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Design of free-space optical transmission system in computer tomography equipment

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Abstract. Traditional computer tomography (CT) based on capacitive coupling cannot satisfy the high data rate transmission requirement. We design and experimentally demonstrate a free-space optical transmission system for CT equipment at a data rate of 10 Gb/s. Two interchangeable sections of 12 pieces of fiber with equal length is fabricated and tested by our designed laser phase distance measurement system. By locating the 12 collimators in the edge of the circle wheel evenly, the optical propagation characteristics for the 12 wired and wireless paths are similar, which can satisfy the requirement of high-speed CT transmission system. After bit error rate (BER) measurement in several conditions, the BER performances are below the value of 10^{-11}, which has the potential in the future application scenario of CT equipment. [DOI: 10.1117/1.OE.57.4.046110]

Keywords: computer tomography; free-space optical transmission; laser phase distance measurement.

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1 Introduction

The technique of computer tomography (CT) uses precise collimation of gamma ray, ultrasonic, x-ray beam, and the high sensitivity of the detector together around certain parts of the body to achieve one-by one scanning.[1–3] Due to the characteristics of faster scanning time and higher resolution images, it can be used for a variety of disease inspection.

High-speed data transmission is one of the key parts in the CT equipment. As shown in Fig. 1, the data transmission is achieved through capacitive coupling between the antennas rotating around the outer edge and the fixed end.[4,5] However, due to the theoretical limitation of the electron migration rate, the techniques based on the capacitive coupling data transmission cannot achieve the data rate more than 2.5 Gb/s, which are also vulnerable to the electromagnetic interference. With the fast increasing in the data acquisition, data rate at 20 Gb/s has been achieved.[6–8] Therefore, the techniques based on the capacitive coupling cannot satisfy the requirement in the future.

Under this circumstance, free-space optical transmission techniques[9–11] can be used to achieve high-speed data transmission in CT equipment. One of the free-space optical transmission schemes is shown in Fig. 2. As shown in Fig. 2, the optical signal is transmitted between the fixed end and the rotating end in the tangent direction of the rotating axis. The outer green circle represents the fixed end of CT. The inner one is the rotating wheel of CT. The main advantage of this scheme is that the free aperture band is only occupied by a small space. However, this scheme requires the length differences are small among the optical paths. Larger differences will introduce symbol interferences among the optical paths, which result in the degradation of the system performance. The tolerance of the optical paths difference is smaller with an increase in the data (symbol) rate. For example, for the on–off keying (OOK) format at the bit rate of 10 Gb/s, the period of each symbol is 100 ps, which corresponding to the optical distance in free space is around 0.03 m. To prevent serious signal distortion, the optical path distance should be < the 1/10 of the optical distance in one symbol period, which is 0.003 m (3 mm). Therefore, the key issue in the design of free-space optical transmission in CT equipment is to fabricate fiber with collimator end in equal length.

In this paper, we experimentally demonstrate a free-space optical transmission system for CT equipment at data rate of 10 Gb/s. Two sections of 12 pieces of fiber with equal length are fabricated and tested by our designed laser phase distance measurement system. It is noted that the 12 pieces of fiber in each section are interchangeable, which facilitate the future replacement if some pieces of fiber are broken. After bit error rate (BER) measurement in several conditions, the BER performances are below the value of 10^{-11}, which satisfy the requirements of the application scenario of CT equipment.

2 Design of Free-Space Optical Transmission System

Our designed free-space optical transmission system is shown in Fig. 3. The original detected signals at 2.5 or 10 Gb/s are directed modulated onto the directed modulated laser (DML)[12,13] or commercially available small form pluggable (SFP) module. Then, an erbium-doped fiber amplifier (EDFA) with maximum output power of 34 dBm and noise figure of 6 dB is used to control and amplify the optical signal followed by 1 to 12 power splitter with 12 pieces of fiber

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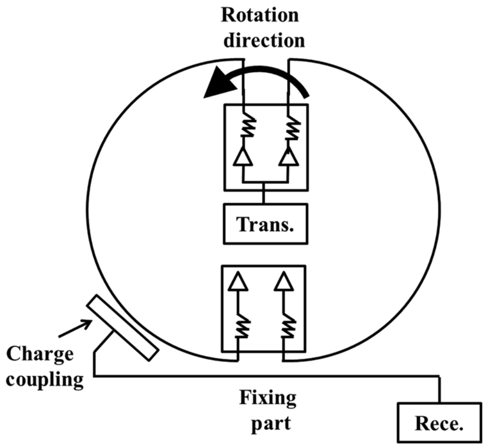

Fig. 1 High-speed data transmission scheme in CT equipment. Trans.: transmitter, Rece.: receiver.

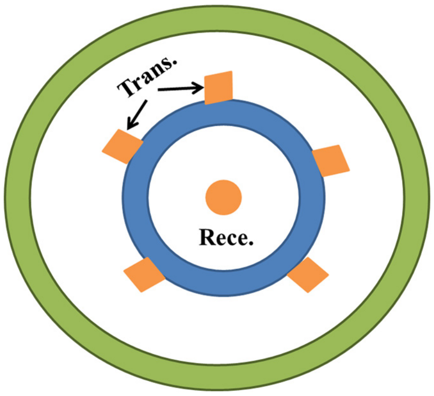

Fig. 2 Free-space optical transmission scheme in CT equipment. Trans.: transmitter, Rece.: receiver.

pigtail in equal length. The 12 fiber ends have 12 flanges to connect 12 pieces of equal-length fibers with corresponding 12 collimators in the end. The fiber used in the experimental demonstration is the standard single mode fiber with loss of 0.2 dB/km. The 12 collimators are located evenly in the edge of a circle wheel. Therefore, the optical propagation characteristics in the air are also the same for every path. As indicated in Fig. 3, the two sections of fiber groups have the same length. This design has the advantage that the fiber with collimator can be easily replaced if the fiber or the collimator is broken. In this way, the 12 streams of optical signals are transmitted simultaneously in the air. After ~50-cm free-space transmission, optical signals will be received by a photodetector or another SFP module. It is noted that the photosensitive surface is located at the center of the circle wheel and exposed in the air for the PD used in the system, where the light beam can arrive at the surface from different angles. The aperture located at the top of the photosensitive surface, as shown in Fig. 3, can guarantee at most two streams of optical signals that are collected by the PD. In our experimental demonstration, the receiver sensitivity of PD is −25 dBm for 10-Gb/s OOK signal. BER is measured by a BER test (BERT) for 2 h, which corresponding to 1.8×10^{13} and 7.2×10^{13} bits for 2.5 and 10 Gb/s, respectively.

One of the key issues in the design of the free-space optical transmission system in CT equipment is the equal optical paths for the 12 streams. For the system shown in Fig. 3, the fiber length in two sections should be seriously considered. One section is that the pigtails of the 1 to 12 power splitter should have equal lengths. Another section is that the distance from one fiber end to the collimator in the other end should also be the same. To test the lengths of the two sections, we design a length measurement system based on the laser phases for the two sections separately, as shown in Fig. 4. One port of a sine wave generator operating at 100 MHz is used to drive the DML to convert the electrical sine wave signal into optical sine wave signal. After transmitting over the device under test (DUT), the optical signal is collected by photodetector and sampled by a digital sampled oscilloscope (DSO) at 250 MSa/s for off-line signal processing. It is noted that the DUT can be the pigtails of the 1 to 12 power splitter or the fibers with collimators in the end. The collimator at the receiver side is also required to focus the light beam for the free-space measurement. For reference, another port of the sine wave generator is

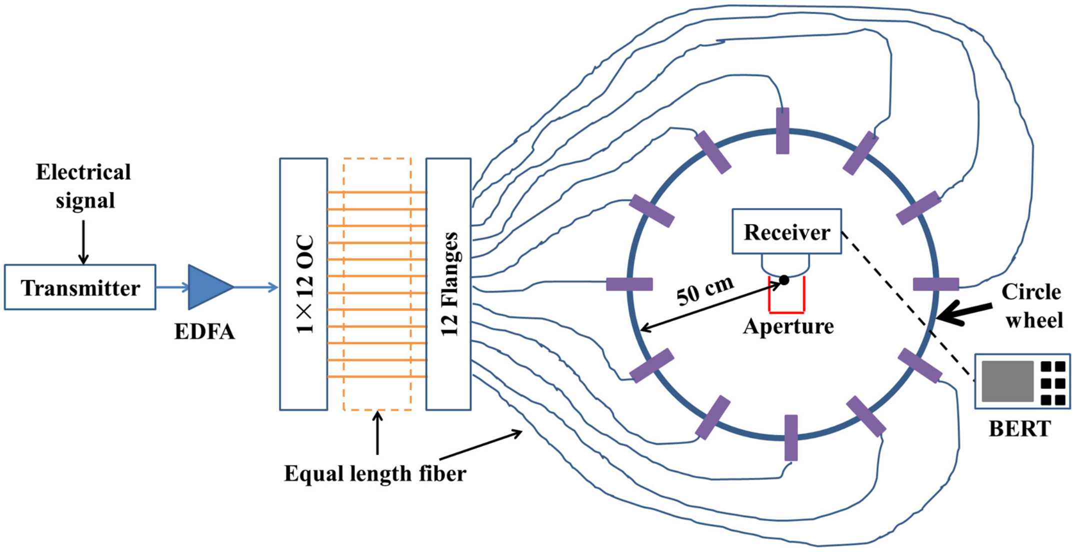

Fig. 3 Designed free-space optical transmission system at 2.5 or 10 Gb/s.

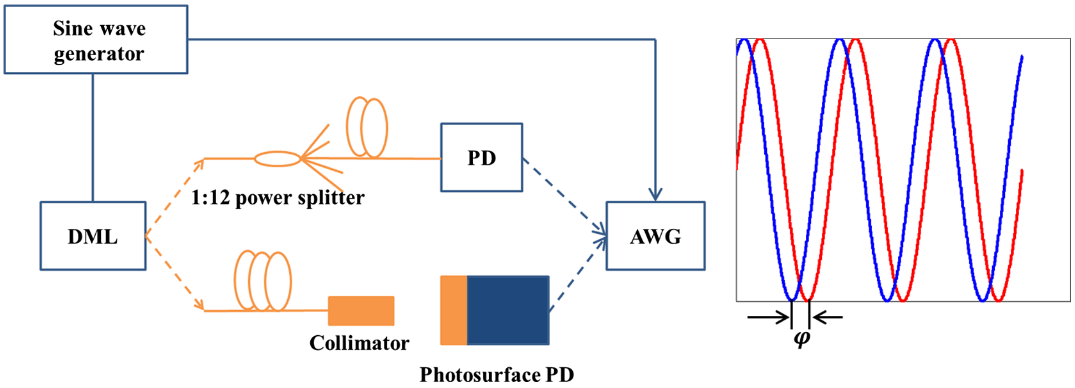

Fig. 4 Scheme of laser phase distance measurement. Inset: phase difference between sine waves.

directly connected to the DSO. As the reference sine wave is not changed over time, we can measure the distance between the two sections of fiber group by comparing the phase differences between the DUT and reference.

The principle of laser phase distance measurement is also illustrated in the inset of Fig. 4. Considering the phase difference of two sine waves is φ, the distance between the two sine waves can be expressed as[14]

$$d = \frac{c}{2\pi n f}\varphi, \tag{1}$$

where c is the velocity of light, n is the reflective index, and f is the frequency of the electrical wave, respectively. Assuming $\varphi = R \times 2\pi + \Delta\varphi$ and R is an integer, Eq. (1) cannot discriminate the case if the phase differences include multiple of 2π. Therefore, a rough measurement is required to guarantee the value of φ is smaller than 2π, or the value of d is smaller than c/nf.[14]

It is noted that the rough measurement is conducted by ruler to prevent the distance difference more than 2 m. As the phase difference between the two sine waves is the same in both frequency and time domains, we take the fast Fourier transform to the sampled two sine waves and then find the phase difference in the peak value, which can be regarded as the value of φ in Eq. (1). It is noted that the accuracy of φ can be improved with a larger number of sampling rate and sampling points. However, a larger number of sampling rate and sampling points may slow down the computer calculation speed. In our experiment demonstration, we find that sampling rate of 250 MSa/s and 1 million sampling points is sufficient to obtain the optimal accuracy, which is further limited by the noise of the system. The value of d is calculated by averaging the results of 1000-time measurements based on Eq. (1). The variance of the 1000 measurements corresponds to the accuracy of our designed laser phase distance measurement system. The distance differences measurement results are shown in Table 1. According to the design of the system, the distance values of fiber pigtails of 1 to 12 power splitter and fiber collimators have almost similar values with variance smaller than 0.2 mm. The differences between the maximum and minimum lengths are also smaller than 1 mm. Therefore, the distance differences of the transmitted 12 channels can satisfy the requirements in CT transmission systems.

Table 1 Results of measured distance differences for the 12 channels.

	Measured distance differences (m)	
Channel index	1:12 power splitter	Fiber collimator
1	1.7751	1.5746
2	1.7751	1.5753
3	1.7746	1.5748
4	1.7747	1.5751
5	1.7746	1.5747
6	1.7749	1.5751
7	1.7745	1.5749
8	1.7751	1.5752
9	1.7746	1.5748
10	1.7749	1.5748
11	1.7751	1.5752
12	1.7746	1.5746

3 Experimental Results

The performances of BER versus transmitter power for 2.5 and 10 Gb/s OOK transmission cases for selected channels are shown in Figs. 5(a) and 5(b), respectively. It can be seen that the BER reduces with an increase in the transmitter power and no BER floor is observed. In both cases, the BER performances can be lower than 10^{-11} when the transmitter power for each path is larger than 17 and 23 dBm for 2.5- and 10-Gb/s OOK signals, respectively. Due to the residual small distance differences, there is a slightly BER performances degradation in the two beams simultaneously reception case. It means that in the practical situation when two beams (Ch5 and Ch6 in our experimental demonstration) are collected by the PD simultaneously, the transmission system can still work at the BER level lower than 10^{-11}. We also show that the BER performances of all the 12 channels are similar at the transmitter power of 17 and 23 dBm for the 2.5 and 10 Gb/s transmission cases, respectively, in Fig. 6.

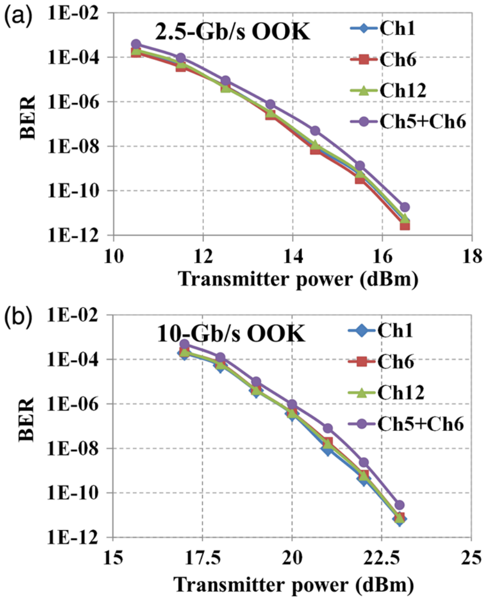

Fig. 5 BER performances of selected channels for (a) 2.5 and (b) 10 Gb/s transmission.

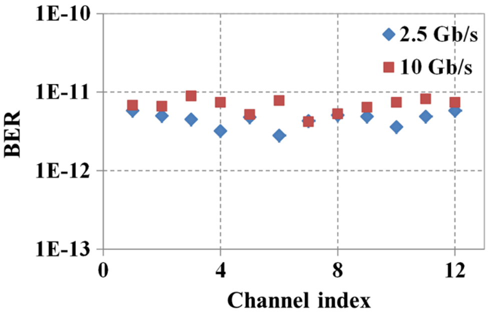

Fig. 6 BER performances of all the 12 channels for 2.5 and 10 Gb/s transmissions.

It is noted that the BER performances are evaluated under static scenario. The BER performances evaluation under rotation scenarios will be conducted in the future study. It is noted that the performance is limited by three factors. The first one is the amplified spontaneous emission noise in EDFA. The second one is the inter-symbol interference induced by the residual small distance differences. The third one is the electrical noise inherently in PD. In our view, high EDFA output power with low noise figure is the key issue to guarantee the stable transmission in CT.

4 Conclusion

In this paper, we design a free-space optical transmission system for CT equipment data transmission. To ensure the steady transmission, 12 pieces of optical fibers with equal length are measured by a specially designed laser phase distance measurement system. By controlling the distance differences among different channels in both wired and wireless scenarios, the BER performances below the value of 10^{-11} can be achieved for both 2.5- and 10-Gb/s OOK signals, which satisfy the requirements in CT data transmission.

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