit is powered with 6.5 V and produces a sawtooth waveform with frequency of approximately 100 kHz and peak to peak voltage about 4.3 V.

The sawtooth waveform is applied to the non-inverting input of the comparator. The audio signal works as the reference voltage and is applied to the inverting input. To realize a duty cycle of 50%, the audio signal is offset at the average voltage of the sawtooth waveform (1/3 of the power supply voltage). The comparator output is equal to the supply voltage when the sawtooth output is a higher voltage than the audio signal.

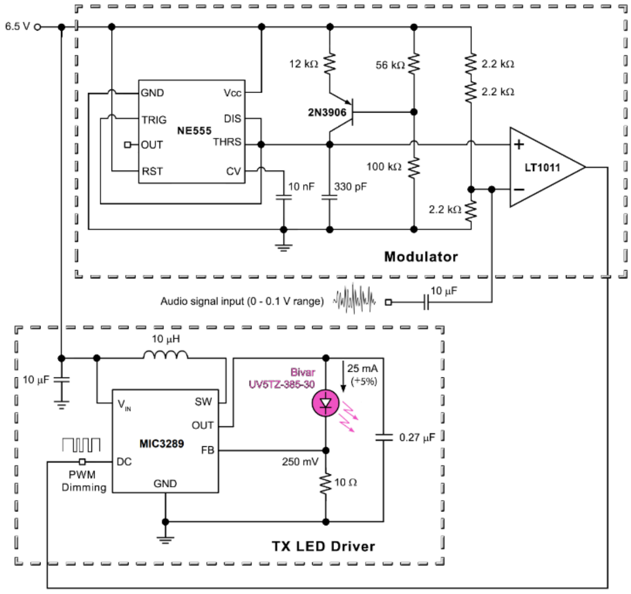

Figure 12. Audio modulator and LED driver.

The LED driver is based on the integrated MIC3289 [90]. It is a PWM boost-switching regulator that is optimized for constant-current LED driver applications. Figure 16 shows the input and output signals in a Pulse Width Modulation process.

To recover the transmitted audio, a receiver unit, mainly composed of photodetector and signal conditioning devices, is used. The photodiode receives the transmitted optical signal and converts the optical signals into the electrical signals. Then, the electrical signal is fed into the recovery circuits and PWM demodulator. Figure 14 shows the block diagram of the receiver unit.

The transimpedance amplifier (shown in the Figure 7) is coupled with a low pass filter. This filter, with cut-off frequency about 1 MHz, uses to reduce the high frequency noise present at the transimpedance amplifier output. The output signal of filter has an amplitude that depends on many external parameters, as well as the distance and misalignment between transmitter and receiver. To obtain a correct reconstruction of the PWM signal, a comparator with variable threshold is used. By means of an integrator circuit, a voltage proportional to the average value of the amplitude of the received signal is obtained. This voltage is used as the threshold of the comparator. The integrator that was used provides an average signal at the output, which is about one third of the amplitude of the signal coming from the filter. In this way, the reconstruction of the PWM signal is obtained which is practically independent of the amplitude of the signal received by the LED used as photodiode. Finally, the reconstructed PWM

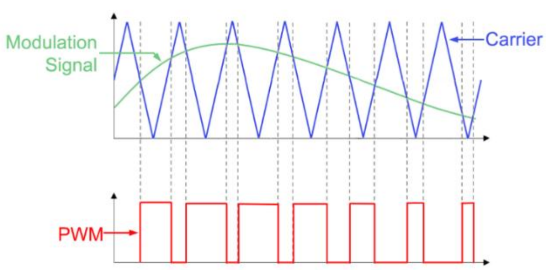

Figure 13. Input and output signals in a Pulse Width Modulation process.

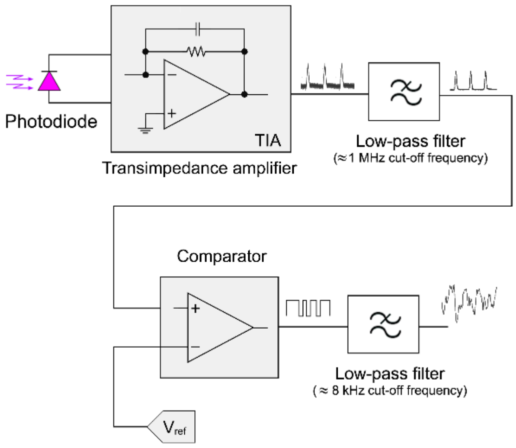

Figure 14. Input and output signals in a Pulse Width Modulation process.

signal (signal with constant amplitude and variable duty cycle) is demodulate by a low pass filter with a cutoff frequency of 8 kHz.

Instead, Figure 15 shows the schematic drawing of the receiving unit.

A low pass filter is sufficient to decode the audio information contained in the PWM signal. By choosing a low-pass filter with an appropriate cut-off frequency, it will be possible to remove the high-frequency component in the PWM signal while keeping only the low-frequency signal (the audio information). Our demodulator is a 4th order Butterworth low pass filter. It consists of two non-identical 2nd order low pass filter. The human ear can perceive sounds with frequencies between 20 Hz and 20 kHz. In any case, the human voice produces sound that are confined to within 8 kHz. Therefore, for verbal communications, a low-pass filter with a cut-off frequency around 8 kHz is sufficient.

The 4th order Butterworth filter we use has a cutoff frequency of approximately 7.8 kHz. Therefore, it is irrelevant for all the sound frequencies emitted by the human voice. On the other hand, at 100 kHz, the filter has an attenuation of 83 dB. This

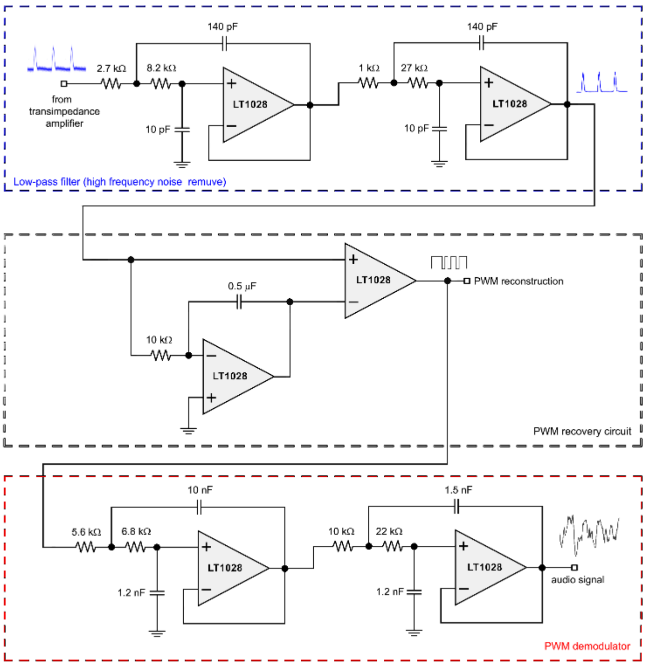

Figure 15. Schematic of the optical receiver circuit.

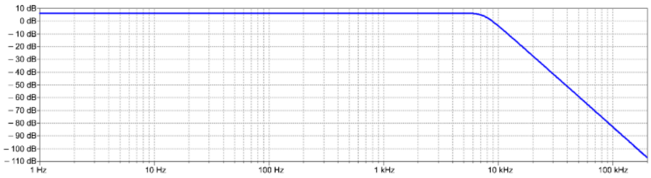

Figure 16. Our 4th order Butterworth Low pass filter frequency response.

indicates that the high frequency carrier is highly suppressed. Figure 16 shows the frequency response of the filter used to retrieve the audio information from the PWM signal

Preliminary tests were conducted to verify the real applicability of our system in underwater wireless voice transmission.

First, a 4 kHz tone was used to check the entire modulation, optical transmission, optical detection, and demodulation system. In Figure 17(a) trace 1 (yellow) is the sinusoidal 4 kHz tone going into the transmitter. While trace 2 (blue) shows the PWM modulation used to drive the Tx LED current. In Figure 17(b) trace 2 (blue) shows the reconstructed PWM signal in the receiving unit. Finally, trace (1) (yellow) of Figure 17(b) shows the reconstruction of the sinusoid at 4 kHz.

The reconstruction of the sinusoid is more than acceptable, even if there is the presence of "noise", related to the harmonics of the carrier signal.

Subsequently, the system was tested by transmitting an audio speech signal. With 2.5 m between Tx and Rx the speech transmitted is perfectly understandable. Figure 18 shows the audio tracks, spectrograms, and frequency analysis of the transmitted audio signal and of the message reconstructed downstream of the receiver.

6. CONCLUSIONS

Underwater Optical Wireless Communication (UOWC) has recently emerged as a unique opportunity. Many studies are present in the literature, however underwater optical communication via near-ultraviolet (UV-A) radiation is not addressed. In this paper, we have shown that in short range when broadband communication is not needed, it is possible to implement a UOWC system that makes use of UV-a radiation. A UV underwater optical wireless audio transceiver was proposed for wireless communication in close range between divers.

We have also verified that this system can be realized via an LED-LED connection. This makes the system simple, economical, light, compact and, above all, not energy-intensive.

The study is mainly designed for military applications. In military applications, it is very important to have systems that cannot be intercepted and possibly not easily identifiable. In addition to have low energy consuming systems. For these reasons, we have developed a system that uses non-visible optical radiation and LED-to-LED transmission, which is energy efficient.

However, considering the simplicity and cost-effectiveness of the developed system, it can easily be used for communications between amateur divers.

In our study, we faced the problem of verifying the feasibility of transmitting a signal, with sufficient bandwidth to transmit an audio signal, at a distance of about 2.5/3 meters. Further studies and tests in the real marine environment are needed.

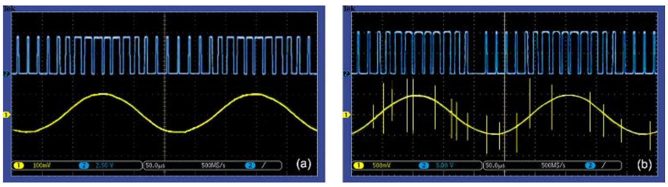

Figure 17. (a) Pulse-width Modulation Waveform. Trace yellow: tone of 4 kHz; trace blue relative PWM modulation. (b) Trace blue: PWM signal recovered in the Rx unit; trace yellow 4 kHz tone present at Rx output.

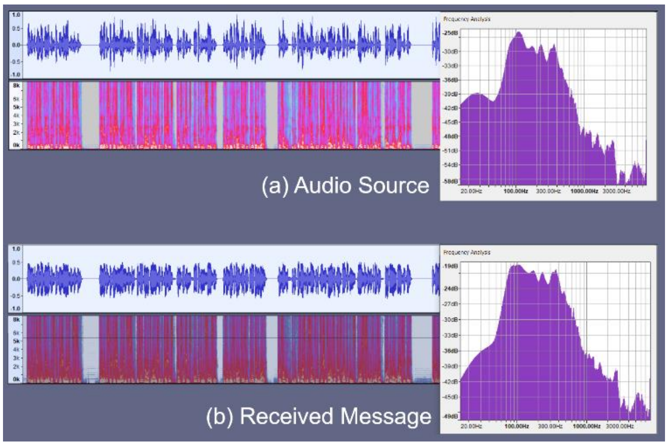

Figure 18. (a) audio track, spectrograms, and frequency analysis of the transmitted audio. (b) audio track, spectrograms, and frequency analysis of the of the retrieved audio signal. Figures obtained by Audacity® software [91].

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