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Resonant-Cavity Two-Dimensional Photodetector Array and its Application to WDM-FSO Communication

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Abstract: We present a resonant-cavity two-dimensional photodetector array device integrated with small photodetector pixels of different cavity lengths. A proof of concept in this device for WDM-FSO communication was successfully demonstrated at 25-Gbps per channel.

Introduction

In the next generation of wireless communication, particularly in beyond-5G communication, increasing demands for high data rates, low latency, and high connectivity will be met with the use of a new radio band over 28–40 GHz. The carrier frequency in the new radio band tends to approach toward 100 GHz [1]. On the other hand, free-space optical (FSO) communication is another promising candidate for wireless communication technology, in addition to conventional radio frequency wireless communications. No frequency band allocation or wide bandwidth comparable to fiber communication is available in the FSO communication field. Although FSO technology has been studied mainly for outdoor communication applications, such as between buildings and satellites, it has been extended to indoor short communication application fields in recent studies [2]. One of the major issues in FSO systems is the optical alignment problem in free space. To solve this problem, a beam positioning system must be installed in the transceivers [3]. Moreover, wavelength-division multiplexing (WDM) technology is widely used in FSO communication to increase the data rate. The WDM-FSO beam under the beam positioning system is aligned to a 10 μm single-mode fiber (SMF) [4] and is de-multiplexed to several outputs by using an arrayed waveguide (AWG) component (see Fig .1 (a)). The drawbacks of this system are its high cost and bulkiness of the FSO transceiver design. If a high-optical-alignment-robustness FSO transceiver is designed with a large-aperture photodetector (PD)-integrated WDM color filter instead of the 10 μm SMF and an AWG, a compact and low-cost transceiver design can be established (Fig. 1(b)). Recently, we developed a two-dimensional high-speed PD array device for space and mode division multiplexing fiber and FSO communication applications [5-6]. In this study, we present a new design for a high-speed WDM PD array device using a resonant-cavity structure based on our high-speed PD array technologies. The design and performance of the device are discussed and an FSO demonstration is presented in this paper.

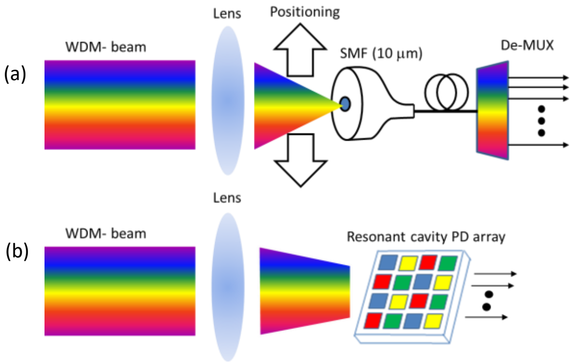

Fig. 1: Schematic view graph of (a) conventional WDM-FSO receiver system and (b) proposed WDM-FSO receiver system using a large-aperture resonant-cavity PD array

Resonant-cavity high-speed 2D PD array

We designed a two-dimensional 4 × 4 high-speed PD array device using the Fabry–Perot interference effect in a vertical resonant-cavity structure. The proposed PD array device exhibits (1) high optical alignment robustness in a 4 × 4 two-dimensional in-plane structure and (2) has the ability to select wavelengths against the WDM-FSO beam. When the 4-WDM-FSO beam hits any four PDs simultaneously, four parallel WDM electrical signals are generated. It is well known that a photocurrent is resonated and enhanced by a front distributed Bragg reflector (DBR) mirror and an end metal mirror in a PIN-PD structure.

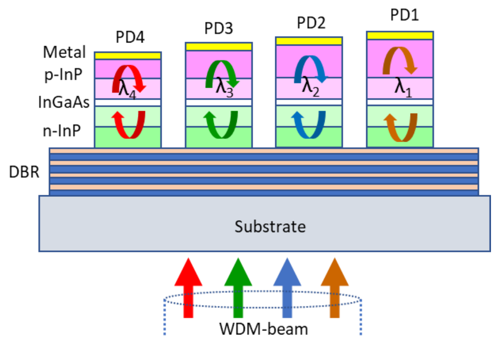

Fig. 2: Cross-sectional view of resonant-cavity PD array

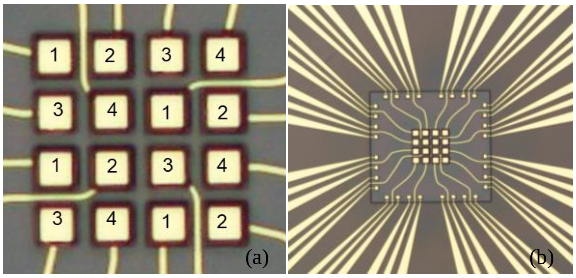

Fig. 3: Photograph of PD array: (a) focused on the 4 x 4 PD array part with the PD1-PD4 location; (b) a wide view

The resonant characteristic of the photocurrent (responsivity) depends on the cavity length, reflectivity of both the front and end mirrors, and the absorption layer thickness. A thick absorption layer and low-reflectivity mirror provide a broad resonant peak performance in the spectral responsivity. Fig. 2 shows the PD pixels consisting of thick-p-InP/thin-InGaAs/thick-n-InP with a DBR front mirror and a metal end mirror. Four different center wavelengths in the C-band were designed, with different cavity lengths for each PD. For simultaneous FSO-beam irradiation of any four PDs with four different center wavelengths, a 30 μm PD pixel layout in the 4 × 4 array was arranged in the order of PD1-PD2-PD3-PD4 in the first and third rows and PD3-PD4-PD1-PD2 in the second and fourth rows, as shown in Fig. 3 (a). Ground-signal-ground Au wiring was used to connect the p and n electrodes (Fig. 3 (b)).

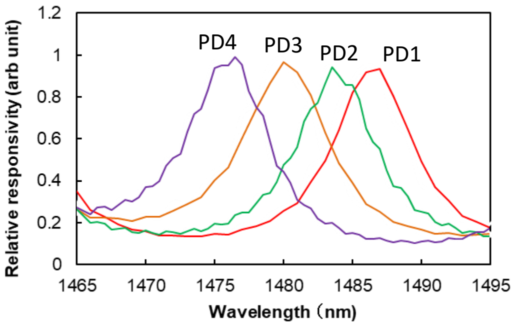

Fig. 4: Measured spectral responsivity in four PDs

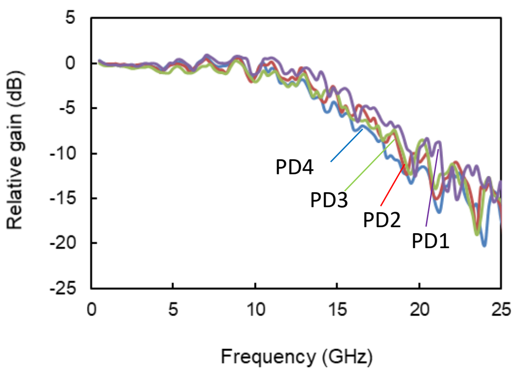

Fig. 5: Measured frequency response in four PDs

We characterized the fundamental properties of both the spectral responsivity and high-frequency response for the fabricated 4×4 PD array device. As shown in Fig. 4, four clear resonant peaks with four different center wavelengths could be observed. These four wavelengths were 1476 nm, 1480 nm, 1483.5 nm, and 1487 nm. These wavelengths were 40-50 nm shifted in the short-wavelength region against our target wavelength (C-band), and the center wavelength pitch in each resonant wavelength was varied from 3 nm to 6 nm against our target pitch (10 nm). The cause was presumed to be the fabrication error in the etching process. Importantly, a relevant factor in this integrated device was the crosstalk effect in each channel for the WDM-FSO demonstration. Focusing on the PD1 channel, the crosstalk was estimated to be as low as 7.1 dB between PD1 and PD2, 14 dB between PD1 and PD3, and 16 dB between PD1 and PD4. A lower crosstalk in the 4-WDM PD array device will be achieved by optimizing the fabrication process. Fig. 5 shows the frequency responses in the 30 GHz range for the PDs with four different cavity lengths. Here, intrinsic InP two-spacer layers sandwiched a very thin InGaAs absorption layer to reduce the junction capacitance and improve the 3 dB bandwidth. Owing to the spacer layers, three times higher 3 dB bandwidth (15-17 GHz) could be successfully obtained, in contrast to using no spacer layers.

WDM-FSO demonstration

Fig. 6 shows the experimental setup for the WDM-FSO communication demonstration using the fabricated 4 × 4 PD array device. To confirm the design concept of our device (high optical alignment robustness and simultaneous WDM beam detection in any 4 × 4 matrix), a 2-WDM FSO setup with 1476 nm and 1487 nm was configured for PD1 and PD4 pixels, as shown in Fig. 6 (left). Two intensity modulators, operating at 1476 nm and 1487 nm, were driven by a pulse pattern generator (20-25 Gbps, NRZ) and two independent laser sources. The two optical power levels were adjusted to be the same, and the output was combined using an optical coupler and launched from the collimator lens to free space. After 1.5 m free space transmission, the 2-WDM-FSO beam was directly detected by the 4 × 4 PD array through a lens. Under a slightly expanded beam condition achieved by changing the focus position, PD1 and PD4 were simultaneously covered by the beam. Here, the crosstalk was as low as 16 dB following the

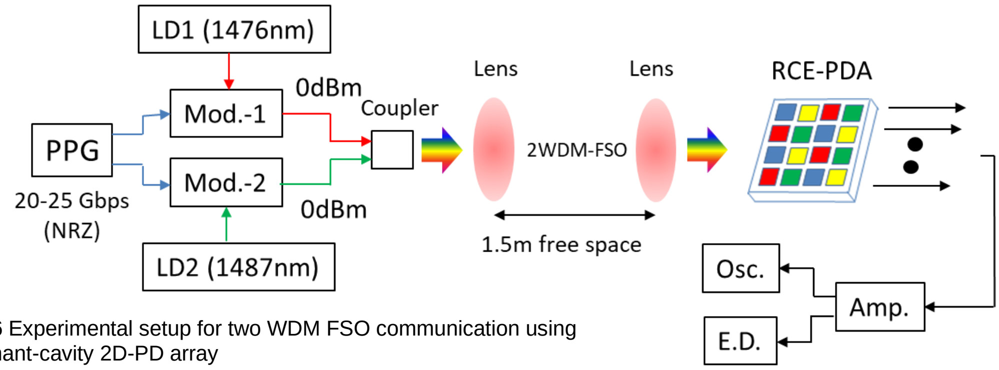

Fig. 6 Experimental setup for two WDM FSO communication using resonant-cavity 2D-PD array

characterization in the previous section. The PD1 and PD4 outputs were amplified by an RF amplifier and analyzed using an oscilloscope and a bit error tester. For optical alignment tolerance evaluation in the FSO system, the four-color CW beam position on the receiver lens was moved to the x-axis in a 15 mm diameter lens. Four photocurrent profiles could be clearly observed from the four PDs aligned to the row side. Each photocurrent profile was seen within a 2 mm range on the receiver lens. Therefore, the optical alignment tolerance of the receiver lens in the FSO system was estimated to be 8 mm.

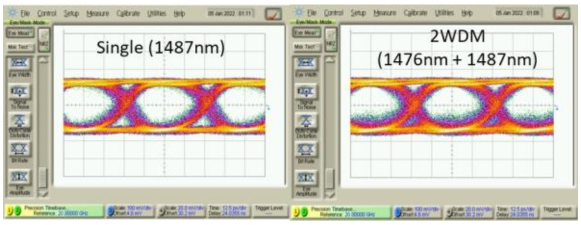

Fig. 7: Eye-diagrams at 20 Gbps in PD1 for single 1485 nm beam (left) and two WDM beam (right) detection

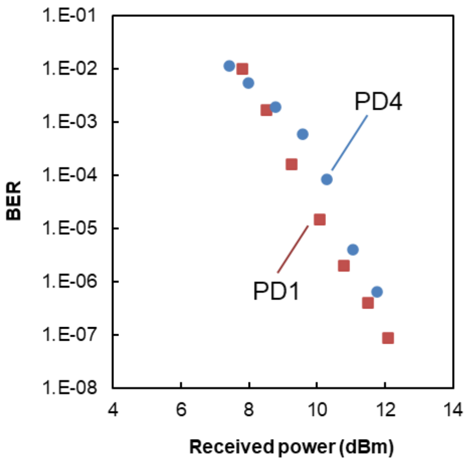

Fig. 8: BERs on PD1 and PD4 for two WDM beam detection at 25 Gbps

In the FSO communication demonstration, we observed the crosstalk feature from the eye diagrams by applying two beam conditions; condition A: simultaneous irradiation of two different-wavelength beams and condition B: irradiation of a single beam. Fig. 7 shows the eye diagrams at 20 Gbps in PD1 outputs under the single 1476 nm beam and two WDM beam (1476 nm + 1487 nm) irradiation conditions. We recognized that very few effects of crosstalk could be observed from the two conditions. Fig. 8 shows a 25 Gbps bit error rate (BER) curve for the simultaneous detection of two WDM-FSO beams in PD1 and PD4. The PDs exhibited very similar BERs, which suggested good uniform characteristics (frequency response and responsivity) between PD1 and PD4. Over +9 dBm simultaneous irradiation to two PDs, a BER lower than 1×10^{-3} could be achieved from each PD with a total data rate of 50 Gbps. By optimizing the fabrication condition in future work, the PD array can potentially achieve 100 Gbps using a channel WDM-FSO condition with low crosstalk.

Conclusions

We designed and fabricated a large-aperture resonant-cavity 4×4 high-speed PD array and demonstrated high data-rate wireless transmission at up to 50 Gbps in two channels. It has considerable potential to achieve both transmission up to 100 Gbps in four channels by optimizing the fabrication process and improvement of high optical alignment robustness.

Acknowledgements

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