Design of a Visible Light Communication System for Deep Sea Divers Based on Analogue Frequency Modulation

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***Abstract*— This paper presents the design, development and test of an underwater visible light communication system for the deep sea divers. To achieve a practical communication range, frequency modulation technique has been utilized to modulate the voice signal which is eventually transmitted using visible light. Blue and green light emitting diodes have been chosen to design a full duplex system for simultaneous communication. The proposed system achieved a bidirectional communication range of approximately 3.5 m using off-the-shelf components and without using any optical concentrator**.

Keywords—visible light, underwater communications, frequency modulation, divers communication

I. Introduction

During the last few decades, visible light communication (VLC) has got plenty of attention by researchers as a complementary technique to the traditional communication systems such as radio frequency (RF) and acoustic systems [1]–[4]. The main reason behind this is the development of low cost light-emitting diodes (LEDs) and also the need for having high-speed real-time communication system for short range applications. Underwater communication using visible light is considered to be one of the potential applications because of the low attenuation of light in water [5]. Some of the common scenarios where VLC can be used in the underwater environment are sensor networks, high speed communications for uploading data from a sensor node to an Autonomous Underwater Vehicle (AUV), real time video transmission and divers communications. A number of high speed underwater VLC communication systems has been reported in [2], [6], [7]. Marek *et al.* demonstrated 1.2 Mbps communication link which reaches a communication range of 30 m using external lenses [7]. More recently, a test result of 6.25 Mbps communication for the range of 2.5 m has been reported which utilizes Manchester coding techniques [2]. To measure the water pollution a prototype is developed using three different colored LEDs [8]. A laser based video transmission system is demonstrated to upload video from a transmitter node to Unmanned Underwater Vehicle (UUV) [9].

Currently, acoustic system is the dominant and mature technology for long distance underwater communication which supports a limited data rate. Time-varying multipath propagation and the low speed of sound in underwater produce a very poor and high latency communication channel, which cannot support real time data transfer such as audio. In case of a short range and real-time communication such as divers communication, visible light can be a handy alternative to the acoustic carrier. Moreover, the VLC system can be used for underwater lighting besides communication purposes.

Until recently, divers used to communicate with each other using the sign language which is not convenient in nature. RF does not propagate well underwater and acoustic system suffers from delay and is not cost efficient. As a result, visible light based communication system could play a vital role, especially for divers communication.

Most of the underwater VLC research focuses on digital modulation techniques such as On-Off keying (OOK), pulse position modulation (PPM) for a reliable communication system [10]. As a communication medium, underwater is very harsh and complex environment, so amplitude based modulation techniques are susceptible to intensity variation due to scattering and other effects. As a result, authors have proposed the analogue frequency modulation (FM) technique for the underwater VLC system to maximize the communication distance between two divers. There are some demonstrations of FM based underwater VLC system which achieved a communication range of 50 cm that is not a realistic range for many applications [11]. Recently, FM based underwater communication system is developed and tested for a specific scenario in Zamani village of Japan [1]. The system was developed for divers communication, and for testing purpose, a copper wire is connected to the VLC transmitter. It is reported that VLC based communication system can play a vital role to increase the tourism in the region.

In this paper, we studied an FM based underwater VLC system. FM transmitter and receiver are built using off the shelf components. The proposed system in this paper achieved a communication distance of 3.5 m in free space which is estimated to be 2.7 m in a harsh underwater environment.

The paper is organized as follows. Section II describes the detailed system design procedure, including the transmitter and receiver modules. Section III presents the specifications of each component used and section IV detailed the testing and experimental results of the proposed system. Finally, in section V, the conclusion is provided.

II. System Design

The block diagram of the designed full-duplex underwater audio system is shown in Fig. 1. Two transceivers are pointed

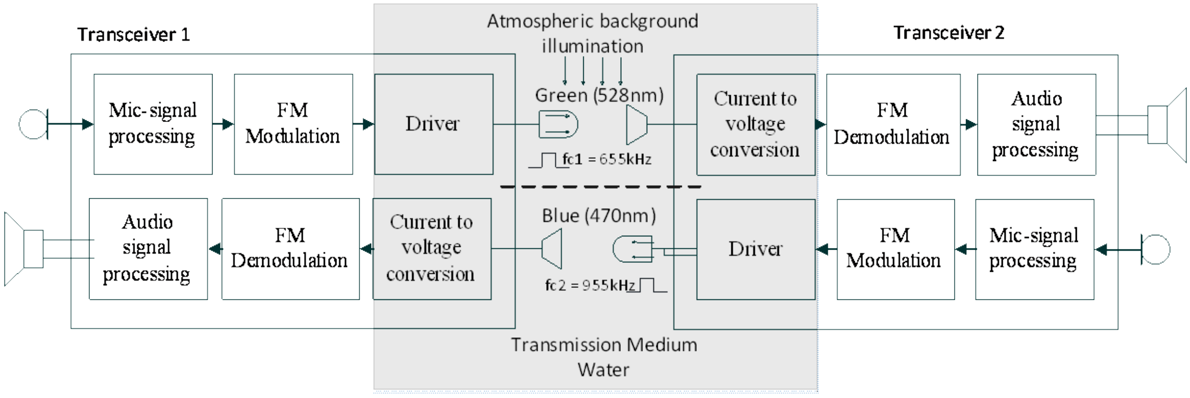

Fig. 1 Block diagram of the propsoed system.

to each other to carry out the voice signals of two divers. For the demonstration purpose, the audio signal is generated using a microphone. In order to improve the signal quality, a signal processing unit, described in the following section, is used to reshape the signal. Afterward, the enhanced audio signal is modulated in the modulation block where an analogue frequency modulator is used. Finally, the modulated signal is transmitted using the LED. In the receiver side, a photodetector receives the light which is then converted to voltage by a current-to-voltage converter. An FM demodulation unit followed by an audio signal processing unit is built to demodulate the signal. Eventually, the signal is passed through the speaker for demonstration purpose. Since the light source and the photodetector are placed on the same device, the photodetector should be able to suppress the wavelengths of its own transmitting LED. Otherwise, the preamplifier of the front-end circuit may reach the saturation stage from its own light.

A. *Transmitter*

The block diagram of the transmitter is shown in Fig. 2. The signal processing unit is composed of the first five blocks. The relevant voice frequency between 0.3 and 3.4 kHz is being amplified, and a pre-emphasis is designed to limit the signal if necessary. The pre-emphasis leads to a rise in the frequencies with 6 dB/Octave from 0.5 to 3.5 kHz. An OPA347 amplifier provides an impedance conversion with variable amplification. The limiting stage limits the signal to ±0.7 V in order to have a limited frequency deviation of the voltage controlled oscillator (VCO). A second order, inverting Butterworth low pass filter (LPF) is designed to suppress all frequencies higher than 3.4 kHz before the signal is passing through to FM stage.

The FM is achieved through the internal VCO of the phase lock loop (PLL) component CD74HCT4046. Since the VCO with the external components such as capacitors, resistors is affected by temperature, a control loop is used to stabilize the carrier frequency. The reference frequency, which is provided by an accurate resonator and a frequency divider, is compared with the divided carrier frequency by the phase detector (PD). The PD adjusts the output carrier frequency to the desired frequency.

The final block of the transmitter circuit is the LED driver. The current through the LED is limited to 350 mA which is accomplished by using a FET (FDN359BN). The switching frequency of this FET is sufficient to support high current. The gate of the FET is driven by the VCO output and the maximal output source or sink current is specified as ± 25 mA. Osram (Black Series, LB H9GP-FZGY-35 & LT H9GP-JZKZ-26-1-350-Z) LEDs are chosen as light sources. Both of the LEDs provide very high intensity (10-50 cd) and comply with the eye safety regulations.

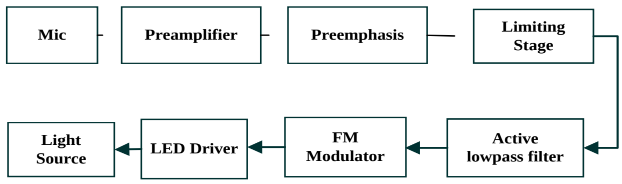

Fig. 2. A transmitter block diagram

B. *Receiver*

The receiver is designed based on the concept of a superheterodyne receiver with a local oscillator as shown in Fig. 3. For the front-end VLC receiver, a transimpedance based circuit is preferred which is implemented using an OPA380 amplifier. The Everlight CLS15-22C photodiode is chosen as a light receiver which has peak sensitivity in the visible light region. The output signal of the transimpedance amplifier is filtered by a bandpass filter. To produce an intermediate frequency (IF), SA602A is used which has 18 dB gain. The local oscillator (LO) frequency is provided by a clock source.

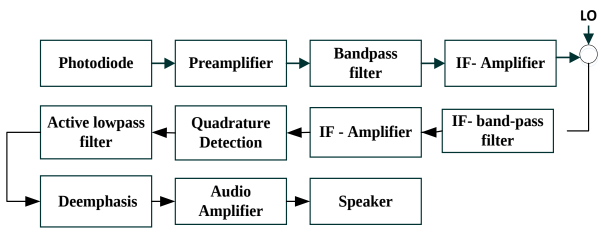

Fig. 3. Receiver block diagram

For the amplification and demodulation of IF signal, SA604AD is used. It consists of two amplifiers to limit the signal and also has a quadrature detector. Furthermore, it provides a signal strength indicator and supports a muting functionality. The mixed signal output from the mixer is filtered by the ceramic filter CFUKF455KA2X-R0 manufactured by Murata. The SA604AD is configured to provide the 90° phase shift of the IF signal for the blue light receiver which is necessary for the quadrature demodulator to recreate the audio signal.

Finally, the signal processing stage of the audio output signal is done. The bandwidth is limited to 0.3 - 3.4 kHz, and de-emphasis is applied before the signal is amplified to drive the speaker.

III. System Specifications

The specifications of the designed system are provided in Table I. Two transceivers are designed using blue and green LEDs with two different carrier frequencies to transmit the audio signal. Transceiver 1 which uses green LED modulates the signal using a 655 kHz carrier signal, whereas transceiver 2 uses blue LED with a carrier frequency of 955 kHz. The IF for both cases is 455 kHz. Green and blue LEDs have been chosen because their attenuation coefficients are less compared to other colors [12].

The picture of the transceiver is shown in Fig. 4. As can be seen, a metal plate is used to separate the transmitter and receiver to avoid the self-coupling of light within the same module.

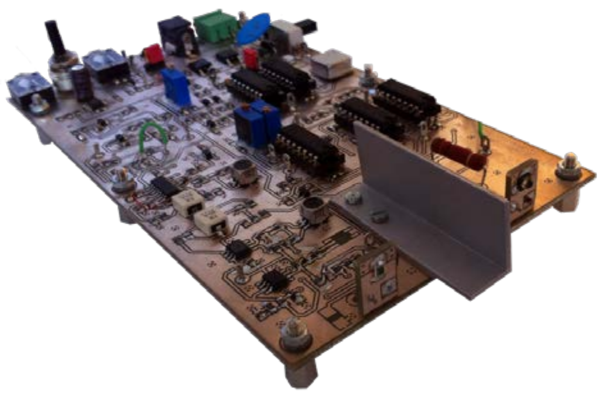

Fig. 4. Picture of the built transceiver.

IV. Testing And Results

Different functional block tests were carried out to measure the performance of each block and to adjust the variable coils of the filters, Q-load of the quadrature demodulator and the output frequencies of the transmitter. The functional test results were analyzed and improvements were made as required. The initial test was done in the laboratory environment and later on some outdoor experiments were performed to measure the performance of the system. The experimental setup for indoor and outdoor is shown in Fig. 5. The following section reports the results of the system test.

TABLE I. Specifications of the Proposed System

	Transceiver 1	**Transceiver 2**
Dominant wavelength	528 nm (Green)	470 nm (Blue)
Luminous flux LED	61-112 lm (Green)	15-24 lm (Blue)
Photodiode Peak sensitivity	470 nm (Blue)	550 nm (Green)
Vin	7.64 V (typ.)	
LED current	350 mA (pulsed)	
Transmitting frequency	655 kHz	955 kHz
Receiving frequency	955 kHz	655 kHz
Intermediate frequency	455 kHz	
LO frequency	500 kHz	200 kHz
Information signal	300 Hz – 3.4 kHz	
Frequency deviation	10 kHz	
Modulation index	2.857	
Bandwidth	27 kHz	
Frequency stability	2 kHz	
Audio output impedance	32 Ohm	

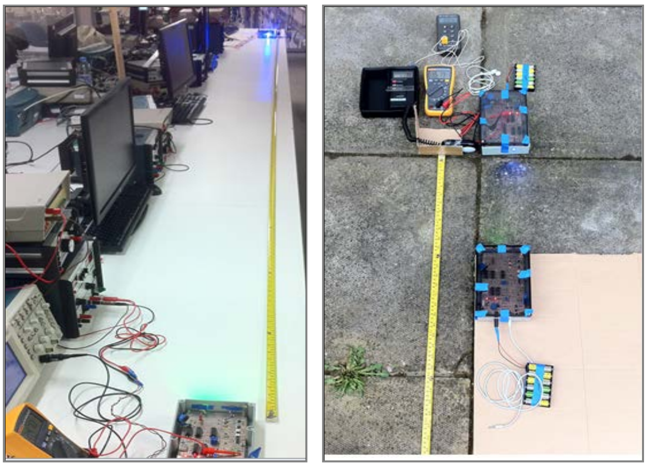

Fig. 5. Experimental setup

A. *Temparature dependency of the system*

The temperature dependency phenomena are very important to the underwater environment because temperature varies significantly in different water environments. At the end of the function tests, the high temperature-dependency of the circuit was noticed. The main problem was the temperature-dependency of the internal VCO of the PLL component, CD74HCT4046A. To overcome the problem a control loop with a reference frequency was designed to regulate the frequency drift caused by the temperature. The temperature dependency of the built system is shown in Fig. 6.

It is clear that the voltage in the feedback path of the original circuit changes approximately by 0.5V/°C. Hence, the system was only working in a temperature range of 23 – 32°C. For higher or lower temperatures, the feedback path forced the additional network to limit the voltage between 0 V and 5 V resulting in terminating the audio signal transmission. The designed circuit is then improved to have a new temperature range of <16°C to 38°C.

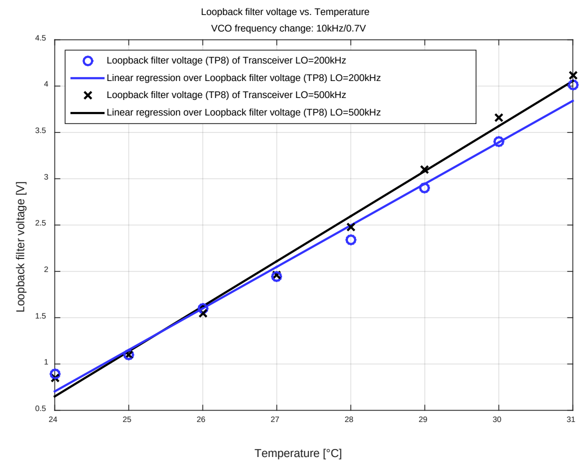

Fig. 6. Temperature dependency of the system

B. *Received signal strength vs. communication distance*

The received signal strength of the SA604A is measured as a function of the distance. The received signal strength indicator (RSSI) voltage decreases when the received signal strength decreases, hence noisier audio signal appeared at the speaker. The measurements are made in different environments and the results are shown in Fig. 7.

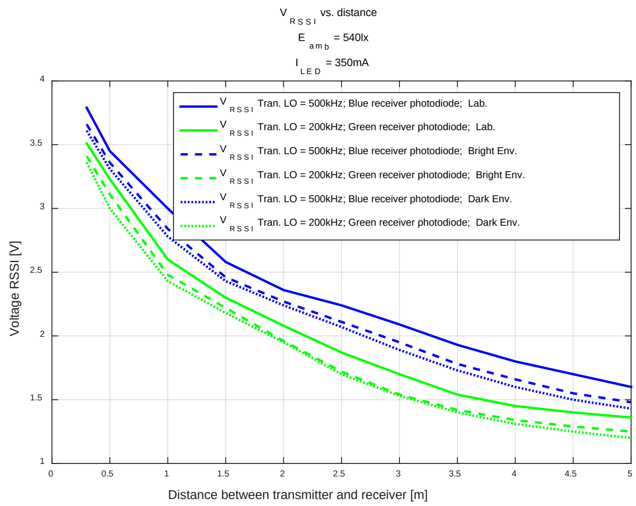

Fig. 7. Received signal strength in different distance

A good quality audio signal is received up to 3.5 m distance, which corresponds to RSSI voltage of 1.7 V for the blue channel and 1.4 V for the green channel (in a dark environment). In bright environments, the RSSI voltage increases because of higher shot noise which is generated in the photodiode. In the laboratory, higher RSSI voltage can be caused by higher noise levels and/or by reflections of the transmitted light. Moreover, for further distances (i.e., >5m) the noise power at the input of the SA604AD is extremely high. The noise level consists of the shot noise (caused by the dark and light current in the photodetector), the thermal noise and the amplifier noise.

C. *Underwater range estimation*

An estimation of the range for underwater communication is calculated using (1)

$$P_{r(\mathrm{UW})}(\lambda) = P_{t\,(\mathrm{FS})}\mathrm{e}^{-k(\lambda)d} \quad (1)$$

where $P_{r(\mathrm{UW})}$ is the received power in underwater link, $P_{t\,(\mathrm{FS})}$ is the received power in free space, $k(\lambda)$ is the attenuation coefficient and *d* is the communication distance.

It was observed that an V_{RSSI} of 1.7 V represents a good speech quality in the receiver side. This V_{RSSI} value is measured at distance of 3.5 m in free space.

Fig. 8 shows the received radiated power for different water turgidities (*k*) as a function of the link distance. It is apparent that the distance of 2.7 m is achieved when the radiated power is -48.5 dBm and water turbidity is 0.2. The link range can be further increased by limiting the transmitter divergence and providing optical gain at the receiver using an optical system.

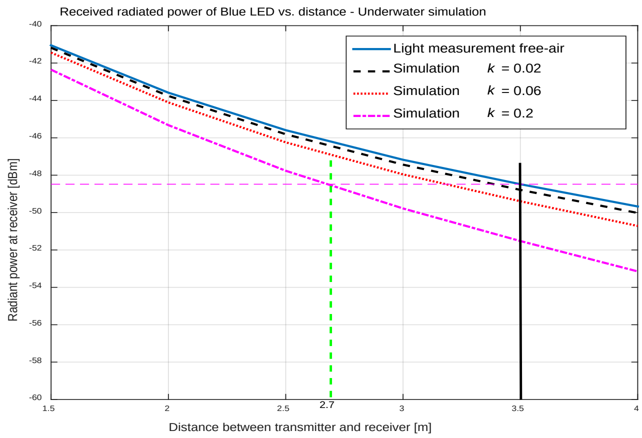

Fig. 8. Estimated underwater range

V. Conclusion

A full-duplex underwater VLC system for voice communication has been presented in this paper. The FM-based system performs in a reasonable range of 2.7 m underwater which can be further increased using optics system. The system performance was measured in terms of received signal strength for both links. The proposed system can be adopted for diver communication and any other voice communication required in underwater.

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