Submillimeter Large High-speed Photodetector for High Optical Alignment Robustness Optical Wireless Communications

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Abstract We present a submillimeter large high-speed photodetector for mitigating optical alignment issues and low-cost receiver design for free-space optical (FSO) communications. In a 10-m FSO communication demonstration, a high data rate of up to 20-Gbps could be successfully achieved with a 4-mm alignment tolerance.

Introduction

Optical wireless communication is an attractive option for mitigating heavy data traffic in 5G/B5G. Two types of optical wireless communication systems exist. Quality aspects of visible light communications (VLC) using LED light sources include a wide field of view (FoV) and making good alignment to receivers easier. However, achieving a high data rate of over 100 Gbps may be difficult. By contrast, a high data rate can be achieved in free-space optical communications (FSO) using a laser light source, as this achieves data rates comparable to those of fixed optical fiber communications. However, achieving good alignment using a small photodetector (PD) in the receiver is a major problem. If a high-speed PD that enlarges the photodetective area to a submillimeter-to-millimeter range is fabricated, a very simple and low-cost FSO system without mechanical functions such as beam tracking and an active alignment function can be realized. Recently, we developed a 6 × 6 parallel output-type photodetector array (PDA) device [1] for a new carrier-less coherent receiver in 40-Gbps mode division multiplexing fiber communications [2] as well as for direct coupling to multi-core fibers in 800-Gbps space division multiplexing communications [3]. A large PD area of 250 μm exists in a 6 × 6 PD array, which has the potential to mitigate optical alignment issues in FSO communications. However, the multi-parallel output design of the PD array may go against a low-cost receiver design but could be modified to a single-output-type design. Some studies on single-output-type large PDAs have reported a 10 × 10 PDA (350 × 400 μm) based on Si/Ge material with a 3-dB bandwidth of 0.7 GHz [4] and a data rate of 1 Gbps with a 10 °-wide FoV in a 4 × 4 PDA for use in VLC communication applications [5]. However, to the best of our knowledge, no large high-speed PDAs greater than 10 Gbps for wireless communications have been reported. In this study, we present a single-output-type submillimeter large high-speed PD that operates up to 20 Gbps. The newly developed PD device and its demonstration of 10-m long wireless communications are discussed in this study.

Design of a submillimeter large PD

Concerning surface or back-illuminated large PDs, a tradeoff relationship exists between the photodetective area (pn junction size) and frequency response. Larger PDs generally xhibit a lower frequency response. To avoid the tradeoff relationship, an integrated large PD consisting of small segmented PDs connected in series and parallel is proposed in this study (see Fig. 1). When the submillimeter large photodetective area is divided into N × N matrixed small PDs, the large junction capacitance (Cj) and resistance (Rj) can be reduced to 1/(N × N). When circuit design techniques are used and small PDs are combined, small Cj and Rj divided by 1/(N × N) can be maintained.

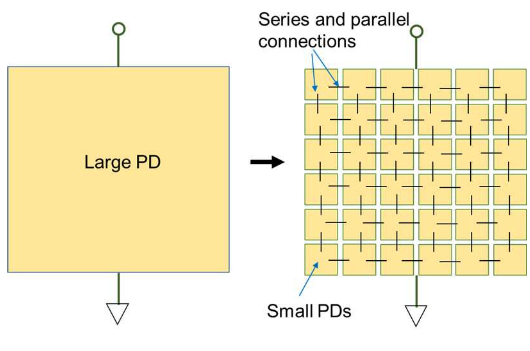

Fig. 1 Design concept of large high-speed PD.

Fig. 2(a) and (b) display representative circuit design models. Models A and B show parallel and series connection methods, respectively. When Model A is adopted, the arrayed junction capacitances connected in parallel in each column can be recognized as N × Cj, and the

978-1-6654-3868-1/21/$31.00 ©2021 IEEE

entire junction capacitance in N × N becomes N × N × Cj. By contrast, the arrayed junction capacitance in each column in Model B exhibits 1/N × Cj, and the entire junction capacitance in N × N becomes 1/N × N × Cj, which is equal to the original small junction capacitance (Cj). In this study, the frequency response was estimated using a microwave circuit simulator in which Cj and Rj were set based on the measurement results for a 40-µm diameter junction. When we assumed a 5 × 5 PD array (40-µm diameter in each PD), it was compared with that in the 40-µm diameter single PD. No difference was found between them (see Fig. 3(a) and (b)). Considering an electrical disconnection under small beam spot irradiation in the N × N PD array, shunt resistors were added to each PD to create a photocurrent path. With 200 Ω shunt resistors, the 3-dB bandwidth was reduced to 8.5 GHz.

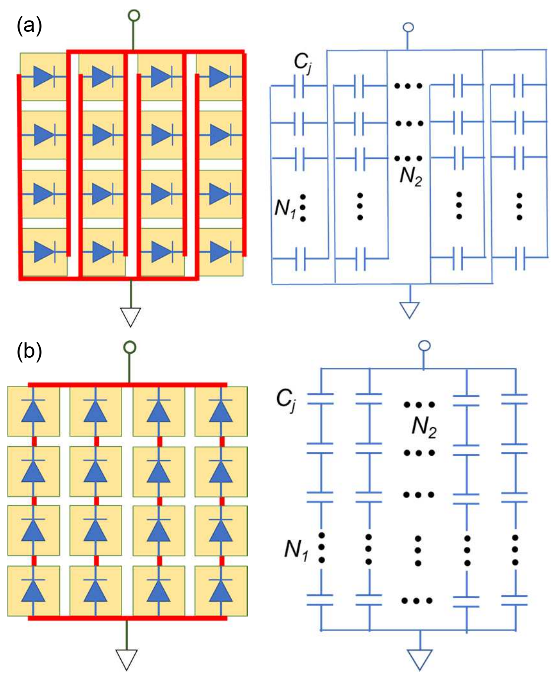

Fig. 2 (a) Model A using parallel connection and its equivalent circuit. (b) Model B using series connection.

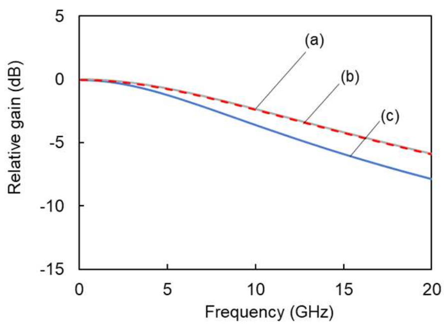

Fig. 3 Simulated frequency response: (a) single PD, (b) 8 x 8 PDA, and (c) 8 x 8 PDA with a shunt resistor.

Fabrication and characteristics

We fabricated an 8 × 8 large high-speed PD, which was internally composed of 40-µm diameter worth square-shaped single PDs. A possible photodetective area of 0.4 x 0.4 mm was designed (see Fig. 4). With an InP/InGaAs PIN layer structure, small PDs were isolated to a semi-insulating InP substrate using a dry-etching process, and an anode in a PD was connected to a cathode in a subsequent 8-series PD. The 8-series connected PD arrays were connected in 8-parallel. The eight cathodes in the 8 × 8 PD array were combined to act as a signal line in the GSG electrode. The eight combined anodes were connected to the ground metal. A lightwave was introduced from the back side of the substrate. To confirm the proposed concept, the frequency response in the 8 × 8 large PD was compared with a small single PD. Fig. 5 shows the measurement results of the frequency response at 20 GHz. We achieved the same 3-dB bandwidth of 8.5 GHz in the 8 × 8 large PD and single PD. At 20 GHz, a 3–4 dB difference between them was observed. This was supposedly due to additional parasitic impedance in the 8 × 8 PD design. The measured radio frequency (RF) performance was sufficient to demonstrate optical wireless communications.

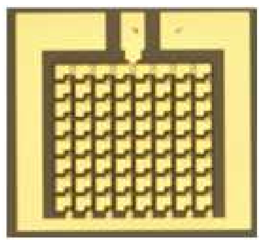

Fig. 4 Photograph of the fabricated 8 x 8 PDA.

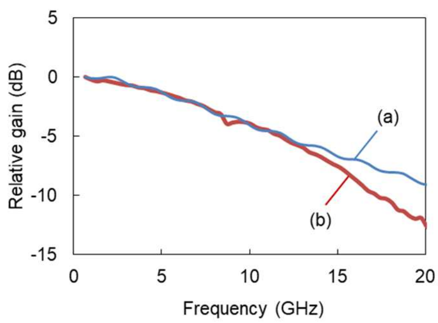

Fig. 5 Measurement results on (a) single PD and (b) 8 x 8 PDA.

10-m wireless communication demonstration

In our optical wireless communication demonstration, a simple configuration for the experimental setup was exploited, as shown in

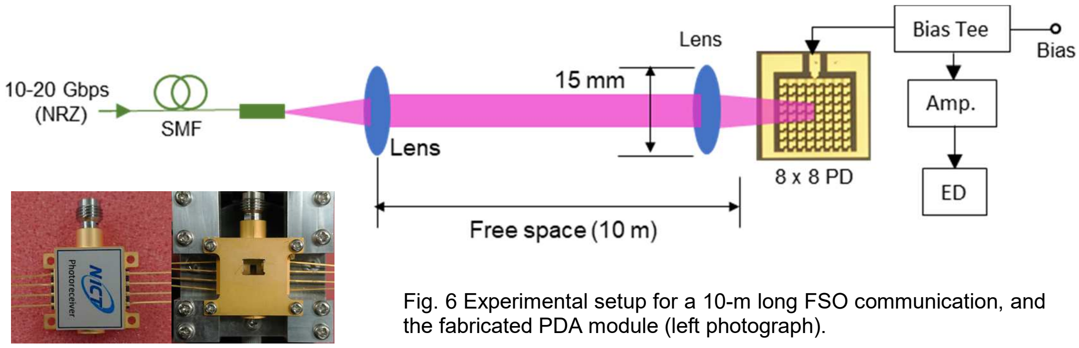

Fig. 6 Experimental setup for a 10-m long FSO communication, and the fabricated PDA module (left photograph).

Fig. 6. No beam tracking or active alignment functions were installed, as our intent was to produce a low-cost receiver design. A single lens and the newly developed 8 × 8 large PD module were constructed to act as a receiver. On the transmitter side, a 10–20 Gbps (NRZ) signal was prepared using an intensity modulator and a 1.55-µm laser source. The collimated lightwave (3.8-mm diameter) was implemented in a 10-m free space and was transmitted onto a 15-mm diameter condenser lens in front of an 8 × 8 PD array. Here, the PD array device was installed in a metal package attached to a V-connector (right side of Fig. 6). On the backside of the package, a small thru-hole was made to receive the beam for the back-illuminated PD. The PD output signal was amplified by an RF amplifier through a bias-tee circuit and was analyzed using an oscilloscope and an bit error rate tester. Fig. 7 shows the bit error rate (BER) measurement results at 10 and 20 Gbps. We determined that a low input power of +4 dBm achieved a BER of < 1×10^{-3} at 10 Gbps, and a higher power (+12 dBm) was required for a BER of < 1×10^{-3} at 20 Gbps. The penalty corresponded to 8 dB. Subtracting the gain difference between the 10- and 20-Gbps amplifiers can improve it to 4 dB.

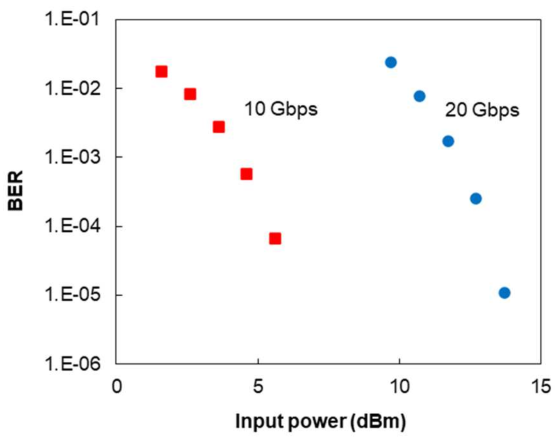

Fig. 7 BER measuremnt results with optical input power at (a) 10 Gbps (squre), and (b) 20 Gbps (circle)

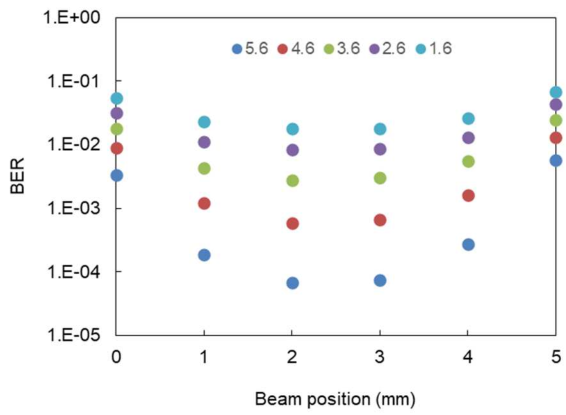

Fig. 8 BER at 10 Gbps when the beam position in 10-m free space is changed, with different input power levels (5.6/4.6/3.6/2.6/1.6 dBm)

Fig. 8 shows the BER measurement results when the beam position in the receiver lens with a diameter of 15 mm is moved. Even when a 10-m long free space communication setup without beam tracking and active alignment functions was produced, a high optical tolerance in the BER curve was achieved. With various optical input power levels, the U-shaped BER curve depended on the input power. At a BER of 1×10^{-3}, a 4-mm large optical alignment tolerance could be confirmed at a +5.6-dBm input power, and a tolerance of 3 mm was recognized at +4.6 dBm.

Conclusion

We designed and fabricated a single-output-type submillimeter large high-speed PDA device configured with series-connected wiring networks to mitigate the optical alignment issue. In a 10-m long FSO communication demonstration, a high data rate of up to 20 Gbps could be achieved with a 4-mm alignment tolerance in free space. A low-cost, short-range indoor wireless communication promises to be a good application for this PDA device.

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