High-Speed Traveling-Wave Photodetector with a 3-dB Bandwidth of 410 GHz

Jeong-Woo Park, Sangpil Han, Donghun Lee, Han-Cheol Ryu, Jun-Whan Shin, Namje Kim, Young-Jong Yoon, Hyunsung Ko, and Kyung Hyun Park

A high-speed traveling-wave photodetector (TWPD) with an InGaAs absorber is designed and realized. The bandwidth of the TWPD is measured using electro-optic sampling techniques. The bandwidth is 410 GHz, which shows that the RC limitation is overcome. While the TWPD shows a low responsivity of 0.06 A/W at 1,550 nm, this value can be improved through further optimization of the structure without a sacrifice in bandwidth.

Keywords: Photodetector, waveguide photodetector, traveling-wave photodetector.

I. Introduction

A traveling-wave photodetector (TWPD) was first proposed in 1990 by Taylor and others [1]. In 1992, Giboney and others provided a more detailed concept of a TWPD with a description of an electrical model and quantified the velocity-mismatch impulse responses and associated bandwidth limitations [2]. In [2], the authors stated that TWPDs can overcome the RC-bandwidth limitations of usual waveguide photodetectors (PDs) by implementing an electrode arrangement designed to support traveling electrical waves with the characteristic impedance (Z_0) matched to that of an external circuit.

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With this concept, they showed a PD with a 176-GHz bandwidth and 50% efficiency exceeding an RC limitation bandwidth of about 80 GHz [3]. Another systemization was conducted by Hietala and others [4]. The authors obtained the output power and frequency response of TWPDs using a small signal analytical method. Even though they did not experimentally and explicitly show the traveling-wave effect, their theory was one of good systemization of TWPDs. In addition, Goldsmith and others induced an analytic frequency response of a TWPD parallel array using the TWPD concept, and their experiment results exceeded the RC limitation of a PD array [5]. They obtained a bandwidth of 18 GHz for one-element, two-element, three-element, and four-element PDs, showing the ability to overcome the RC limitation, considering that bandwidth degradation occurs with parallel attachment of more PD elements in a normal RC limitation case.

In this letter, we present a TWPD that overcomes the RC limitation with a high 3-dB bandwidth of 410 GHz. We include an example of exceeding the RC limitation for traveling-wave-type electro-optic (EO) devices. This kind of device can be useful for very high-speed optical telecommunications and photomixers for THz generations.

II. Design

In our previous work, to obtain a high fiber coupling efficiency with optical fiber, we adopted a thin absorption layer approach [6]. Furthermore, subsidiary layers were used to enhance the fiber coupling efficiency. Figure 1 shows the structure of the PD.

Figure 2 shows the validity of our design for a high responsivity. As shown in Figs. 2(a) and 2(b), a thin core layer with a subsidiary layer provides a desirable mode size

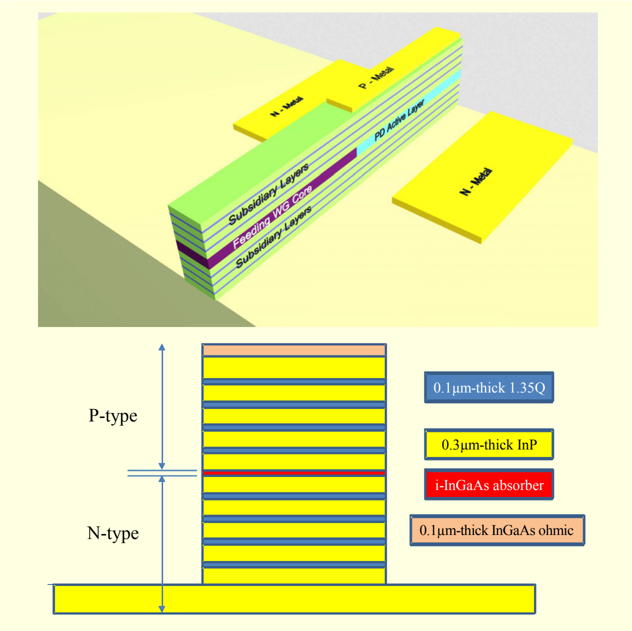

Fig. 1. Conceptual view of PD designed for high responsivity and epitaxial structure of PD waveguide.

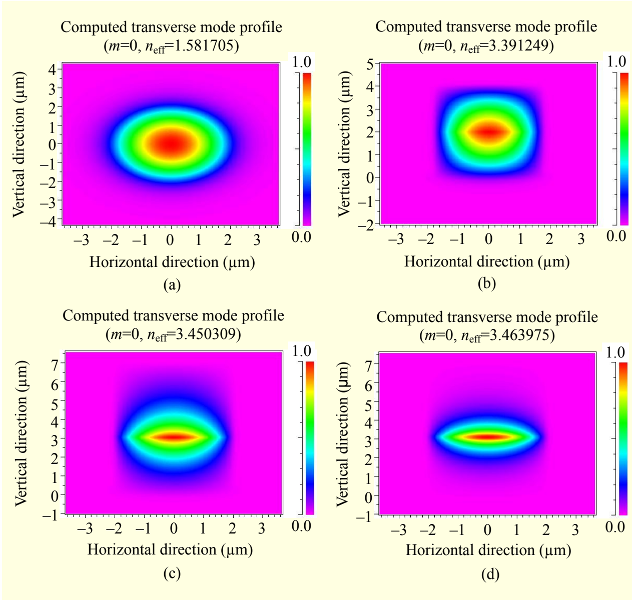

Fig. 2. Eigen-mode 2D profiles of waveguides for (a) lensed fiber with 3-μm beam diameter, (b) 0.1-μm core layer with subsidiary layers, and (c) 0.1-μm and (d) 0.2-μm core layers only.

matching with lensed fiber with a 3-μm beam diameter, the beam size of which is shown in Fig. 2(a).

For a 0.1-μm core layer only, mode size matching is expected to be worse than for a 0.1-μm core layer with subsidiary layers, as reflected in the mode size comparison shown in Fig. 2. In addition, for a 0.2-μm core layer only, the mode size matching is expected to be worse than in the case of a 0.1-μm core layer only. We can expect a satisfactory coupling efficiency for the case of a 0.1-μm core layer with subsidiary layers. The calculated coupling efficiency for this case is greater than 95%.

To design a TWPD, the Z_0 of the electrical waveguide should first be determined. To match with the external circuits, the target Z_0 of the TWPD designed in this letter is 50 Ω. For a p-clad doping concentration of 5×10^{18} cm^{-3} and an n-clad doping concentration of 1×18 cm^{-3}, the calculated Z_0 for a PD width of 2.5 μm is plotted in Fig. 3. For a narrower width than 2.5 μm, the value of Z_0 increases; as the width increases, the value of Z_0 decreases. For proper impedance matching, we choose a PD waveguide width of 2.5 μm. These calculations are based on a previously reported work [7]. As shown in Fig. 3, the value of Z_0 for the PD waveguide is not constant.

This nonconstant Z_0 value can generate a power reflection at the output port for 50-Ω external circuits. However, the power reflection at the PD output port is not significant. The calculated result for the Z_0 shown in Fig. 3 and a 50-Ω external resistor are presented in Fig. 4. The figure shows that the power reflection at the PD output port can be about 10% for a frequency range from the DC to 1 THz.

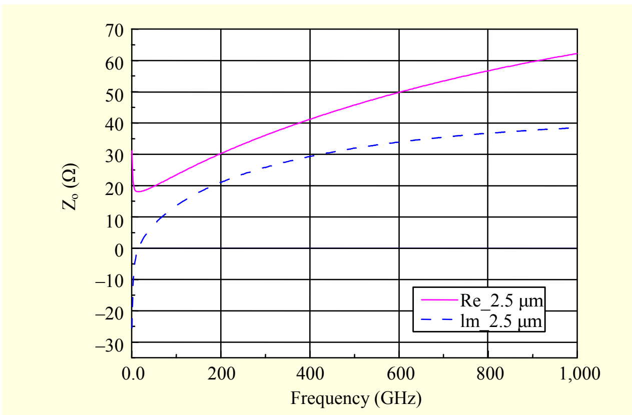

Fig. 3. Calculated Z_0 of PD waveguide with width of 2.5 μm.

As shown in Fig. 4, the reflected portion of incident power at the output port can be about 10% to 15%. This reflected power returns to the input facet. For input matching termination, only 10% to 15% of this reflected power returns again to the output port. As a result, 1% to 2.25% of the power re-enters the output port after propagating the length of the TWPD twice. This 1% to 2.25% can be ignored. Therefore, for simultaneous input and output matching, the nonconstant Z_0 value shown in Fig. 3 does not greatly influence the bandwidth characteristics compared to the effect in the case of perfect matching. For an open-input termination, about 10% of the initial power re-enters the output port. In addition, this amount of power may generate an insignificant degradation of the bandwidth characteristics. The measured results described in section III support this reasoning.

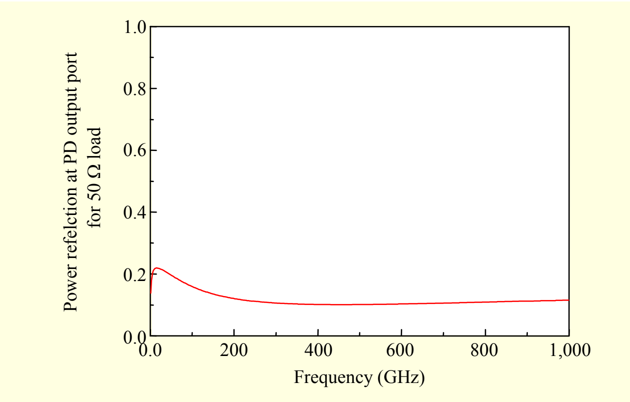

Fig. 4. Calculated power reflection at PD output port for Z_0 in Fig. 3 and 50-Ω matching resistor at output port side.

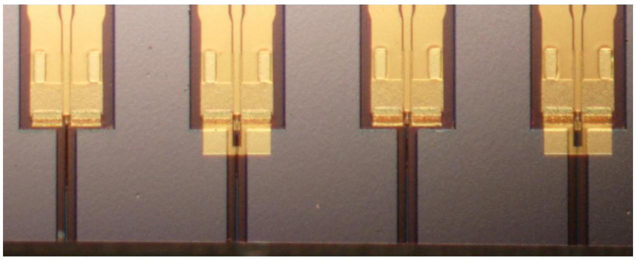

Fig. 5. Photography of fabricated TWPDs.

III. Fabrication and Measurements

TWPDs with the structure shown in Fig. 1 and the doping concentrations described in section II are fabricated. Bisbenzocyclobutene (BCB) is used for the insulation and planarization. The final coplanar waveguide is on the same BCB plane, allowing for the placement of an EO crystal for EO sampling measurements. Figure 5 shows the fabricated TWPDs.

Using lensed fiber with a 3.5-μm mode diameter, the responsivity measures 0.06 A/W at an input wavelength of 1,550 nm for a 10-μm length without an antireflection coating at the input facet. The responsivity is lower than expected. We attribute this to an excessively enlarged mode field diameter in the active PD waveguide. The use of four subsidary layers in the upper clad layer provides an excessively large mode field diameter. The tail of this enlarged field might reach the InGaAs ohmic layer and p-ohmic metal, which may give rise to excess optical loss. In future work, it would be beneficial to reduce the number of subsidiary layers to prevent a low responsivity. According to our simulation results, we can obtain a coupling efficiency of more than 90% with normal lensed fiber even if we use two subsidiary layers in the upper clad and the lower clad, respectively. This could enable us to achieve responsivity of more than 0.8 A/W at a 1,550-nm wavelength input.

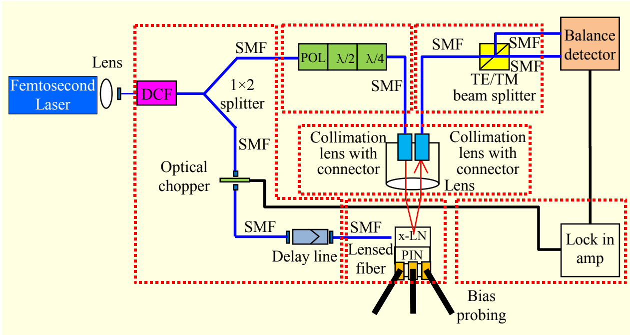

Fig. 6. EO sampling measurement setup used in measure of impulse response of TWPDs.

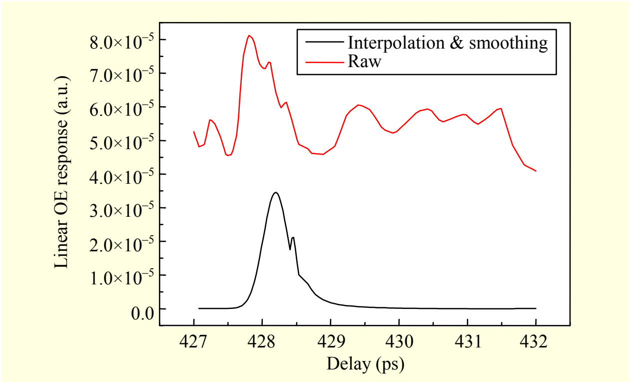

Fig. 7. Impulse response of TWPD measured through EO sampling (upper waveform: raw data; lower waveform: smoothed and interpolated data).

Time domain responses are obtained through EO sampling measurement, which is usually used in the measurement of high-speed PD. Figure 6 shows a conceptual scheme of the EO sampling measurement setup. We use x-cut LiNBO3 as the EO material. The optical pulse source used has a full width at half maximum (FWHM) pulse width of 140 fs with a repetition rate of 100 MHz.

Figure 7 shows raw impulse response data and the processed fitting waveform. The FWHM of the output waveform is about 0.9 ps. We divide raw data into two regions at a delay time of about 428.3 ps. One is a fast Gaussian waveform and the other is a slow Gaussian waveform because a slow component is shown at the falling tail. We cannot suppress the noise at a time interval of "zero," even though we use a lock-in technique. We set this noise as nearly zero in the fitting process.

The frequency-domain response of a TWPD is obtained through the Fourier transform of the interpolated and smoothed waveform shown in Fig. 7. The frequency response is plotted in Fig. 8.

Although the intended thickness of the InGaAs absorber is 0.1 μm, the real thickness is about 0.07 μm, according to a cross-section of the fabricated TWPD, inspected using a

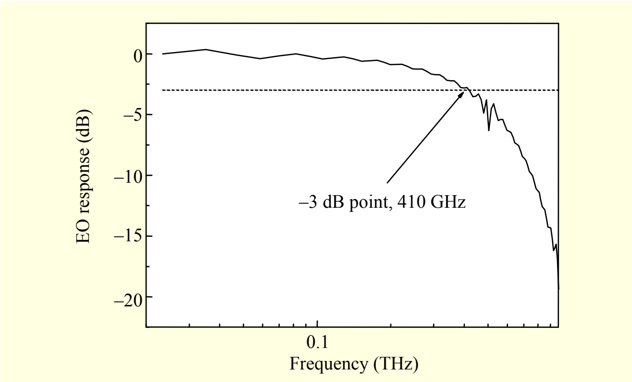

Fig. 8. Frequency response of TWPD.

scanning electron microscope. The estimated transit-time limited bandwidth is about 432 GHz for the 0.07-µm-thick InGaAs absorber. In the estimation, the drift velocities of the electron and hole in the InGaAs are assumed to be 7×10^6 cm/s and 4.8×10^6 cm/s, respectively [8]. The bandwidth limitation from the velocity mismatch between the electrical phase velocity and the optical group velocity in the TWPD waveguide is shown in (1). The derivation procedure is presented in [9]. In (1), v_o is the optical group velocity, and v_e is the electrical phase velocity. In addition, Γ, α, and L are the confinement factor, absorption coefficient of the absorption layer, and device length, respectively.

$$BW = [2\cdot(\frac{1}{v_e}-\frac{1}{v_o})\cdot(L-\frac{\ln[0.8+0.2\cdot\exp(\Gamma\cdot\alpha\cdot L)]}{\Gamma\cdot\alpha}) - \ln(0.2)\cdot\frac{2}{\Gamma\cdot\alpha}\cdot(\frac{1}{v_e}+\frac{1}{v_o})]^{-1} \cong \frac{\Gamma\cdot\alpha\cdot v_e}{4\cdot\ln 5}, \quad (1)$$

for input-open/output matching and $v_o > v_e$.

For the 0.07-µm-thick absorber layer, the confinement factor (Γ) is calculated as 8.5%. Assuming v_o and v_e are 9×10^9 cm/s and 6×10^9cm/s, respectively, the bandwidth limitation from the velocity mismatch is calculated as 810 GHz for a 20-µm device length.

The total 3-dB bandwidth when considering both the velocity mismatch and transit-time limit is about 381 GHz. This sufficiently agrees with the measured bandwidth of 410 GHz, with a deviation of about 7%.

The measured TWPD has a series resistance of about 8 kΩ, which originates from an imperfect p-ohmic process. The capacitance is larger than 0.8 pF. If the device is RC-limited, the 3-dB bandwidth should be about 25 MHz. However, the measurements show that the RC limitation is significantly surpassed.

IV. Conclusion

A TWPD was fabricated, and its characteristics were measured. The responsivity was 0.06 A/W, which is relatively low. This low responsivity comes from the excessively large beam height during the propagation of the input optical beam in the TWPD waveguide, which can easily be overcome by maintaining a high coupling efficiency through a different configuration of the subsidiary layer from the present method. The 3-dB bandwidth of the TWPD was 410 GHz, substantially exceeding the RC limitation. This estimated 3-dB bandwidth agreed with the measured 3-dB bandwidth, with a deviation of about 7%. Even though an exact impedance match at the interface between the TWPD electrical waveguide and CPW line was not achieved, a severe degradation of the 3-dB bandwidth did not occur.

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