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An ultraviolet laser communication system using frequency-shift keying modulation scheme*

PENG Di-yong (彭帝永)**, **SHI Jun** (施军), **PENG Guang-hui** (彭光辉), **XIAO Sha-li** (肖沙里), **XU Shan-he** (徐山河), **WANG Shan** (王珊), **and LIU Feng** (刘锋)

Key Laboratory of Optoelectronic Technology and Systems, Ministry of Education, Chongqing University, Chongqing 400044, China

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A communication system based on an ultraviolet (UV) laser at 266 nm is presented to improve the communication distance. The pulse frequency-shift keying (FSK) modulation scheme is studied and improved in order to reduce the bit error rate (BER), and is put into practice on a field programmable gate array (FPGA). The mathematical models of the modulation and demodulation are established. A test platform is set up to measure the energy density and pulse response under different distances and receiver elevation angles. It is shown that the omnibearing communication can be realized, and the bit rate is limited to 12.5 Mbit/s. The BER is estimated to be less than 10^{-7} at distance of 300 m in line-of-sight (LOS) communication model and to be less than 10^{-6} at distance of 80 m in non-line-of-sight (NLOS) communication model.

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Ultraviolet (UV) communication has become an interesting alternative for military communications in the last two decades. In the UV band (200–280 nm), because the sunlight is filtered by the ozone layer and the background radiation is low, weak signals can be detected by the receiver. Meanwhile, the UV light can propagate for only several kilometers due to the high atmospheric scattering and absorption, so the hostile forces cannot detect the signal on our part. UV communication becomes an important military application when radio, wire or fiber communication links are unavailable, unreliable or untrustworthy. It has attracted the attention of researchers because of its good secrecy in recent years. A scattering communication link at ultraviolet frequencies was put forward by Sunstein[1] in 1968. A single scattering channel model for non-line-of-sight (NLOS) was proposed by Luettgen et al[2] in 1991, and became an authoritative cited reference[3-6]. The experimental performance using this model was studied for pulse-position modulation (PPM) or on-off keying (OOK) modulation on light emitting diode (LED) based test bed[5,7,8]. However, the communication distance is restricted to dozens of meters because the light output power of LED is finite.

In this paper, a pulse laser is utilized as the UV source to increase the communication distance. The mathematical models of modulation and demodulation are established. The binary frequency-shift keying (2FSK) is applied and improved to adjust the laser device, and a modified quaternary frequency-shift keying (4FSK) is imported for comparison. A statistic bit error rate (BER) is conducted to explain the performance of the communication system.

The UV communication system consists of two basic components: the transmitter (Tx) and the receiver (Rx)[9]. In the transmitter, a pulse laser is modulated by a field programmable gate array (FPGA) to carry digital signal generated from a computer. The output UV light is scattered through atmosphere channel to establish a communication link. At the receiver, a photomultiplier tube (PMT) aided by a solar-blind optical filter is employed for light detection, and another FPGA is utilized to demodulate the signal adopted from the preprocessing circuit. The schematic diagram of the UV communication system is illustrated in Fig.1.

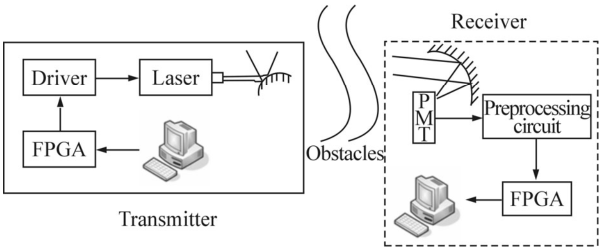

Fig.1 Schematic diagram of the UV communication system

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** E-mail: pengdiyong@cqu.edu.cn

The key devices of the system are a laser (MPL-F-266) made by Changchun New Industries Optoelectronics Tech. Co., Ltd. and the PMT (R7154)[10] from HAMMATSU. The solid state UV laser at 266 nm has the features of high compactness, long lifetime, low cost and easy operation, which is widely used in UV communication, micro-electronics, CD carving, laser medical treatment, scientific experiment, etc.

For UV communication, the common modulation methods are OOK, PPM and FSK. OOK is a bit-serial modulation scheme in which a '1' represents a pulse and a '0' represents the absence of a pulse. In PPM, a $\log 2^L$ bit signal represents the position of a single pulse in a frame consisting of L time slots. FSK takes different frequencies to stand for the bits. PPM is quite popular in UV communication mechanism with LED as the optical emitter because of the high energy efficiency and considerable data rate with constrained pulse repetition rate. We attempt to accept the method, but find that the laser pulse cannot be controlled well and numerous bit errors emerge. That is maybe because the mechanization engendering laser is miscellaneous, and the laser cannot be produced punctually.

In addition, PPM is suitable for communication applications which are energy-constrained and low-rate distributing sensing, but the laser can offer adequate energy to consume. And FSK is of particular interest relative to PPM, because it has the same theoretical sensitivity advantage over binary formats but has lower peak power, electronic bandwidth and compatibility with high-power semiconductor optical amplifiers. Therefore, we choose FSK to investigate the transmitter performance and communication distance sensitivity.

FSK is a frequency modulation scheme in which the digital information is transmitted through the discrete frequency changes of a carrier wave[11]. In this paper, ideally, the laser is generated at a maximum pulse repetition frequency (PRF) of 7 kHz when a high level signal is input into the laser. Otherwise, there is no pulse signal emitted by the laser. The influence of electrical signal input into the laser within one symbol duration of T can be expressed as

$$g(t)=\begin{cases}0 & (\xi_i-1)\tau_i<t\le(\xi_i-Q)\tau_i \\ A & (\xi_i-Q)\tau_i<t\le\xi_i\tau_i\end{cases}, \tag{1}$$

where A is the amplitude of electrical signals input into the laser, Q is the duty cycle of the rectangular waveform signals (the number of pulses emitted by the laser in a duration of T can be changed by adjusting Q), i represents the transmitted symbol, and τ_i is the period of the rectangular waveform signals input into the laser while transmitting symbol i. ξ_i is a positive integer, and $\xi_i=\{1,\cdots,\xi_{i\max}\}$. When $\xi_{i\max}=N$, the number of rectangular waveform signals is N in a duration of T. That is to say, the waveform of $g(t)$ is the superposition of a series of rectangular waveform signals in the time domain in a duration of T, the number of rectangular waveform signals is N, and the period of the rectangular waveform signals is $\tau_i=T/N$.

In this case, the intensity of the transmitted laser pulse can be described as

$$I_{\mathrm{Tx}}=I_0\sum_{\xi_i=1}^{N}\int_{nT}^{(n+1)T}\delta\left\{t-\left[\left(\xi_i\tau_i-\Delta\tau_i\right)+nT\right]\right\}\mathrm{d}t, \tag{2}$$

where I_0 is the amplitude of laser pulse, n is a natural number, and $0<\Delta\tau_i<Q\tau_i$, so it could be ensured that the laser pulse occurs at high level. While it is a random variable influenced by the electrical input signal from FPGA and other stochastic factors, $\Delta\tau_i$ can alter the pulse quantity. If $\Delta\tau_i$ gets out of the range described above, they contribute to the primary bit errors.

The corresponding demodulation algorithm can be obtained from the modulation algorithm given above. Firstly, the number of pulses received in duration of T can be calculated as

$$M=\frac{I_{\mathrm{Rx}}}{I_0}=\frac{I_{\mathrm{Tx}}}{I_0}, \tag{3}$$

where I_{Rx} is the intensity of the received pulse, and I_{Tx} is the intensity of the transmitted pulse. Ideally, $I_{\mathrm{Rx}}=I_{\mathrm{Tx}}$. M is the number of pulses emitted by the laser or received by the PMT in a duration of T.

From Eqs.(2) and (3), for instance, if Q=50%, $\xi_0=2$ (correspondingly, the symbol e is 0), and $\xi_1=1$ (correspondingly, the symbol e is 1), as illustrated in Fig.2, it shows the pulse signal modulated by the 2FSK scheme. The original 8 bit binary sequence is 10101010 (baseband signal), and they are replaced by a series of rectangular waveform signals with different τ_i. It can be clearly seen that there will be a pulse signal while sending '1', and two pulse signals while sending '0'.

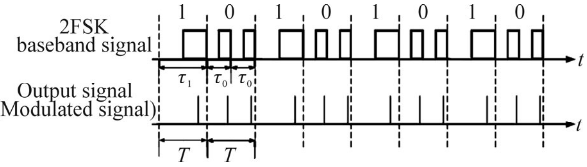

Fig.2 The ideal operating characteristics of 2FSK modulation

Fig.2 also can be expressed as

$$M=\begin{cases}2 & \text{when} \quad e_{\mathrm{Tx}}=0 \\ 1 & \text{when} \quad e_{\mathrm{Tx}}=1\end{cases}, \tag{4}$$

where e_{Tx} is the symbol of baseband signal, and M is the number of pulses emitted in a duration of T. Unfortunately, there could be one or more pulses absence or excess for some random factors, which means that $\Delta\tau_i$ does not satisfy $0<\Delta\tau_i<Q\tau_i$, so unexpected errors appear as demonstrated in Fig.3.

In view of this situation, some measures should be taken to improve the performance of fault tolerance and reduce the error rate of the communication system.

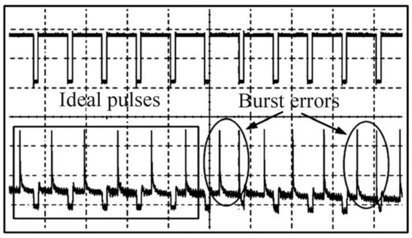

Fig.3 Laser pulses controlled by the FPGA

So we modify the algorithms of 2FSK modulation and demodulation as follows. For the modulation algorithm, the number of the transmitted pulses will be not less than n_0 when emitting bit ‘0’, while be less than n_1 ($n_0 \geq n_1$) for bit ‘1’, which can be expressed as

$$\begin{cases} M \geq n_0 & \text{when} \quad e_{\text{Tx}} = 0 \\ M < n_1 & \text{when} \quad e_{\text{Tx}} = 1 \end{cases}, \tag{5}$$

where M is the number of pulses emitted in a duration of T. On the other hand, for the demodulation algorithm, the symbol will be judged to be bit ‘0’ if the number of detected pulses is not less than n_0, and bit ‘1’ for less than n_1, which can be expressed as

$$e_{\text{Rx}} = \begin{cases} 0, & M \geq n_0 \\ 1, & M < n_1 \end{cases}, \tag{6}$$

where e_{Rx} is the received symbol, and M represents the number of pulses received in a duration of T at the receiver. So when the number of laser pulses changes from a fixed value to a variable range of integers, the difference of the numbers of pulses between different symbols is expanded.

Similarly, the modified algorithms of 4FSK modulation and demodulation can be described as

$$\begin{cases} M \geq n_{00} & \text{when} \quad e_{\text{Tx}} = 00 \\ n_{00} > M \geq n_{01} & \text{when} \quad e_{\text{Tx}} = 01 \\ n_{01} > M \geq n_{11} & \text{when} \quad e_{\text{Tx}} = 11 \\ M < n_{10} & \text{when} \quad e_{\text{Tx}} = 10 \end{cases}, \tag{7}$$

$$e_{\text{Rx}} = \begin{cases} 00 & M \geq n_{00} \\ 01 & n_{00} > M \geq n_{01} \\ 11 & n_{01} > M \geq n_{11} \\ 10 & M < n_{10} \end{cases}, \tag{8}$$

where n_{00}, n_{01}, n_{11} and n_{10} are positive integers, $n_{00}>n_{01}>n_{11}\geq n_{10}$, and $n_{00}-n_{01}\geq 2$, $n_{01}-n_{11}\geq 2$. Numerous experiments show that the modified algorithms of modulation and demodulation above can enhance the robustness of the communication system and decrease the BER significantly.

A UV laser communication platform is built based on the algorithms mentioned above. Outdoor experiments are conducted by applying our test platform in a cloudy afternoon. A series of recordings are made for the pulse response and the energy density corresponding to different receiver elevation angles and communication distances.

Taking advantage of the geometric relation in Ref.[12], it is possible to calculate the energy received at the detector as a function of time, i.e., the pulse response. The pulse response indicates how the multipath scattering affects a transmitted pulse. The dispersion suffered by a pulse transmitted from a source located at 300 m away from the receiver is displayed in Fig.4. The full width at half maximum (FWHM) of the pulse response is about 80 ns, which implies that the bit rate is limited to 12.5 Mbit/s or less[4].

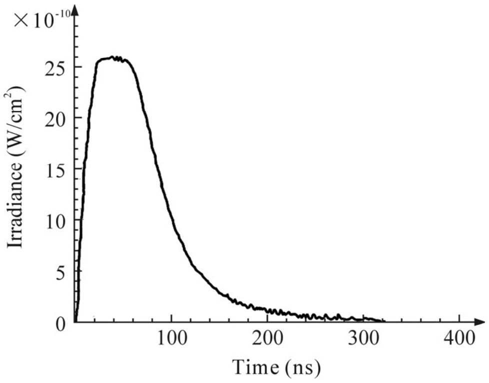

Fig.4 Pulse response with Tx and Rx elevation angles of π/2

Homoplastically, the energy distribution can be calculated by measuring the output signal from the PMT sustaining a fixed magnification. The energy distribution is a significant factor affecting the signal noise ratio (SNR), the communication distance and BER. With the transmitter elevation angle staying around π/3, the energy densities as a function of the communication distance and the receiver elevation angle are shown in Figs.5 and 6, respectively.

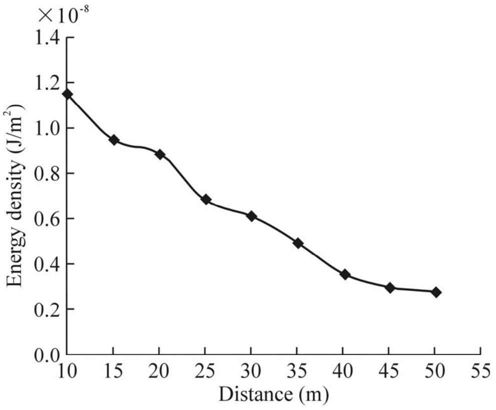

Fig.5 Energy density versus communication distance with Tx and Rx elevation angles of π/3

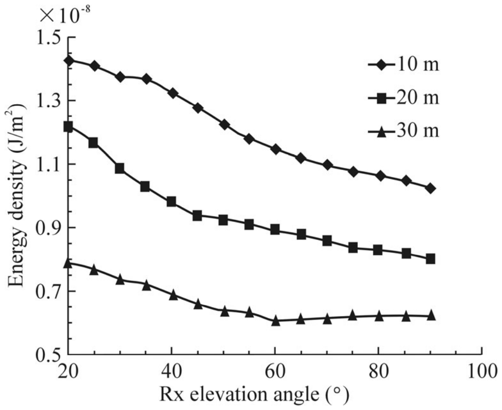

Fig.6 Energy density versus Rx elevation angle for different distances

It can be seen that the energy density experiences an exponential extinction loss with the distance, and the receiver elevation angle has a more and more slight effect on the energy density as the distance increases, so the omnibearing communication can be realized.

Finally, the BER is evaluated in a statistical method with bit rates of 0.6 kbit/s and 1.2 kbit/s for 2FSK and 4FSK, respectively. The results in line-of-sight (LOS) and NLOS communication models are shown in Tab.1. It needs to be specified that the amplification factor of the receiver preprocessing circuit should be accommodated for different communication distances.

Tab.1 BER performance under different conditions

Communication link	Distance (m)	Modulation scheme	Bit rate (bit/s)	SNR (dB)	BER
NLOS	80	2FSK	600	>20	$<10^{-6}$
	80	2FSK	600	>7	$<10^{-1}$
	80	4FSK	1 200	>20	$<10^{-5}$
	80	4FSK	1 200	>7	<0.6
LOS	300	2FSK	600	>20	$<10^{-7}$
	300	2FSK	600	>7	$<10^{-2}$
	300	4FSK	1 200	>20	$<10^{-5}$
	300	4FSK	1 200	>7	<0.4

In order to learn which conditions explicitly impact BER, Tx and Rx elevation angles are fixed at 30° in NLOS communication model at a communication distance of 80 m. The corresponding BER results shown in Tab.1 illustrate that the BER with Tx and Rx elevation angles fixed at 30° can drop from 0.6 to about 10^{-6} when the modulation scheme, bit rate and SNR are adjusted appropriately, while the BER in LOS communication model can drop from 0.4 to about 10^{-7}. Compared with NLOS, it is not difficult to draw a conclusion that BER can be further reduced when pointing approaches LOS communication.

In this paper, the mathematical models of the modulation and demodulation are established, and a number of experiments are conducted to measure the pulse response, the energy density under different conditions and BER for short range NLOS and LOS UV communications on our test platform. Firstly, the pulse response results reveal that the bit rate is limited to 12.5 Mbit/s when UV pulse is utilized as the communication carrier. Secondly, we confirm that the UV extinction loss follows an exponential trend. Thirdly, the energy density changes along with the overlapping area between the transmitter beam width and detector field of view in the geometry model. Lastly, the BER estimated in 2FSK scheme can meet the requirements of some special applications, like transmitting the trigger command of the missiles.

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