100-Gbps 2-SDM 2-WDM FSO beam direct detection using resonant cavity 4x4 photodetector array

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Abstract: We fabricated a high-speed resonant cavity 4x4 photodetector array, which has two functions for high optical alignment robustness and specific wavelength selection. In the 2-SDM 2-WDM FSO communication, 100-Gbps high data rate was successfully demonstrated.

1. Introduction

Optical wireless communication is a promising candidate for wireless communication technology, in addition to conventional radio frequency (RF) wireless communications in beyond 5G (B5G). In particular, a high-data-rate wavelength division multiplexing–free-space optical (WDM–FSO) communication has been demonstrated using a beam positioning system to a single-mode fiber and de-multiplexed to multi-parallel optical outputs using an arrayed waveguide grating (AWG) [1]. A limitation of this system is the lack of compactness and a high-cost design owing to the beam positioning and tracking system. The positioning system and parallelized receivers connected to the AWG should be simplified as much as possible to overcome this problem. Meanwhile, space division multiplexing (SDM) technology using multi-core fibers has been studied to increase the data rate in advanced optical fiber communication networks. High-density multi-core fibers such as 32 multi-core and 3-mode 38 multi-core fibers have been developed [2]. Recently, the core number has been reduced to 4-multi-core fibers to decrease the expanded cladding diameter [3]. The fiber technology enables a data rate of 400 Gbps using the pulse amplitude modulation 4-level (PAM-4) format [4] for short reach communications such in as data center networks. Therefore, SDM technology compatible with FSO might be demanded for future communication technologies in B5G or 6G communication. Seamless communication technology between SDM and FSO has been considered (see Fig. 1). In this paper, we present a newly developed large-aperture 4×4 resonant cavity photodetector (RC-PD) array device applied from our PD integration technology [5] and the 2-SDM 2-WDM FSO communication demonstration to both improve the optical alignment robustness and select a specific WDM wavelength in free space. It will be scalable to NxN RC-PD array devices for high data rate SDM-WDM FSO beam direct detection. The high-speed RC-PD integrated array device, characteristics, and its demonstration for 2-SDM-2-WDM communication are discussed.

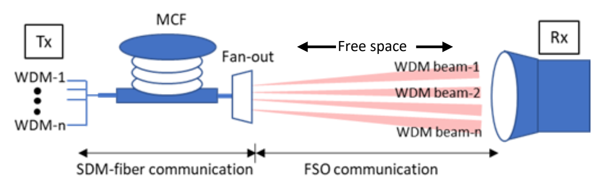


Fig. 1 A concept for seamless communication between SDM fiber communication and FSO wireless communication

2. Resonant cavity 4×4 photodetector array

Assuming a large-aperture NxN 4-λ RC-PD array device in Fig. 2, a small-scale model of 4×4 PD array device was fabricated in this study to confirm a proof of our concept for SDM–WDM–FSO communication (Fig. 3) ; it was integrated with 30-μm small PD pixels with four different cavity lengths with back illumination. The aperture size of the entire 4×4 PD array region as large as 162 μm × 162 μm would facilitate improving optical alignment robustness.

Fig. 2

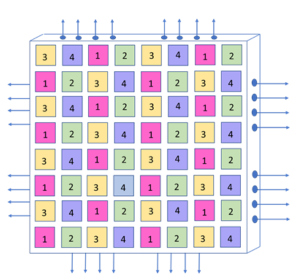


Fig. 3(a)

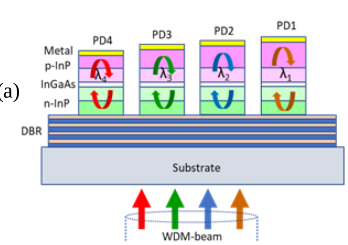


Fig. 3(b)

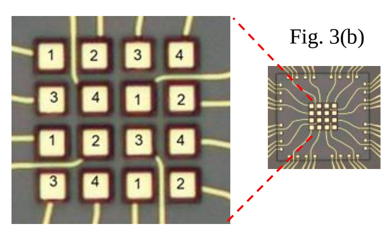
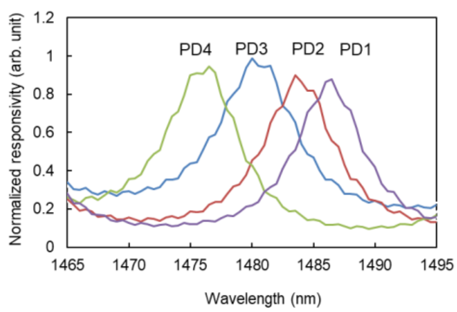


Fig. 2 Schematic of an n-λ integrated N×N RC-PD array device for SDM–WDM beam direct detection, Fig. 3 (a) Schematic cross-sectional view of 4-λ RC-PD, (b) top-view photo of the fabricated 4×4 RC-PD array.

An RC-PD device structure based on p-InP/i-InP//i-InGaAs/i-InP/n-InP on a distributed Bragg reflector (DBR) mirror layer on InP substrate was employed (Fig. 3(a)). The DBR was designed using multi-stacking thin films consisting of InGaAlAs and InP materials to obtain 75%–80% reflectance in the C-band as a front mirror. The top Ti/Pt/Au metal had the roles of both p-ohmic contact metal and reflective end mirror. Because of the back illuminated RC-PD structure, 75%–80% reflectance from the Ti end mirror in Ti/Pt/Au was expected. Considering an inter-channel crosstalk less of than 10 dB between PDs, each resonant response characteristic in spectral responsivity was adjusted by optimizing the cavity length from the front and end mirrors. During fabrication, the etching process was conducted carefully using a very low etching rate to ensure a difference of several tens nm in each cavity length between four PDs. When assuming that the 4-WDM beam hit any 4-PDs in the 4×4 array, four different λ PDs were aligned in order of "PD1, PD2, PD3, and PD4" in the first and third rows in the 4×4 PD array, and they were aligned in order of "PD3, PD4, PD1, and PD2" in the second and fourth rows (Fig.3(b)). In the WDM–FSO communication demonstration, spectral responsivity (quantum efficiency) profiles for the four PDs were measured as shown in Fig. 4. A maximum quantum efficiency of 25 % at the peak point, a resonant wavelength region of 1465–1495 nm, and wavelength distances as large as 5 nm between the peaks were observed including a variation in the film growing and etching processes. Although crosstalk between neighboring PDs (PD1 and PD2) was as large as 5 dB, a lower crosstalk less than 10 dB between PD1 and PD3 or between PD2 and PD4 was obtained. Fig. 5 shows the measurement results on the frequency response for four presentative PDs located at the center region in the 4×4 PD array. The 3 dB bandwidth of 13–15 GHz was obtained from four PDs, and good uniformity in each characteristic was confirmed.

Fig. 4



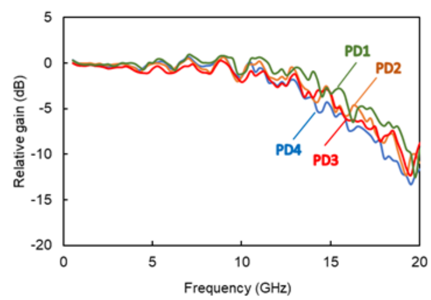


Fig. 5

Fig. 4 Measured spectral responsivity (quantum efficiency) profiles in 1465–1495 nm for 4λ PDs. Fig. 5 Frequency response for 4λ PDs.

3. 2-SDM 2-WDM FSO demonstration using the 4×4 RC-PD array

In the SDM–WDM–FSO communication demonstration using the fabricated RC-PD array device, a scalable configuration on a 1.5 m free space was constructed as shown in Fig. 6, where no beam positioning system including beam tracking and active alignment function were installed. On the transmission side, two cores in a triangular shape aligned arrangement seven multi-core fiber (MCF) with a 1 km long, 43 μm core pitch was used. Subsequently, two 25 Gbps (NRZ) optical signals multiplexed with two different wavelengths (1476 and 1483 nm) through two sets of intensity modulators were transmitted to one of seven-multi-core fibers, and two other 25 Gbps optical signals with two different wavelengths (1481 and 1487 nm) were provided by swapping the two sets of intensity modulators above and were connected to another core. After a 1 km transmission, the seven multi-core fiber with triangular shape aligned cores with 43 μm pitch was coupled to a 1 m long square shape aligned arrangement four-bundle fiber to convert the comparable core pitch (152 μm) to the PD pixel pitch between PD1 and PD4 in the first row. The partially use of the bundle-fiber in MCF might be one of good candidates for the cost-effective core pitch conversion. A total data rate of 100 Gbps (25 Gbps × 4) in 2-SDM 2-WDM communications demonstration was set up.

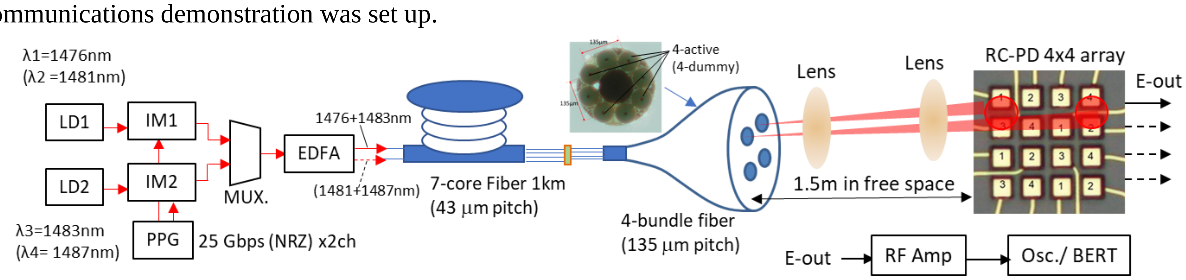


Fig. 6 Experimental setup for 2-SDM 2-WDM FSO communication demonstration at 25 Gbps OOK using newly developed 4×4 RC-PD

After a 1.5 m free space transmission, the expanded WDM beams were located at a part covering "PD1 and PD3" and "PD2 and PD4" at the edge of PD pixels (A and B in Fig. 7). Note that the four-beams from the four-bundle fiber was located at center of any four PD pixels in the 6×6 or 8×8 PD array for 4-WDM 4-SDM beam detection. The RF output in each PD was amplified using an RF amplifier and was analyzed by an oscilloscope and a bit error rate (BER) tester. For the crosstalk of 2-WDM communications using the RC-PD array, the spectral responsivity (quantum efficiency) of "PD1, PD3" and "PD2, PD4" was estimated as shown in Fig. 8. For 1476 nm + 1481 nm WDM beam detection using PD1 and PD3 in "spot-A," low crosstalk of -10 and -11 dB were obtained. In 1481- and 1487-nm WDM signal detection using PD2 and PD4 in "spot-B," -10 and -7 dB low crosstalk were expected as well.

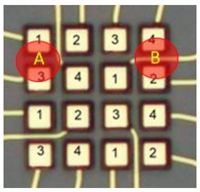
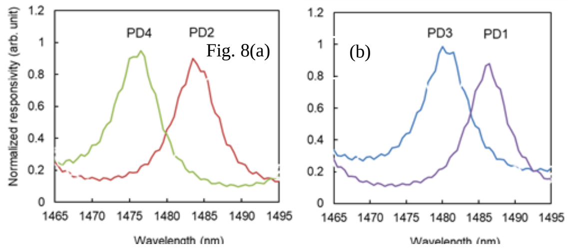


Fig. 7



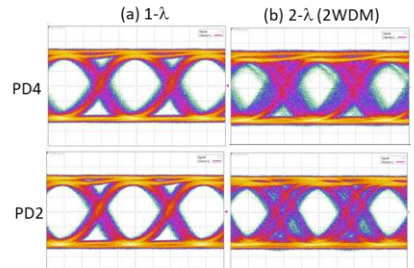
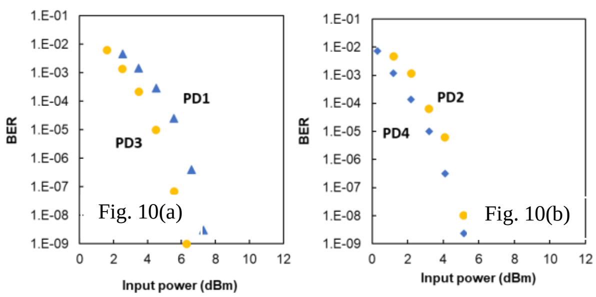


Fig. 7 Beam spot locations for 2-SDM FSO. Fig. 8 Normalized quantum efficiency on (a) "PD1, PD3" and (b) "PD2, PD4." Fig. 9 Eye diagrams of single λ and 2λ detection on (a) PD2 and (b) PD4.

Fig. 9

Next, we evaluated eye diagrams in 25 Gbps OOK 2-SDM 2-WDM FSO communications in a 1.5 m free space. At beam spot location A, eye diagrams on PD4 were measured and compared using two conditions (1-λ input (1475 nm) and 2-λ inputs (1475 and 1483 nm)). Owing to the crosstalk of -9.5 dB, Fig. 9(b) was recognized as noisy eye diagram compared with eye diagram in Fig. 9(a). The same eye diagram feature on PD2 was also recognized in the 1-λ input (1483 nm) and 2-λ input (1476 and 1483 nm). Importantly, eye-opening were still remained. BER curves for different 1-λ inputs for PD1, PD3 and PD2, PD4 are shown in Fig. 10(a) and (b). A good BER performance was confirmed from each PD. At BER=1×10^{-3}, the optical power to PDs was in range of 1.6 to 3.5 dBm, and was in 5 to 7.5 dBm at near BER = 1×10^{-9}. The BER curves with 2-λ (1479 nm, 1487 nm) inputs on PD1 and PD3, and with 2-λ (1475 nm, 1483 nm) inputs on PD2 and PD4 are shown in Fig. 11(a) and (b). At BER=1×10^{-3}, a 3.5–5 dB power penalty was observed in comparison with Figs. 10 and 11, and approximately the same power penalties were revealed at near BER = 1×10^{-9} owing to the inter-channel crosstalk between the PD pixels. When the fabrication process is optimized, the penalties will be potentially reduced with a decrease in the crosstalk between 4-λ PD.



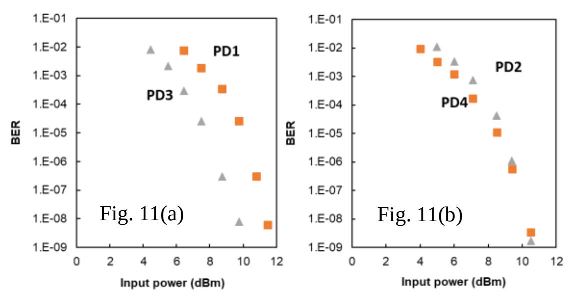


Fig. 10 BER curves for different single λ inputs for (a) PD1, PD2, and (b) PD3, PD4. Fig. 11 BER curves with 2λ (1479 nm + 1487 nm) inputs on "PD1 and PD3" and with 2λ (1475 nm + 1483 nm) input on "PD2 and PD4"

4. Conclusion

We fabricated a high-speed RC-PD array device for both high optical alignment robustness and specific wavelength separation instead of multi-parallel receivers connected to AWG in FSO communication. It has the potential to simplify the system configuration of the WDM–FSO receiver. In an FSO demonstration, a high data rate of 100 Gbps (in total) was successfully achieved to confirm the proof of our concept using the RC-PD array device.

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5. Reference

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