400-pixel high-speed photodetector for high optical alignment robustness FSO receiver

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Abstract: We fabricated a 400-pixel high-speed photodetector with a 0.85-mm large square size, while maintaining high frequency performance. The high frequency characteristics and optical alignment robustness in a 20 m long distance FSO communication was demonstrated.

1. Introduction

Optical wireless communication technologies, including "Light Fidelity (LiFi)" based on LED light sources and "free space optics (FSO)" based on laser light sources, are very attractive options in beyond-5G wireless communication technology. In particular, high-speed FSO has been studied for indoor optical wireless communication [1], as well as outdoor point-to-point communication applications between buildings and between satellites. For successful FSO, it is essential to receive the laser beam stably. There are two representative FSO system configurations to receive laser beam in free space. One configuration uses mechanical beam positioning systems [2], allowing very precise beam positioning control to 10 μm single mode fiber connected with a small high-speed photodetector (PD). The advantage of this method is that the same power level in free space is maintained in the fiber and on the PD at the receiver side, enabling high data rate communications. However, the positioning system might be unsuitable for low-cost, compact transceiver designs for short-range indoor communication. Excluding the beam positioning system will be helpful for compact indoor transceiver designs such as LiFi systems [3]. The other option for FSO systems is a rough alignment method, where a spreading FSO beam is roughly aligned to a highly sensitive large-area avalanche photodetector (APD) to compensate for low optical power density at the APD. This system aids in compact transceiver design by mitigating the large footprint of the mechanical positioning components. However, the data rate in the FSO system is dominated by the low-bandwidth APD performance. If a high-speed photodetector with a large aperture is developed, a very compact FSO transceiver can be established for indoor FSO communication applications. In this paper, we present a 400-pixel high-speed PD, which is an extended design from our previous works [4-5]. We also discuss the demonstration of 25 Gbps FSO communication in 20 m free space, using the fabricated large aperture (0.85 mm x 0.85 mm) 400-pixel PD.

2. 400-pixel high-speed photodetector

There is a trade-off relationship between photodetector size and 3 dB bandwidth. In general, the larger PD has a lower 3 dB bandwidth. Here, the two factors of CR time constant (f_{CR}) and carrier traveling time (f_{TR}) act as dominant factors to define the 3 dB bandwidth. Roughly speaking, the entire 3 dB bandwidth is dominated by f_{CR} under the thinner absorption layer condition, while f_{TR} is dominant under the thicker absorption layer condition. When adopting the f_{CR} dominant condition in an InGaAs layer, we can design and discuss the 3 dB bandwidth using an electronic circuit (lumped element) model. Here, we propose a large photodetector operating at over 10 GHz, consisting of series and parallel connections of small photodetector pixels using circuit design techniques. Fig. 1 shows our design concept for "a large photodetective area high-speed PD," intended to overcome the trade-off relationship between PD (p-n junction) size and frequency response.

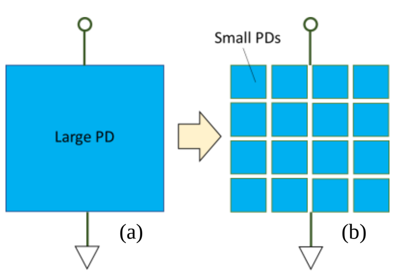

Fig. 1 Design concept of large aperture high-speed PD: (a) conventional design, (b) proposed design with segmented small PDs

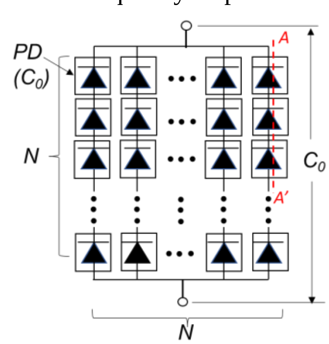

Fig. 2 Circuit design for series and parallel connected PD network in this work

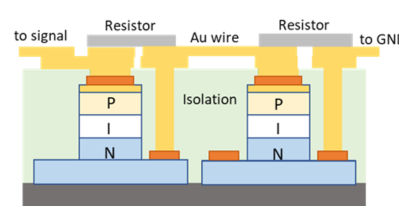

Fig. 3 Cross-sectional view of 400-pixel PD (focusing to A-A' cross-section in Fig. 2)

The large PD area in Fig. 1(a) is divided into smaller 30 μm segmentations (pixels), as shown in Fig. 1(b); the entire photodetective area is preserved between Fig. 1(a) and Fig. 1(b). Each small segmented 30 μm PD is designed for high frequency operation at around 10 GHz. By using circuit design fundamental techniques, the same 3dB bandwidth configured in Fig. 1(b) as that in a 30 μm single PD pixel can be expected from the following technique. Fig. 2 shows the N × N matrix circuit model configured using 30 μm PDs. Assuming junction capacitance C_0 and junction resistance R_o is equal in all small PDs in a 10 × 10 matrix structure (see Fig. 2), the series connected one-dimensional (1-D) array capacitance in each column becomes $C_0/10$. Meanwhile, the entire junction capacitance through the two-dimensional array capacitance with the 1-D parallel connection becomes $C_0/10 \times 10 = C_0$. In addition, series connected junction resistance in the series connected 1-D array section becomes $10 \times R_0$, while the overall resistance of the 10 × 10 PD array is one tenth of $10 \times R_0$. Therefore, the entire junction capacitance and resistance between output port and ground in Fig. 1(b) and Fig. 2 should be equal to C_0 and R_0 in the 30 μm single PD. Thus, a large size PD can be designed to maintain high 3dB bandwidth, without sacrificing high frequency operation. This method would bypass the trade-off relationship.

We fabricated 20 × 20 PD array chips using the circuit design technique above, with a 0.85 mm x 0.85 mm photodetective area, targeting operation above 10 GHz. These large-scale high-speed PDs including 400 pixels were integrated into a small chip as shown in Fig. 4. In a PIN structure based on III-V compound semiconductor, a number of 30 μm pixels were formed and isolated via dry etching process. Subsequently, the PD pixels were connected in series and parallel using a Au-wiring process. To bypass the photocurrent generated by some but not all pixels, we formed additional photocurrent paths using shunt resistors to each PD. The lightwave was illuminated from the backside of substrate. Fig. 5 shows the frequency response measurements. We compared the characteristics among three different PDs: single PD (1-pixel), 2 × 2 PD array (4-pixel), and 20 × 20 PD array (400-pixel). The 3 dB bandwidth (11.8 GHz) in the single PD was in good agreement with that in the simulated result. We found that the 3 dB bandwidths in the 4-pixel and 400-pixel PDs were slightly lower: 10.4 GHz and 10.2 GHz respectively. However, we successfully achieved high bandwidth exceeding 10 GHz, even though the photodetective area was expanded up to 0.85 mm (400-pixel). Note that the 3 dB bandwidth in the several-MHz range was calculated for a 0.85 mm conventional single PD design. Thus, it was confirmed that our design concept was effective.

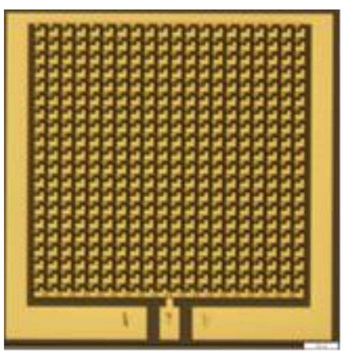

Fig. 4 Photograph of the fabricated 400-pixel high-speed photodetector

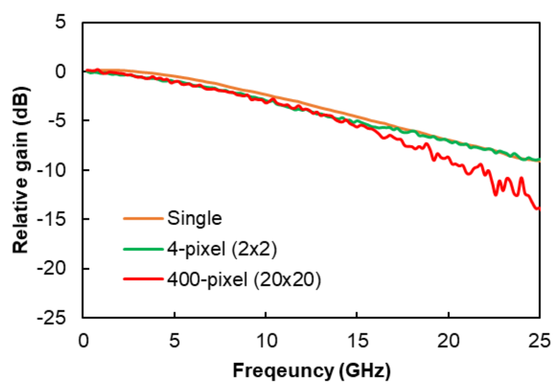

Fig. 5 Measurement results on frequency response for single, 4-pixel, and 400-pixel PDs

3. FSO demonstration using 400-pixel high-speed photodetector

The fabricated 400-pixel PD device was demonstrated for 20 m long distance free space optical (FSO) communication. Fig. 6 shows the experimental setup for the demonstration. On the optical transmitter side, a 20 mm diameter collimator lens attached to single mode fiber was prepared. A 10-25 Gbps (NRZ) optical modulated signal was created by an intensity modulator and a pulse-pattern generator. At the 10 m far point from the optical transmitter, an optical mirror was placed to reflect the optical beam. This resulted in a total distance of 20 m under loop-back conditions. On the receiver side, no mechanical beam positioning system was used, in keeping with a low cost, compact receiver design. It consisted of a condenser lens and a 400-pixel PD module. The fabricated PD was implemented in a metal package attached to an RF connector and a 3 mm thou-hole on the back side of the package. The optical beam through the 70 mm diameter condenser lens was focused onto the 400-pixel back-illuminated PD through the 3 mm thou-hole. The PD output (RF connector) was connected to an amplifier through a bias-tee, which applied bias voltage to the PD. The output signal from amplifier was analyzed using an oscilloscope and a bit-error tester.

We first investigated the optical alignment tolerance between incident beam and the FSO receiver system using 400-pixel PD device, examining it in more detail. While moving the beam position across the receiver lens in the 14 mm range, 20 Gbps BER performance was measured at 1.5 m short distance. As shown in Fig. 7, a U-shape BER curve, less than 1×10^{-7} and 1×10^{-3} at +7.3 dBm and +5.3 dBm, respectively, could be obtained in 14 mm all region on receiver lens. The 14 mm alignment tolerance was caused by the limitations of the moving stage and the 3 mm thou-hole on the package, and not by that of the PD device aperture size.

It was expected that the alignment tolerance for the 400-pixel receiver system would be more than 14 mm. The BER curve at different data rates (10, 20, 25 Gbps) was measured at 20 m long distances. As shown in Fig. 8, we recognized straightforward BER curves from three different data rates, with clear eye-openings in the oscilloscope measurements. A BER of $<1 \times 10^{-8}$ could be obtained at +5 dBm beam power, and a BER of $<1 \times 10^{-3}$ could be confirmed below +3.5 dBm at 10 Gbps. The power penalty of 2.5 dB between 10 Gbps and 25 Gbps could be seen at BER = 1×10^{-3}, due to the short 3 dB bandwidth of 10.2 GHz in 400-pixel PD. Fig. 9 shows the 20 Gbps BER comparison between 1.5 m short and 20 m long distance communications. Here, no difference could be found. We expected that a penalty should be exhibited in the 20 m BER as compared against 1.5 m BER, if the optical alignment tolerance between incident beam and PD were not sufficient. Based on this, we concluded that the 400-pixel PD exhibited high optical alignment robustness in 20 m free space.

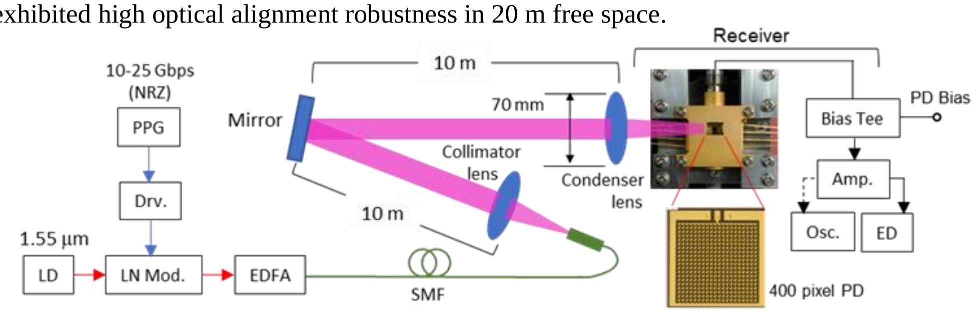

Fig. 6 Experimental setup for 25-Gbps (NRZ) FSO communications in 20 m long free space using 400-pixel PD

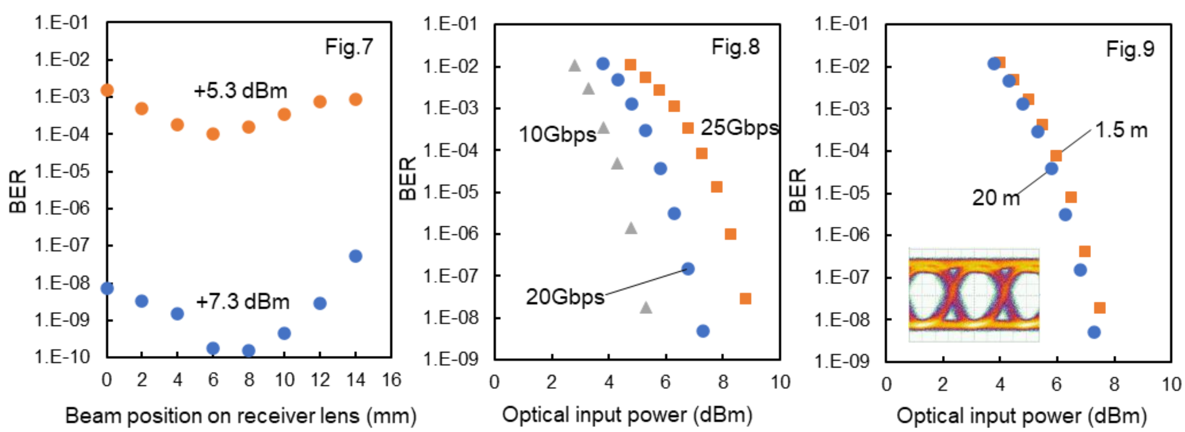

Fig. 7 Optical alignment tolerance measurement results on BER at different beam powers in 1.5 m free space (at left), Fig. 8 BER curves at 10/20/25 Gbps in 20 m long free space (in center), Fig. 9 Comparison of 20 Gbps BERs between 1.5 m short and 20 m long distances (at right).

4. Conclusion

We designed and fabricated a 400-pixel high-speed PD, which allowed us to include a 0.85 mm x 0.85 mm photodetective area while maintaining high frequency performance. This is a proof of design concept for overcoming the tradeoff relationship between high bandwidth (high data rate) PD performance exceeding 10 GHz and high optical alignment robustness, as shown in a 20 m long FSO communication demonstration.

This research has been partly conducted under the contract "R&D of high-speed THz communication based on radio and optical direct conversion" (JPJ000254) made with the Ministry of Internal Affairs and Communications of Japan.

5. References

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