Multi-Stacked Large-Aperture High-Speed PIN-Photodetector for Mobile-FSO Communication

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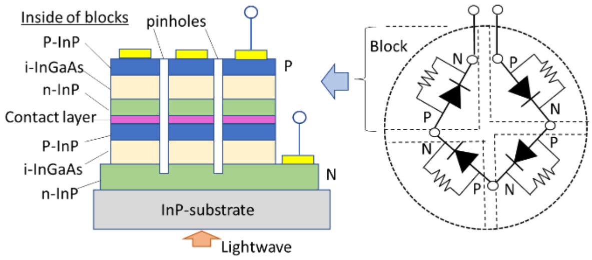
Abstract We demonstrated a high-data rate mobile-FSO communications up to 20 Gbps assuming 10-20 m short distance communication using a newly developed multi-stacked large PIN-PD and a compact transceiver including the beam tracking system.

Introduction

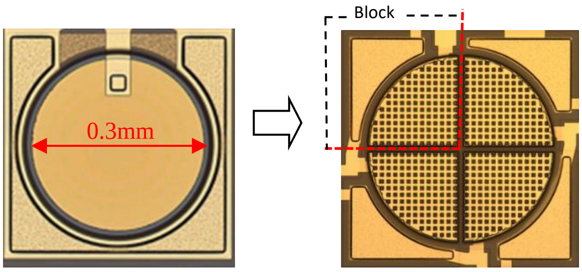
Optical wireless communication is a good candidate for beyond 5G (B5G) technology, in addition to the conventional micro-wave to millimeter-wave wireless communications. Although it has been mainly studied for outdoor applications between satellites, including buildings [1], short-range communication including indoor applications [2], must be considered and investigated as a part of B5G. High data rate over 50 Gbps /λ is reported in the fixed point-to-point outdoor wireless communication [3] such as back-haul links. In addition to the fixed optical wireless system, the high data rate in the short-range mobile communications might be highly demanded for office, factory networks, and drone, drive-thru communications etc. in the future. In this study, we successfully demonstrated a mobile-FSO communication operated at moving speed of 400 mm/sec using a newly-developed multi-stacked large PIN photodetector and a compact mobile FSO transceiver assuming short-range communications.

Multi-stacked larger-aperture PIN-PD

We designed and fabricated a 0.3-mm diameter large aperture size high speed photodetector (PD) operated up to 7.6 GHz bandwidth using multi-stacked PIN structure applying a photodetector's integrated technology in our previous works [4]. As the FSO beam is always moving in the mobile communication, the beam position on photodetector surface might be varied and fluctuated, even though a beam tracking function is used in the receiver system. Therefore, the effective aperture size (photodetective area) in the photodetector should be designed as large as possible. However, a trade-off relationship between the photodetective area (p-n junction size) and 3-dB bandwidth exists. For example, a 100–200 MHz range 3-dB bandwidth can be expected from a 0.3-mm diameter photodetector. To overcome the trade-off relationship, we proposed a multi-stacked PIN photodetector structure to reduce the junction capacitance to 1/64 theoretically compared to the conventional large PIN photodetector structure.



(a) Fig. 1 (b)



(a) Fig. 2 (b)

Fig. 1 (a) Cross-sectional view of a two-stacked PIN-PD block, (b) schematic circuit diagram of four series connected two-stacked PIN-PD blocks, Fig. 2(a) top-view of 0.3 mm diameter conventional PIN-PD, (b) fabricated 0.3 mm diameter four-series connected two-stacked PIN-PD blocks

Fig. 1(a) shows the proposed schematic device structure, which comprises a two-stacked PIN structure in the vertical direction to the substrate with 5-μm small pinholes (1/2 fill factor). Each factor provides a 1/2 reduced junction capacitance against the capacitance (C_{j0}) of a conventional 0.3-mm large diameter photodetector (see Fig. 2(a)). Each part in the four divided areas in Fig. 1(b) can allow 1/16 x C_{j0}. By connecting the four divided parts in series, 1/64 x C_{j0} can be expected. Under applying a reverse bias condition for the high frequency response, the boundary between n-InP and p-InP in two-stacked p-InP/i-InGaAs/n-InP can be recognized as the forward bias state through the contact layer. In the measurement results of frequency response for (a) sample-A: a fabricated conventional 0.3 mm PIN-PD (see Fig. 2(a)) and (b) sample-B: our proposed multi-stacked 0.3 mm PIN-PD in this work (see Fig. 2(b)), we found the apparent difference between samples A and B. The 3-dB bandwidth in sample B could be extended to 7.6 GHz from 0.2 GHz in sample A, in which 38 times extension could be successfully recognized, as shown in Fig. 3. In the in-plane responsivity distribution of the multi-stacked 0.3 mm PIN-PD, we could not recognize any affection against 5 μm pinholes by scanning the beam position on the PD surface, but a “drop” of the responsivity at the center region (non-sensitive region) could be found with the small beam spot. However, it was mitigated and flatten with the expanding beam size.

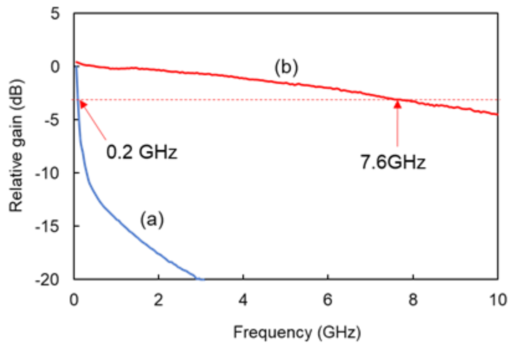


Fig. 3 Frequency response for (a) conventional Φ0.3 mm PIN-PD, (b) fabricated two-stacked Φ0.3 mm PIN-PD

Compact mobile-FSO transceiver

We developed a compact mobile FSO transceivers installed with FSO beam positioning and tracking system applied from our previous works [5]. Cascaded coarse and fine-tracking processes were implemented to realize a stable communication link while the FSO transceivers are moving. In the coarse-tracking process, a 15-mm diameter two-axis fast steering mirror, an IR camera as the acquisition sensor, and a reference beacon light (940 nm LED) with a large beam divergence were implemented. Additionally, fine-tracking process was implemented, which consisted of both movable lenses and 3-axis voice-coil motors actuators that are implemented to provide auto-focus and optical image stabilization functionalities, to prevent from the effects of the random beam angle of arrival fluctuations. Using the developed beam control and prediction software, the tracking latency less than 5 msec could be obtained. The wide field of view (FoV) was realized to be 11.5° using the two-axis fast steering mirror. The main antenna body size was 5 cm × 5 cm. The newly developed photodetector implemented into a metal package was placed behind the movable lens. The distance between the transceivers in this demonstration was set to 2.1 m, and the position of the transceiver and its moving speed could be controlled by the programable x-z moving stage put under the FSO transceivers. The moving stage can swing in 0.4 m range in the x-(horizontal) direction and in the 0.1 m range in z-(vertical) direction respectively. Assuming that the 10-20 m short distance indoor/outdoor movable FSO communications, the maximum speed could be controlled up to 400 mm/sec (1.44 km/h) at a 2.1-m far distance point in this demonstraion, which corresponded to a relative moving speed of 6.9–13.7 km/h at 10–20 m far distance point between transceivers, where the demonstration was provided by moving transmitter side between the two transceivers. (see Fig. 4).

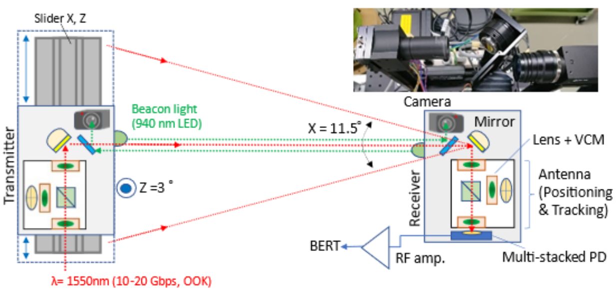


Fig. 4 Experimental setup for movable FSO communication demonstraion at 400 mm/sec in 2.1 m

Mobile-FSO communication demonstration

First, we evaluated the tracking and alignment capability in our fabricated movable FSO system by using different aperture size PDs, where sample A is a 0.1-mm diameter in conventional PIN-PD, sample B is the 0.2-mm diameter in conventional PIN-PD, and sample C is the 0.3-mm diameter in multi-stacked new PIN-PD. The DC photocurrent from the PDs was monitored and recorded, in which the recorder’s sampling speed is 20 sps and the recording time is 50 sec, when a 1.55-μm laser beam from the transmitter with moving speed of 400 mm/sec was tracked by the receiver at 2.1 m far point. Here, the photocurrent fluctuation or variation should appear when the alignment to PD is not sufficient during the moving stage. In Fig. 5(a), many long dips in the photocurrent suggested that the beam was located out of the 0.1 mm PD. By increasing the diameter to 0.2 mm, the dips was not seen with a small periodic fluctuation (see Fig. 5(b)). In the result, the minimum size of the PD diameter in our movable FSO system was required to be more than 0.2 mm at least. The periodic fluctuation in Fig. 5(b) was mitigated in sample C (Fig. 5(c)), but it exhibited short dips due to the non-photoresponse region between four blocks in Fig. 2(b). By changing the moving speed of 0, 50, 100 and 400 mm/sec, the DC photocurrent in sample C was recorded. Except the 0 mm/sec result, the photocurrent variation level was almost same, suggesting that the tracking function contributed sufficiently to the new PD (sample-C) up to 400 mm/sec. Using a limiting RF amplifier, we considered that the short dip affection due to the 20 % photocurrent variation could be mitigated to a minimum in OOK communication demonstration.

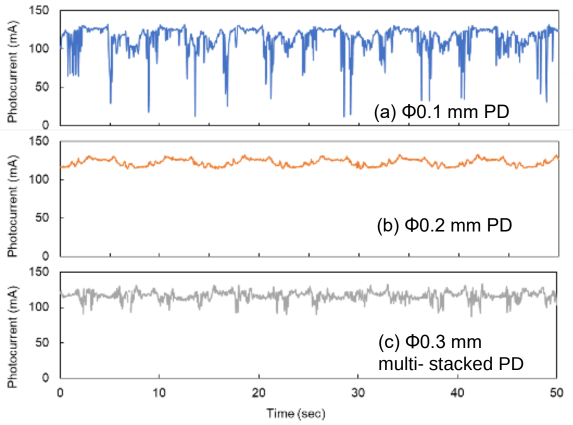


Fig. 5 Tracking and alignment testing in the FSO system while moving stage using (a) (b) 0.1-mm and 0.2-mm diameter conventional PDs, (c) newly developed two-stacked 0.3mm PD

Subsequently, we had a demonstration for a movable FSO communication using the new PD at 10 and 20 Gbps (OOK). Fig. 6 (a)(b) shows the eye diagrams and BER curves without the moving condition. A straightforward BER curve at 10 Gbps could be obtained, and 7 dB power penalty was found at BER= 1 × 10^{-6} between 10 and 20 Gbps curves. When moving the transmitter at 100 and 400 mm/sec, the BER level was measured at 10 Gbps and monitored for 60 min. to confirm the communication stability (Fig. 7(a)). The initial BER level of 10^{-8}-10^{-9} with stopping at -1.5 dBm optical input power was changed to 10^{-7} and 10^{-6} at 100 and 400 mm/sec, respectively. Comparing those two results on different moving speed, the 100 mm/sec lower moving speed allowed more stable BER results in 60 min. long term measurement. At 20 Gbps, the BER level at +3 dBm optical input was monitored simultaneously under both x-direction and x-z direction (zigzag) moving conditions at 400 mm/sec (Fig. 7(b)). Few differences were found between them, and the BER level for 60 min. was maintained below 3.8 × 10^{-3} (7% FEC limit).

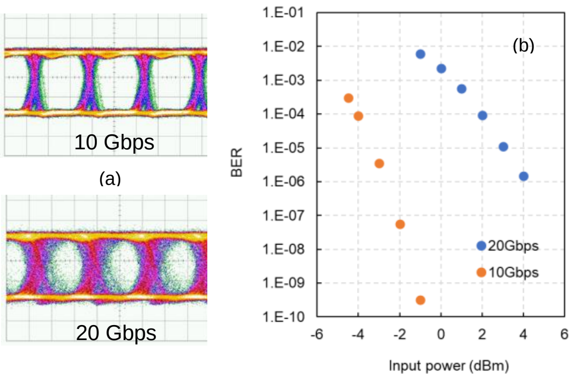


Fig. 6(a)(b) Eye diagrams and BER curves at 10/20 Gbps (OOK) when the stage is stopped,

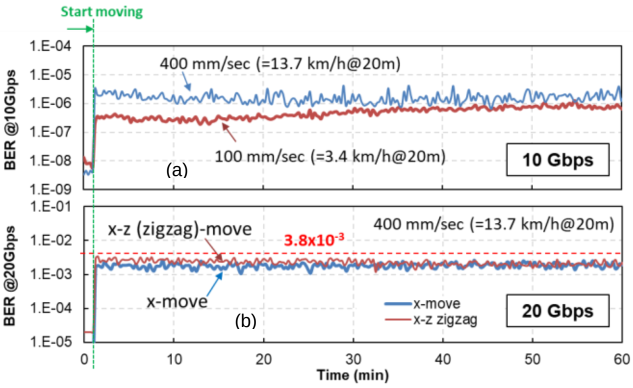


Fig. 7 (a) 10 Gbps BER variation in 1 hour when moving the stage at moving speed of 100 and 400 mm/sec, (b) 20 Gbps BER variation with simultaneous moving to x-z direction (zigzag) and only to x direction at 400 mm/sec

Conclusions

We demonstrated a high-speed mobile FSO communication operated at 400 mm/sec in 2.1 m distance using a newly developed multi-stacked large PIN photodetector and a compact mobile FSO transceivers installing beam positioning and the tracking system, where it was assumed that the relative moving speed was 6.9–13.7 km/h in 10–20 m short range communication. In the demonstration, the high data rate FSO communication up to 20 Gbps could be successfully achieved.

Acknowledgements

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