1.725Gb/s underwater visible light communication system based on a silicon substrate green LED and equal gain combination receiver

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Abstract— **Underwater communication is a significant area which is important to research and develop the oceans covered about 2/3 on the earth and filled with several kinds of resources. Decades ago, researchers were using acoustic communication or RF communication underwater. However, these systems have lots of problems. To be specific, the BER performance of these systems is higher than its in free space link. Underwater optical communication using laser confront a big problem which is twisted light spot in rushing ocean water. Considering all the factors, in this paper, we report experimental demonstration of underwater visible light communication (VLC) system based on a pure silicon substrate green LED (SSG-LED) and discrete multi-tone (DMT) modulation employing advanced post-equalization and Equal-Gain combining (EGC) technology. A total data rate of 1.725 Gb/s over 120-cm underwater transmission is successfully achieved with the BER under 7% FEC limit of 3.8e-3. As far as we know, it is the fastest data transmission speed using green silicon based LED. The results show the benefit and feasibility of SSG-LED and DMT modulation using EGC in underwater VLC systems.**

Keywords—underwater communication; LED; DMT modulation; EGC

I. Introduction

With the development of human society, the resources are significant for all the countries. Ocean covers about more than 2/3 surface on the earth which contains energy resources such as biological resources, mineral resources, chemical resources, renewable energy, and tourism resources [1]. Developing and researching it are approaching the corner for the whole world. The key point is underwater wireless information transfer. A few of areas such as industry, military need underwater communication technology to help them to do pollution monitoring, oil control and maintenance, climate change monitoring, tactical surveillance, oceanography research and so on. That's why there is an increasing emphasis on underwater communication.

In recent years, underwater optical communication is a hot topic which draws a lot of researchers to investigate this technology. As we all know, there are three main methods (RF, acoustic and optical communication) utilizing underwater. An approach based on RF is suited for common speed and short distance transmission, while acoustic communication is used to realize long distance and low-speed transmission. In RF communication, the frequency range is 300 KHz ~ 300 GHz. Though data speed can be up to maximum 100Mbps and it is able to avoid being affected by reflection and scattering in short distance, RF signals suffer deeply from transmission loss because of strong conductivity in pure water resources. Sendra S showed a 17cm underwater communication system with a speed of 11Mbps/2.4GHz [2]. While the acoustic communication is a mature way used underwater and reaches a long distance with a lower speed. The reason why it can only transmit at a low speed is that relationship of transmission loss factor and its frequency. When frequency equals to 10MHz, the loss can be up to 30dB/m. That's why the bandwidth is limited to hundreds of KHz. Stojanovic M realized a 1km underwater acoustic communication system with a speed of 10 kbit/s in [3].

The underwater optical wireless communication includes two parts which are based on LED light or laser. Hassan M. Oubei in [4] experimentally demonstrate underwater wireless optical communications (UWOC) employing 450-nm TO-9 packaged and a fiber-pigtailed laser diode (LD) directly whose data rate of up to 4.8 Gbit/s over 5.4-m transmission distance is achieved. A 10-Gbps 16-QAM-OFDM UWLT system based on light injection and optoelectronic feedback techniques is proposed and experimentally demonstrated by Chun-Ming Ho in [1]. For laser communication, it can provide large bandwidth and capacity. But the background light has a bad effect on BER performance. The detrimental effect of water turbulence due to the relatively small aperture size is another problem. For examples, the blue and green laser has a wide bandwidth and a smaller attenuation in water, which make it possible to support a long distance transmission. But it is restricted by the demand of precise collimation.

Visible light communication is intensively studied recently [5-7]. Compared with LD source, the LED is a kind of highly efficient light emitters and very cost-effective. LED can be easily integrated into LED arrays and can achieve more than 100 W output power that have been widely used in street lighting. Therefore given the LED with enhanced modulation bandwidth and optimized optics system, the data communication rate and distance using an LED can be significantly improved. Considering all these factors, utilizing LED light is a better

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method. Firstly, by increasing the power of LED, we can realize a long distance transmission. Secondly, light spot of LED is larger than laser. Rushing water cannot completely twist the light spot and degrade the performance of communication system. The loss of blue-green light in the underwater transmission is relatively small, with the potential as a carrier for high-speed and long-distance transmission. What's more, the light spot of LED can become large enough in order to realize the array receiver.

High speed underwater optical communication technologies has obtained dramatic progress. However, most of the experiments are based on laser diode. Chao Wang realized a data rate up to 50Mbps using LED underwater link larger than 420m in [8]. In this paper, we proposed a novel scheme that is an underwater optical system with an aggregate data rate of 1.725 Gbit/s over 1.2m water link which as we know is the fastest data transmission speed using green silicon based LED (SSG-LED), enabling technologies including pre-emphasis hardware circuit, EGC differential receiver, post-equalization algorithm. Under our acknowledgement, is the first demonstration of LED based underwater visible light communication systems (UVLC) beyond Gb/s.

II. PRINCIPLE

We use DMT and zero padding techniques to modulate the signal to a novel silicon substrate green led transmitter. Meanwhile, DMT demodulation and EGC are applied to the offline processing on the receiver end.

A. *Silicon based LED*

Today, the majority of LEDs are constructed from a combination of GaN, which features a band gap suitable for emitting photons in the visible part of the spectrum, and sapphire substrate. The manufacturing process used to fabricate the wafers from which the individual chips are cut is difficult and employs exotic materials such as gallium nitride (GaN) deposited on sapphire or silicon-carbide (SiC) substrates. In our experiment, the light source is silicon substrate LED. The center wavelength λ of the LED is 518nm, which can well fit the transmission window of water. Silicon is the material routinely used to fabricate billions of integrated circuits (ICs) every year. Apart from potentially reducing the cost of LEDs, the use of mature complementary metal oxide semiconductor (CMOS) IC technology would allow fabrication in conventional wafer fabs that have spare capacity.

B. *Principle of DMT*

In terms of DMT modulation, every eight adjacent bits of the input random serial data is set into one group and mapped by 64 quadrature amplitude modulation (64QAM for each tone) in format of complex values $C_m = A_m + jB_m$. The cyclic prefix (CP) is set to 1/32. As the lower frequency component would cause bad influence on signal detection, the bias-Tee will bans the lower frequency component. Therefore, to make sure all data could be well transmitted by the transmitter, six subcarriers with low frequency is set to zero, which is named as zero padding. Meanwhile, to divide high-speed binary serial data into lower-speed parallel data, a deserializer is introduced into the DMT process. In order to realize parallel communication, the available bandwidth of the system is divided into 256 sub-channels. However, the channel of VLC system cannot transmits complex valued data. Therefore, to acquire real-valued data after IFFT, data with $2M$ points is necessary, in which the second half (C_{2M-m}) has a complex conjugated structure with the first half (C_m). The second half could be express as $C_{2M-m} = C_m^*$, where, M is the total number of bits of the input data. Then, IFFT is applied to transform frequency-domain signal into time domain, and the value in time domain is always real-valued, which could be proven as follow, [9]

$$
\begin{aligned}
f(g) &= \frac{1}{\sqrt{2M}} \sum_{m=0}^{2M-1} C_m \, exp\left(j2\pi m \frac{g}{2M}\right) \\
&= \frac{1}{\sqrt{2M}} \sum_{m=0}^{M-1} \left\{C_m \, exp\left(j2\pi m \frac{g}{2M}\right) \right. \\
&\qquad \left. + C_m^* exp\left[j2\pi(2M-m)\frac{g}{2M}\right]\right\} \\
&= \frac{1}{\sqrt{2M}} \sum_{m=0}^{M-1} \left\{C_m \, exp\left(j2\pi m \frac{g}{2M}\right) + \left[C_n \, exp\left(j2\pi m \frac{g}{2M}\right)\right]^*\right\} \\
&= \frac{1}{\sqrt{2M}} \sum_{m=0}^{M-1} 2 \cdot Re\left\{C_m \, exp\left(j2\pi m \frac{k}{2M}\right)\right\} \qquad (1)
\end{aligned}
$$

$$g = 0,1,\ldots,2N-1$$

Where the *Re* indicates the real part. According to the analysis above, $f(g)$ is a real-valued number set including *2M* points in the time domain. After 4 times up-sampling, a parallel-to-serial process is performed to generate valid serial data. Finally, the last step before digital-to-analog converting is to add cyclic prefix into the real-valued time sequence.

On the receiver end, two PIN diodes are used to convert the optical signal into electrical signal. To achieve the best performance of receiver and broaden bandwidth, 12V reversed bias is set onto PIN diodes. Therefore, one PIN diode is connected to a TIA followed by a differential amplified receiving circuit to perform common mode cancellation. The differential amplified receiving circuit can minus one received tributaries with another to eliminate common mode noise and optimize the SNR of the receiver signal. Furthermore, the signals received by two PINs will be processed by EGC before demodulated.

C. *Principle of EGC*

Equal gain combining is one of the simplest linear combining technique [6], which combines all channels with same gains. The condition that suit EGC should satisfy four assumption as follow,

1) The noise added on the signals from all channels is independent. The noisy signal could be express as: $y_i(t) = x_i(t) + n_i(t)$ where s_j is the sigal and n_i is the noise.
2) Signals from different channels are same over a short period T. This could be express as $x_i(t) = a_i u(t)$, where a_i are fading coefficients that slowly vary with time. The formula indicates that all signal have same phase.

3) In terms of noise $n_i(t)$, over same time T in part 2), $\langle n_i n_j \rangle = 0$ where, $i \neq j$. That is to say, the noises in channels are different and have zero local average power.

4) Statistically, the local rms values of the data sequences are independent.

Depending on the assumption above, the noisy signal could be express as,

$$y_i = x_i + n_i \quad (2)$$

Equal gain system could be best characterized by following function,

$$Y_{EGC} = \frac{1}{N}\sum_{i=1}^{N} y_i \quad (3)$$

From (2) and (3), we could have,

$$Y_{EGC} = \frac{1}{N}\sum_{i=1}^{N}(x_i + n_i) \quad (4)$$

During the EGC process, the phase deviation of two channels is modified to combine two signals received by to PIN diodes. To be specific, in this way, the BER of the system could be improved significantly. Finally, the output signal after EGC will be demodulated [10].

III. Experimental setup

The Fig.1 describes the experimental setup of the under-water single input multiple output (SIMO) VLC system. The multiple receivers used in the system could increase the system SNR; thereby enhance the channel capacity. In other words, the usage of the multiple outputs is to enhance received signal and minimize signal fading. This system utilizes AWG with offline Matlab® program to generate the signal waveform. Then, a hardware pre-equalizer is applied to optimize signal bandwidth. After that, an electrical amplifier (EA) enhances the strength of the signal that will be coupled with direct current via Bias TEE. According to the output current, the direct component drives a green led, and the alternating component contents the signal should be transmitted. The function of the utilized SSG-LED is to transform the electrical signal into optical signal that fits the transmission window of water; thereby, realize 1.2m underwater wireless communication. Additionally, to perform the long-distance transformation, a paraboloid reflector is used to collimate the light emitted from the SSG-LED that is installed at the focus point of the reflector. The picture on the right sides, it is clear to see that the glass tank is filled with pure water.

On the receiver sides, to modify the SNR, differential receivers are installed at the focus points of two convex lenses that capture and a couple more light onto two S10784 PIN diodes. Since the light spot of LED transmitter is much larger than LD, multiple receivers could be utilized on the receivers sides to enhance SNR. Meanwhile, The PIN diode is integrated with a TIA and a differential amplified receiving circuit. Then, four amplified output differential signals without common mode noise are amplified by four EAs independently. Finally, the data sequences are saved by an oscilloscope in real time prepared to be processed with offline Matlab® program.

In terms of offline processing, the positive tributary of each PIN is minus by the negative one, which leads to two enhanced signals from tow differential receivers. Then, these two signal are linearly added up with equal weight, so that only one signal is going to be demodulated, which could decrease the complexity of computation. After removing CP, Down-sampling process is applied to the data sequences. Before FFT, the high-speed serial data is converted into lower-speed parallel data. The data in the frequency domain after FFT is processed with channel estimation and post-equalization. Finally, the modified data is de-mapping according to QAM.

IV. Experimental results and discussions

In the under-water SIMO VLC system, the relationship between Q factor and the volt peak-to-peak value of the signal (V_{pp}) is measured to figure out the best signal driving voltage of AWG. According Fig.2, it is clear to see that the best signal driving voltage of the LED is 0.8V. When the V_{pp} is lower than 0.8V, the Q factor is increasing along with the increasing of V_{pp}. Once the V_{pp} is getting higher than 0.8V, the Q factor is decreasing.

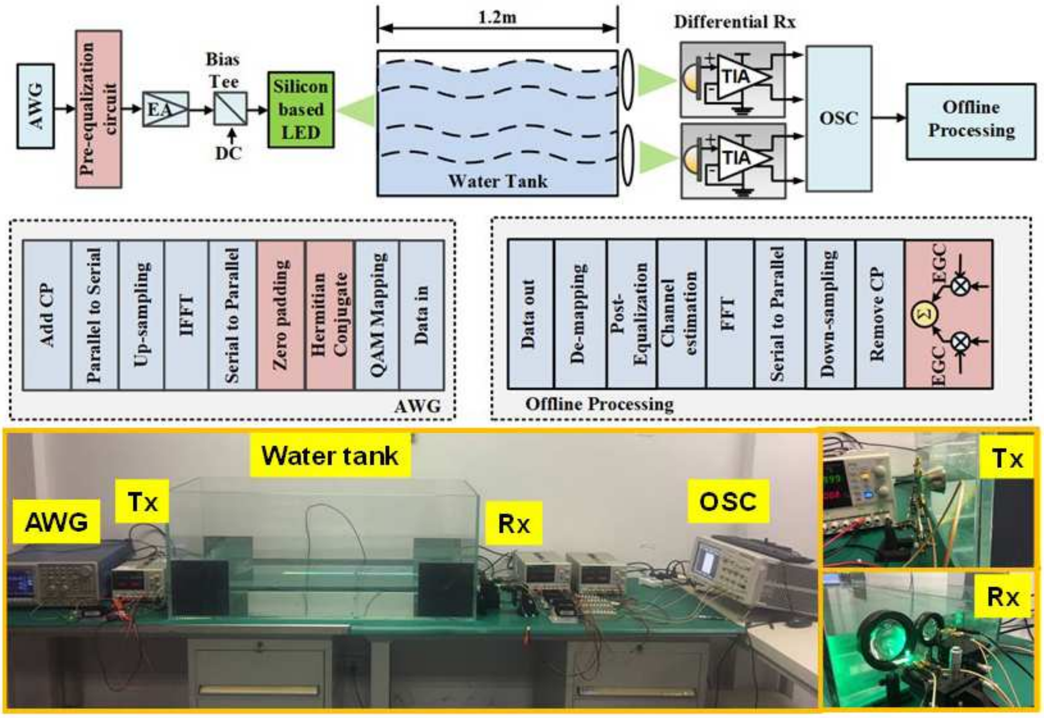

Fig. 1. The setup for underwater VLC system.

Because, with the increasing of Vpp, signal cannot stay in the linear area affected by the nonlinearity, which leads to the distortion. In other words, BER performance degrades and the Q factor deeply decreases. Additionally, when the V_{pp} is set to 0.6, The EGC can increase the Q factor of the system by 1.2dB, which can be intuitively observed from the constellation on the right hand. The constellation of EGC result at 0.6V is clearer than Rx1 and Rx2. Therefore, the Q factor versus V_{pp} curves of Rx1, Rx2 and EGC indicates that EGC could significantly improve the performance of the VCL system.

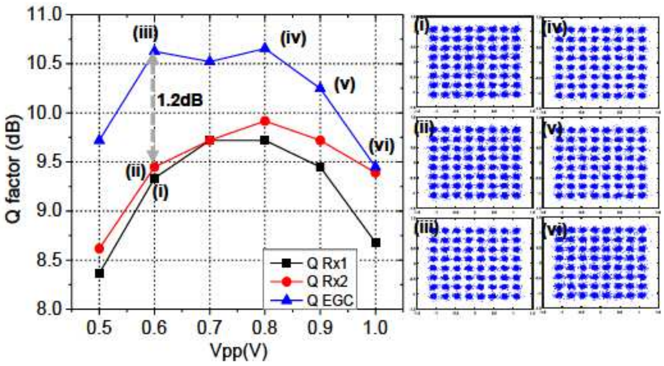

Fig.2 Measured Q factor as a function of driving signal peak-to-peak voltage. The inset figures show the constellation of different Vpp conditions.

According to the analysis above, when we measured the BERs versus bias current of SSG-LED, The V_{pp} is set to 0.8-V_{pp}. Fig.3 describes the relationship between Bias current for LED and BER. The optimal bias current is 140mA. At this current, the BER is the lowest. As the bias current is increasing, the output luminance is increasing. However, the high intensity will lead to saturation of PIN diode, which will cause a bad influence on BER. Similarly, the BER results of EGC are much smaller than Rx1 and Rx2. The benefit of EGC is proved again.

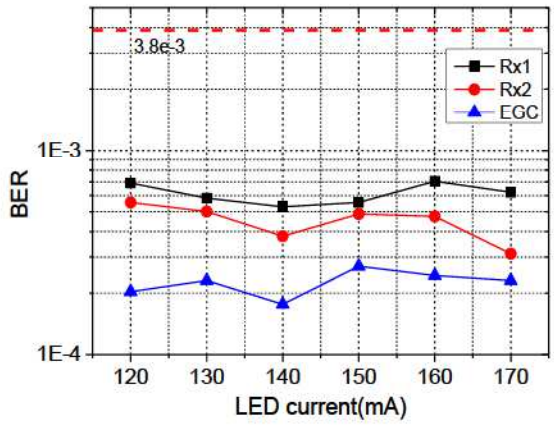

Fig.3 Measured BER as a function of LED current for differential receiver 1, receiver 2 and the EGC receiver

In order to find out the maximum bitrate with BER less than the hard-decision forward-error-correction (HD-FEC) threshold of 3.8×10^{-3}, V_{pp} and Bias I are set to 0.8 V_{pp} and 140 mA, respectively. The relationship between BER and Bit Rate shown in fig.4 indicates that the maximum bitrate under HD-FEC threshold is 1.725 Gbit/s. At this point, although the BER of Rx1 and Rx2 is higher than HD-FEC threshold, the BER after EGC is less than HD-FEC threshold. When the bit rate is higher than 1.725 Gbit/s the, the BERs of Rx1, Rx2 and EGC are no longer satisfy the HD-FEC threshold. Additionally, at same bit rate, fig.4 also indicates that BER performances of EGC is much better than both Rx1 and Rx2.

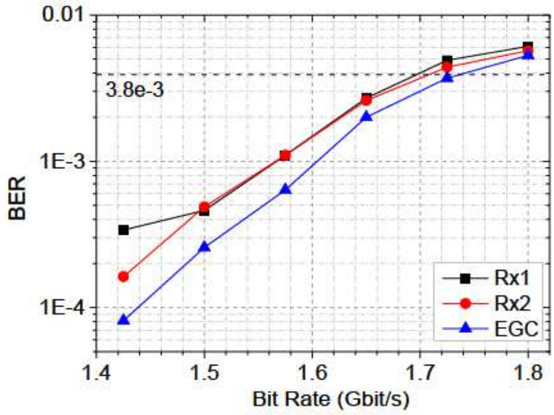

Fig. 4. The measured BER versus bit rate (Gbit/s)

Fig. 5 illustrates the eletrical spectrum of the signal at various data rate after FFT transfer. When the data rate is 1.425 Gbit/s, the spectrum of Rx1 and Rx2 are showed as Fig.5 (a) and (b). Out-of-band noise can be seen from the spectrum marked by red circles. After the EGC processing, the out-of-band noise disappears as showed in Fig.5 (c). Then, we increase the bit rate which equals to 1.725 Gbit/s. Spectrum of Rx1 and Rx2 are showed as Fig.5 (d) and (e). And the Fig. 5 (f) is the spectrum of signals based on EGC. The low frequency noise of signals utlizing EGC is smaller than that of Rx1 and Rx2. Comparing the spectrums of signals at different bit rates, we can figure out the base band of signals at 1.425 Gbit/s is more flat than that at 1.725 Gbit/s. What's more, the side of base band in Fig. 5 (c) is sharply declined in Fig. 5 (f).

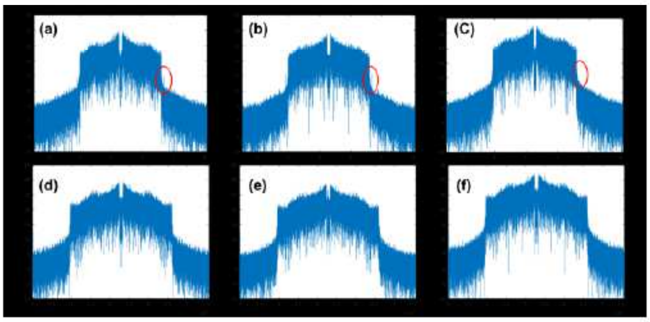

Fig.5 Electrical spectrum of the signal at various data rate after FFT transfer for (a) Rx1 at 1.425Gbit/s, (b) Rx2 at 1.425Gbit/s,(c) EGC at 1.425Gbit/s, (d) Rx1 at 1.725Gbit/s, (e) Rx2 at 1.725Gbit/s, (f) EGC at 1.725Gbit/s.

Fig.6 lists 64 QAM constellations of Rx1, Rx2 and EGC at 1.425 Gbit/s and 1.725 Gbit/s. In comparison with 1.425Gbit/s and 1.725, it is clear to see that the constellations in first row is much clearer than the constellations in second row. In other words, there are more noisy points in the constellations in second row than first row. That is to say, the VCL system with low bit rate has batter SNR performance than system with high bit rate. In terms of same bit rate, the constellation of EGC is clearer than Rx1 and Rx2.

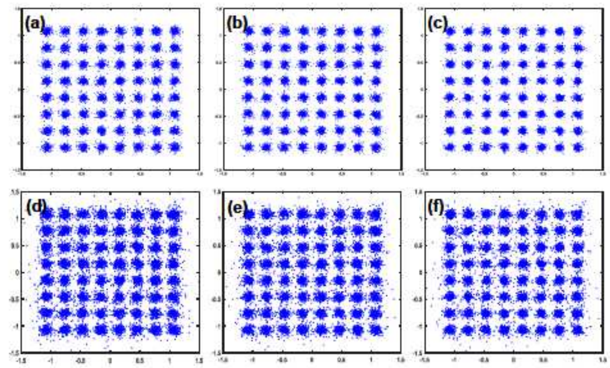

Fig.6 Constellations of the signals at various data rate for (a) Rx1 at 1.425Gbit/s, (b) Rx2 at 1.425Gbit/s, (c) EGC at 1.425Gbit/s, (d) Rx1 at 1.725Gbit/s, (e) Rx2 at 1.725Gbit/s, (f) EGC at 1.725Gbit/s.

V. Conclusion

We propose a novel 64 QAM DMT modulation in 1×2 SIMO under water VLC system based on a silicon substrate green LED. The received two signals are processed and added up via EGC; thereby, the VCL system achieve 1.725 Gbit/s over 1.2m underwater transmission with 6.738Mbit/s of each channel. According to our acknowledgment, it is the highest speed in LED-based underwater VLC system over 1.2m. The experimental results prove that EGC could dramatically improve the performance of SNR in underwater VLC system and the SSG-LED can be a promising candidate for future high-speed underwater communication system.

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