A design of underwater wireless laser communication system based on PPM modulating method

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***Abstract*—Underwater laser communication has been developed in the field of deep-sea exploration, also become a highlight of modern communication technology research. It has the edges of hidden, safe, non-contact and rapid mobility. By now, most data exchange and transmission between underwater sensors and devices are achieved by RS-232 serial ports communication. But it is not able to meet the demands of present underwater communication due to the limitations of transmitting rate and distance. For the first version of our laser system the signals flowing through the RS-232 ports had not been modulated. Therefore, the bit error rate of our previous work was adversely high. In this paper, we progress our system by introducing in a novel signal modulating module, which mainly consists of FPGAs and PPM method. Considering with the effect of absorption and scattering [1], a series of experiments are performed in this paper: unmodulated and modulated underwater laser communication experiments under different visibility water. By comparing the bit error rate results, we suggest that the whole underwater laser communication system is compact, efficient and reliable. Finally, we based on multiple of visibility, the theoretical communicationn distance of the system can be estimated.**

Keywords—Underwater wireless laser communication; RS232; PPM; FPGA

I. INTRODUCTION

Equipped with different marine instruments, AUV (Autonomous Underwater Vehicle) is applied in many ocean engineering areas, such as pipeline laying, subsea inspection, data collection, drilling support, subsea construction, and maintenance of underwater equipment. Such sensors usually transmit significant amounts of data which require a high bandwidth link to the outside world[2].Generally, information collected by electronic devices and sensors inside the AUV is transmitted via RS-232 serial ports.

Primary RS-232 serial port only enables point-to-point communication between different devices, which can hardly meet the underwater communicating needs of several-to-one or many-to-many modules. Otherwise, the maximum transmission distance of RS-232 serial port is limited to 15m and the transmittal process can easily sustain defects including electromagnetic interference and signal attenuation. The highest communication rate of RS-232 serial port is 230400 bps. However, the state-of-the-art method of serial port communication with this transmission rate is obviously incompetent, once the access of real-time and high speed information is required.

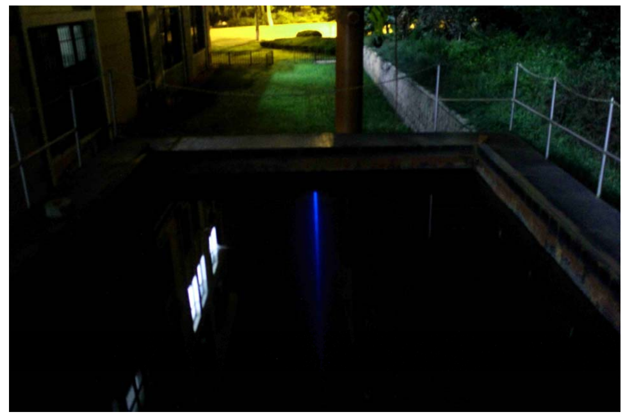

Fig. 1. The experimental water tank.

Developing efficient, safe and land-based or air-based underwater communication has been the national defense research hotspot for decades. At present, the most well-developed communication measures include acoustic communication, long wave communication and optical communication. Underwater Laser Communication takes full advantage of the window attenuation effect of seawater on the laser [3]. It has been developed and applied to deep ocean explorations, because of its advantages of compact structure, high transmitting rate, suitable for any communication protocols, good hidden traits and strong confidentiality, and fast response capability, etc.

For the first version of our laser system, the capacity of transmitting signals at relative high rate was validated [4]. But the signals flowing through the RS-232 ports had not been modulated. Therefore, the bit error rate of our previous work was adversely high. In this paper, we progress our system by introducing in a novel signal modulating module, which mainly consists of FPGAs and PPM (Pulse Position Modulation) method. Research has shown that PPM is a near optimal coding for background-limited optical communications, and it is also appears to be the best approach for communicating in the optical scatter channel [5-7].At first, the basic principle and mathematical model of PPM are elaborated in this paper. Then the PPM modulation system based on FPGA is designed, which includes the modulator unit, demodulator unit, digital synchronous signal extraction unit and other units.

II. THEORY

A. BER

The Bit Error Ratio (BER) is calculated by the value of the number of bit errors divided by the total number of transferred bits during a studied time interval. BER is a unitless performance measure, often expressed as a percentage [8].

In communication systems, BER of the receiver side may be affected by transmission channel noise, interference, distortion, bit synchronization problems, attenuation, wireless and multipath fading, etc.

In state-of-art works, it has been validated that BER could be improved by various approaches including choosing a stro -ng signal strength, choosing a slow and robust modulation scheme or line coding scheme, applying channel coding sche -mes such as redundant forward error correction codes.

In this paper, our underwater laser communication system is quite power efficient and it also provides abundant bandwidth resources. It can reach adequate transmission rate with small power cost. To achieve this, we performed PPM in signal modulating process.

B. The principal of PPM

PPM was first proposed by PierceJ.R.. It's an orthogonal modulation method which made each laser pulse moving in linear relation in accordance with the sampling value of information signal at nominal position.PPM has the advantages of simple, high energy efficiency and high power transmission efficiency. It only needs to control the pulse position according to the data symbols, and it is not necessary to control the amplitude and polarity of the pulse, so it is convenient to realize the modulation and demodulation with lower complexity. PPM can be used to achieve the highest data transfer rate with minimum average power, which can reach to 1000Mb/s in laser communication system under certain laser pulse repetition frequency [9].

PPM is widely used in laser communication systems, primarily because of its high average power efficiency [10-11] and the pulse duty cycle is very small [12]. Typical synchronous PPM signal is illustrated as Fig.2.

T_f is a frame of the PPM . T_Q is signaling period. T_D is silence period. τ is transmission slot [13-14].

At the transmitting end, laser opens at the transmission slot τ to send out a sign, the remaining time is closed. At the receiving end, the detection judgment light pulse position in the frame, so as to restore the binary information.

As shown in Fig.2, since PPM uses one pulse per M information slots, it has a duty cycle of (Q+D) T_s. In other words, PPM signal has an average repetition frequency of $1/(Q+D)T_s$. At the same time, PPM has a peak-to-average power ratio of (Q+D).

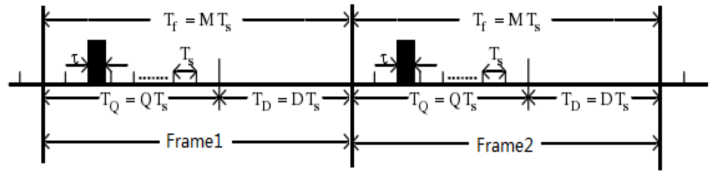

Fig. 2. Typical PPM signal format.

Even though the energy of laser pulse keeps huge, the average power can be relatively low when (Q+D) is big enough. So PPM modulation decreases the average power greatly, and is well suitable for wireless optical transmission. For a M-ary PPM signal, the data bits per pulse can be $\log_2 M$. So PPM communication has an average data rate equal to

$$R_b = \log_2 Q/(Q+D)T_s \tag{1}$$

In order to improve data transmission rate, we can increase signaling period or decrease the silence period as possible. The silence period is mainly determined by the type of laser. For example, there is a minimum time interval of about 20ms for solid state laser, while semiconductor diode laser has a much shorter time interval which can be ignored compared with signaling periods. In our underwater wireless laser experimental system, M=16.

C. The Cyclone-IV FPGA

Due to the advantages of performance, cost, flexibility and power consumption, signal processor based on FPGA has been widely used in various signal processing fields. In this paper, the FPGA unit is responsible for the signal modulation and demodulation. Modem system is mainly composed of several FPGA processing boards.

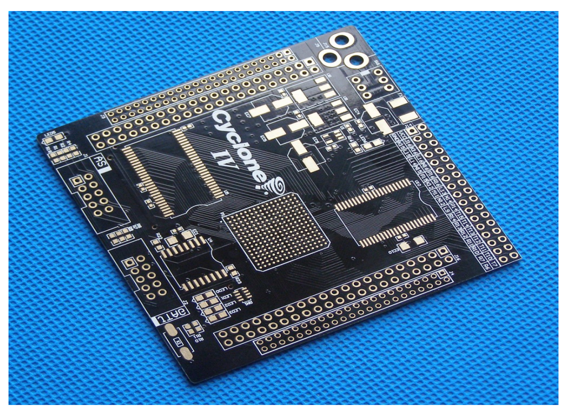

Fig. 3. The circuit board of Cyclone-IV.

Altera's new Cyclone-IV (shown as Fig.3)series FPGA devices continue the Cyclone series tradition of offering an unprecedented combination of low power, high functionality, complete design resources(Quartus II and Nios II), and low cost. The Cyclone-IV FPGA architecture consists of up to 115K vertically arranged LEs, 4 Mbits of embedded memory arranged as 9-Kbit (M9K) blocks, and 266 18x18 embedded multipliers ,as TABLE.I.

TABLE I. Product description of Cyclone-IV

Product Desciption (All Specs are subject to Datesheet)	
Part NO.	EP4CE15F17C8N
Manufacture	Altera
Package	256-FBGA (17x17)
Description	IC CYCLONE IV FPGA 15K 256FBGA
Number of LABs/CLBs	963
Number of Logic Elements/Cells	15408
Total RAM Bits	516096
Number of I /O	165
Number of Gates	-
Voltage - Supply	1.15 V ~ 1.25 V
Mounting Type	Surface Mount
Operating Temperature	0°C ~ 85°C
Supplier Device Package	256-FBGA (17x17)

The architectures include highly efficient interconnect and low-skew clock networks, providing connectivity between logic structures for clock and data signals.

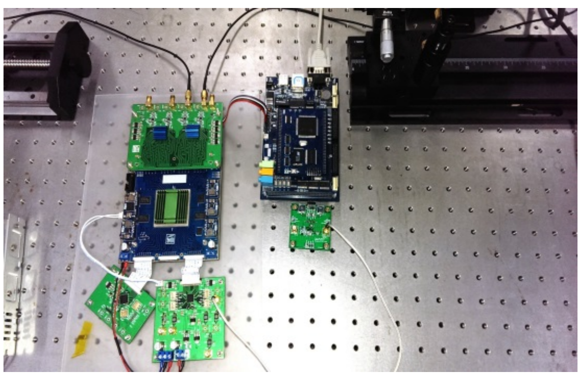

Fig. 4. The FPGA unit.

Taken together(performance and cost), we used Cyclone-IV in this paper. The circuit board of Cyclone-IV was shown as Fig.4.

III. SYSTEM IMPLEMENTATION

A. the diagram of entire system

An experimental wireless laser communication system employing PPM scheme is built. The realization diagram of entire system (Fig.7) is given out.

The source unit is responsible for the generating, receiving, and analyzing RS-232 serial signals. Received data and original data will be analyzed and processed at the PC side.

The FPGA unit is responsible for the signal modulation and demodulation as showed in Fig.4. Modem system is mainly composed of several FPGA processing boards. RS-232 serial signal is modulated by the FPGA modulation unit and then proceeds to the laser. We use another FPGA chip to demodulate signals on the receiving side. The received data is then plugged into the serial port unit. Furthermore, we use two high-performance Cyclone-IV series EP4CE15F17C8 FPGA chips in our system. QuartusII 11.0 and Verilog hardware description language are utilized to design modulation unit and demodulation unit.

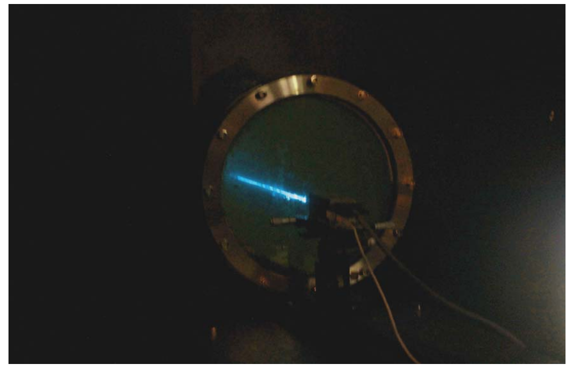

Fig. 5. The 488nm laser of Oxxius.

The underwater laser communication unit is responsible for the transmission and reception of the modulated signal, as showed in Fig.12 and Fig.13.On the side of the emission end, a 488nm laser of Oxxius is chosen as the light source, as shown in Fig.5.On the side of the receiving end, a photomultiplier(PMT) of Hamamatsu 1527 was used to transform the laser energy to the current signal, as shown in Fig.6.The signal processing and shaping units include circuits such as transimpedance amplifier and Automatic Gain Control (AGC). Thereafter, the BER (Bit Error Rate) is subjected to statistical analysis in PC.

Fig. 6. The PMT of Hamamatsu 1527.

B. PPM modulation units

In the modulation unit, the unmodulated signal is modulated into a PPM signal by the FPGA chips. The design of Cyclone-IV series EP4CE15F17C8 FPGA chip-based modulator is shown as Fig.8. The difficulty of modulator design lies on achieving PPM narrow pulse generation and get the accurate time delay of pulse. Consequently, we fully utilized the feature that EP4CE15F17C8 FPGA chips can be easily and accurately generate PWM square wave. By designing hardware circuits, such as internal oscillator circuit, starting shaping circuit, asynchronous serial interface circuit, etc. We completed the conversion from PWM to PPM, and ultimately solved the key problems of PPM modulation.

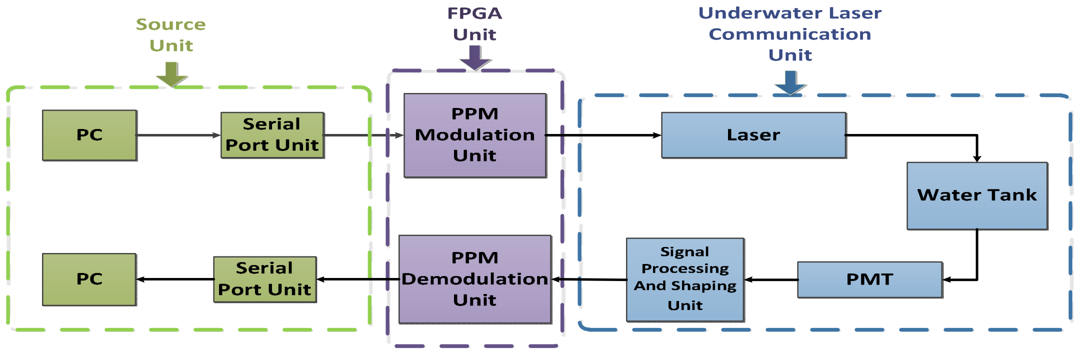

Fig. 7. The realization diagram of entire system.

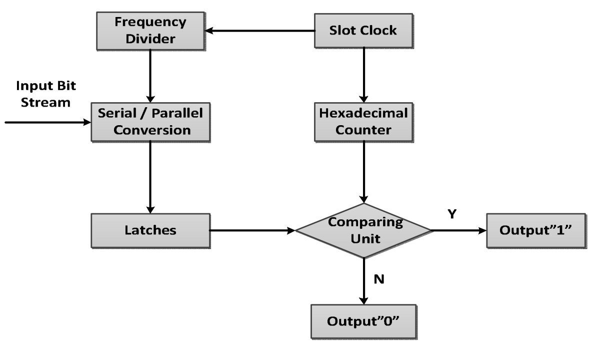

Fig.8 The block diagram of PPM Modulation.

C. PPM demodulation unit

In the demodulation part, we use FPGA unit to demonstrate a maximum likelihood PPM demodulation. Demodulation system exploits an Altera's Cyclone-IV series EP4CE15F17C8 FPGA chip, which enables high computational performance. Altera's Quartus II 11.0 and Verilog hardware description language are separately employed as integrated development environment and coding language in module demodulator design(realization diagram shown in Fig.9).

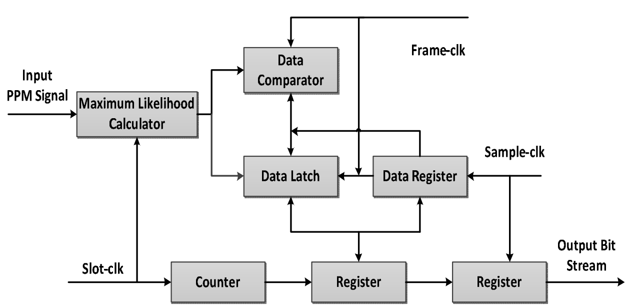

Fig.9 The block diagram of PPM Demodulation.

Synchronous signal unit

In laser communication system, synchronization is a significant part. Poor performance synchronous system can directly result in lower communication system performance. Because of this, in order to guarantee the qualification of the transmission of information, the synchronization system should have higher reliability.

In our work, underwater laser communication system clock signals are generated by the synchronization unit in the receiver system. The synchronization unit includes a slot synchronization system (Fig.10) and frame synchronization (Fig.11) system.

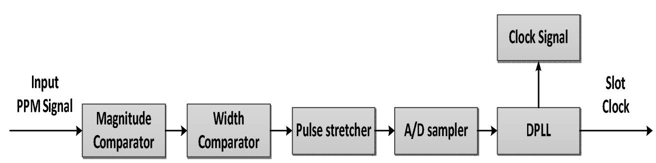

Fig.10 The block diagram of slot synchronization signal extracting.

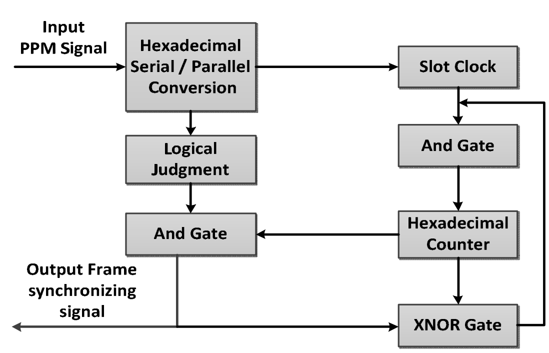

Fig.11 The block diagram of frame synchronization signal extracting.

IV. INSTALLATION AND VALIDATION

A. *Experimental condition*

The test was implemented in a tank of 2m*3m*8m, as showed in Fig.1. The transmitter Fig.12 and the receiver Fig.13 were placed apart at a distance of 8m. At the transmitting end, the 488nm laser of Oxxius was set to be 50mw output in a constant optical power. On the side of the receiver, a photomultiplier (PMT) of Hamamatsu-1527 was used to transform the laser energy to the current signal, as showed in Fig.6. In addition, the subsequent circuit like transimpedance amplifier and Automatic Gain Control (AGC) were used to provide the applicable signal for the serial port processing.

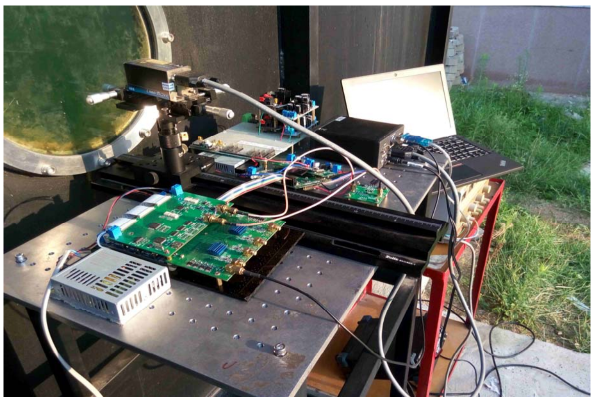

Fig.12.The transmitting laser and the PPM modulation unit.

In addition, the driver of modulator crystal can provide a 20MHz bandwidth. At the receiving end, the photomultiplier with a bandwidth of 200MHz was placed at another end of the tank , right confronting with the direction of the transmitting laser beam.

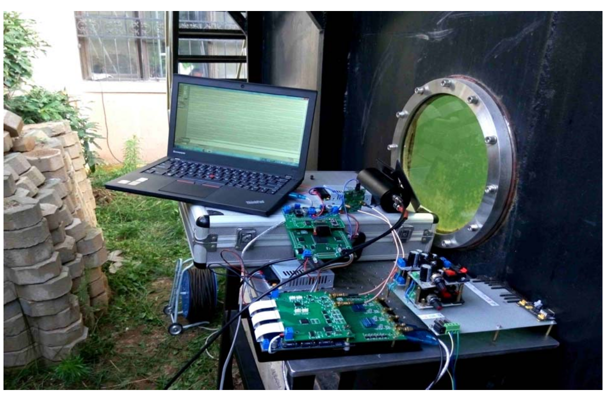

Fig.13.The receiver PMT and the PPM demodulation unit.

B. *Experimental contents and Results*

The optical hardware link was built as the framework in Fig.7.On the basis of this optical hardware, two experiments were performed to verify the performance of unmodulated and modulated digital RS-232 underwater laser communication link in different visibility condition.

The aluminum hydroxide was added to the tank to get different water visibility. As shown in Fig.7, the PC analyze part acquires the original signal stream and final received signal stream and computes the BER of the signal streams.

In these experiments the data transmitting rate was set at a rate of 10MBits/s. Fig.14 shows the BER when the water visibility varied from 0.5m to 5m(because of the length limit of the tank，the maximum visibility that could be controlled was limited at 5m). Meanwhile, the BER of from 1 to 5 times visibility were obtained, when the visibility was fixed at 0.5m, as showed in Fig.15.

C. *Experimental result analysis*

As displayed in Fig.14, it indicates that the BER improves as the water visibility increases, as expected. Moreover, it can also be seen that the BER of the RS-232 serial port communication reduced tremendously with our modulated method in the same visibility.

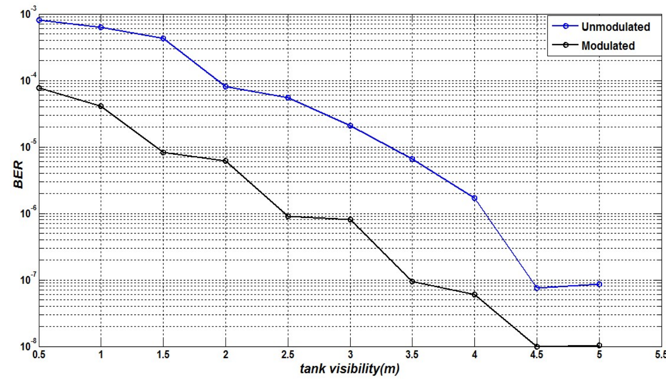

Fig.14. The BER VS tank visibility(10Mbits/s transmission rate).

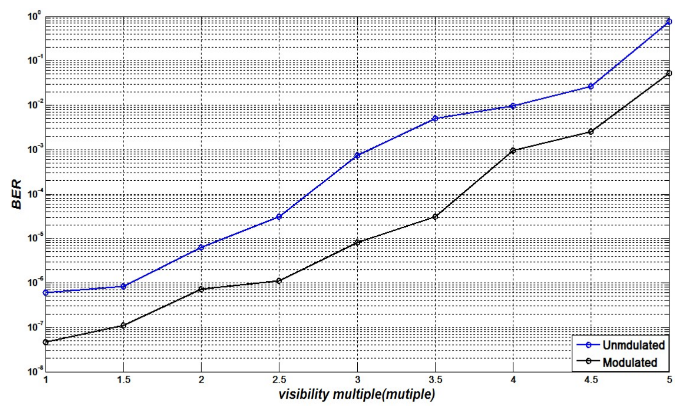

Fig.15. The BER VS multiple of visibility(one multiple visibility is 0.5m).

At the visibility of 5m, the BER downs to 10^{-8}, because of the limitation of tank, the visibility scale of control is within 5m, and we suggest that a low BER can be achieved in clearer water. In Fig.15, experiments with a fixed communication distance varied from 5 multiple visibilities were implemented and elucidated. The data shows that the BER has increased to a anomalous high level(10^{-5}) at 3.5 multiple, which may result from progressing absorption and scattering in a long transmission path. This aberration indicated that above the distance of 3.5 multiple visibility, this underwater communication system could be infeasible. Encouragingly, within the distance of 3.5 multiple visibility, the BER of our system is acceptable. It infers that in the sea area of normal visibility such as 10m, this system could get an acceptable serial transmission effect at a distance of 35m.

V. CONCLUSION

In the experiment, the performance of the experimental serial port communication link is proved to be satisfactory. In addition, results of no modulation and modulation underwater laser communication experiments in different visibility condition were obtained and analyzed. Thereafter, the bit error rate was subjected to statistical analysis in PC. Validation result shows that the whole underwater laser communication system is compact, efficient and reliable. Furthermore, we propose that research of this PPM modulation can provide valuable reference to other optical communication system.

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