

High-performance modified uni-traveling carrier photodiode integrated on thin-film lithium niobate platform

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Lithium niobate on insulator (LNOI) has become an intriguing platform for integrated photonics for applications in communications, microwave photonics, and computing. While integrated devices including modulators, resonators, and lasers with high performance, have been recently realized on the LNOI platform, high-speed photodetectors, an essential building block in photonic integrated circuits, have not been demonstrated on LNOI yet. Here, we demonstrate for the first time, heterogeneously integrated modified uni-traveling carrier photodiodes on LNOI with a record-high bandwidth of 80 GHz and a responsivity of 0.6 A/W at 1550 nm wavelength. The photodiodes are based on a n-down InGaAs/InP epitaxial layer structure that was optimized for high carrier transit time-limited bandwidth. Photodiode integration was achieved using a scalable wafer die bonding approach that is fully compatible with the LNOI platform

1. INTRODUCTION

Photonic integration holds the promise for realizing high-performance, low-cost, scalable solutions for communication, sensing, and quantum computation applications. Lithium niobate (LN) is one of the most suitable material platforms for integrated photonic circuits due to its unique material properties including large electro-optic coefficient, large second-order nonlinear susceptibility, and a wide optical transparency window (350 nm to 5 μm) [1]. LN-based devices, like electro-optic modulators, have been the workhorse of the optoelectronic industry for decades [2]. Recently, the revolutionary technology of LNOI and breakthroughs in nanofabrication techniques have made high-performance integrated nanophotonic components possible and the

manufacturing of wafer-scale, high-quality devices on LNOI has become fully commercialized [3]. Moreover, these nanostructure devices like optical modulators and nonlinear wavelength converters have already outperformed legacy devices in bulk form [2]. Nanofabrication breakthroughs enabled ultra-low-loss resonators to be built on LNOI which realized novel applications like optical frequency combs and quantum transducers [3]. LNOI high-speed electro-optic modulators have become commercialized and work fully compatible with CMOS voltages [2]. Lately, lasers were proven to have the compatibility to be integrated on the LNOI platform with low loss [4]. To date, almost all building blocks for a complete photonic system have been realized on the LNOI platform with outstanding performance, except one— photodetectors.

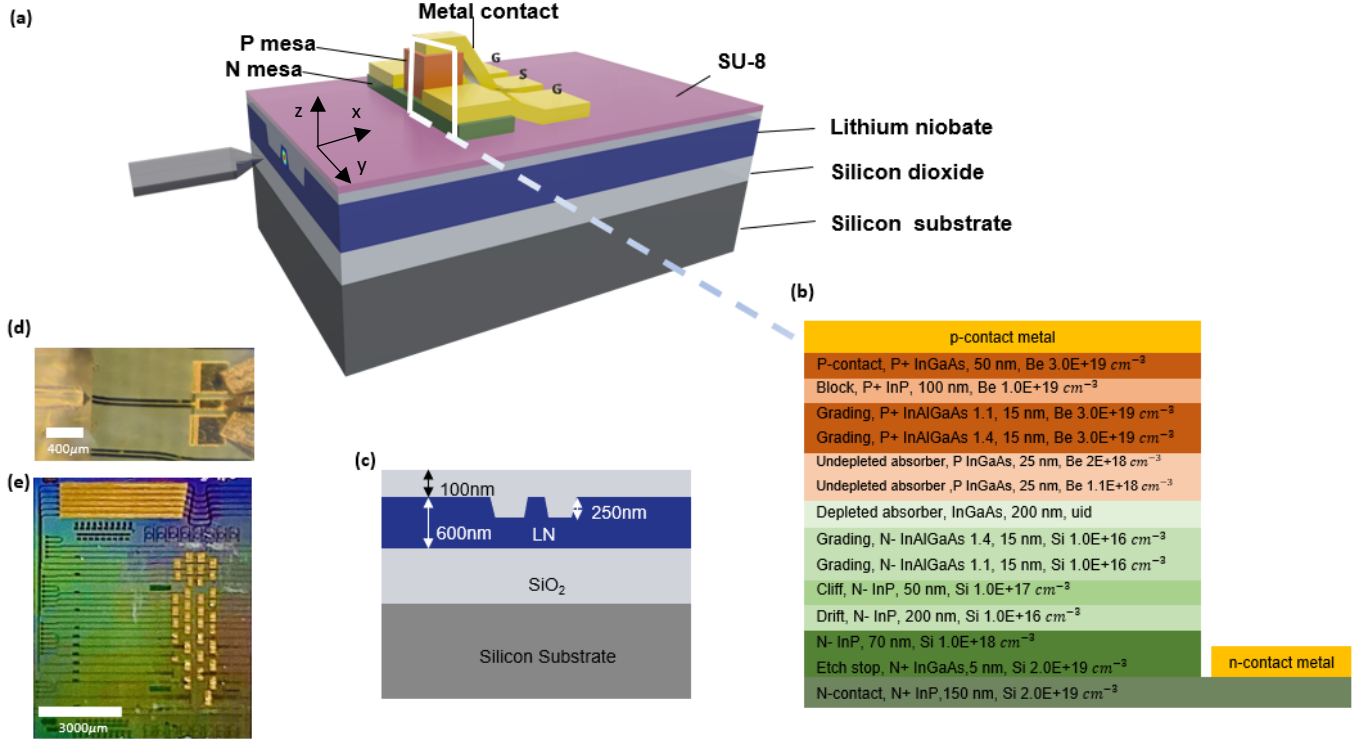


Fig. 1. MUTC PDs integrated on TFLN. (a) Structural illustration. (b) Epitaxial structure of the n-down PD. (c) TFLN waveguide cross section. (d) Microscope image of a device under test with lensed fiber and RF probe. (e) Microscope image of chip with integrated PDs.

Photodetectors that convert high-speed optical signals into the electrical domain are essential components in optical communication networks and microwave photonics systems. Conventionally, output optical signals from a photonic system are fiber-coupled into a discrete photodetector. This, however, introduces additional loss, and is not compatible with the need for fully integrated chip-scale photonic solutions. In the past years, various efforts on integrated photodetectors on non-native substrates have focused on platforms including silicon and silicon nitride [5,6] and bandwidths approaching 70 GHz have been reported [7]. An early attempt was made on integrating photodiodes on LN waveguides using GaAs [8] and one demonstration of an integrated silicon photodetector on LNOI with 10 MHz bandwidth for visible wavelengths was made [9].

Here, we advance the LNOI platform's functionalities by demonstrating heterogeneously integrated modified uni-traveling carrier (MUTC) photodiodes (PDs) on thin-film lithium niobate (TFLN) that achieve a record-high bandwidth of all reported heterogeneously integrated PDs on non-native substrates to date. We use an MUTC structure with optimized thicknesses of the depleted and undepleted absorbers based on InGaAs/InP which enables 80 GHz bandwidth, low dark current of 3 nA, high internal responsivity of 0.6 A/W, and ability to detect a 40 Gbit/s data stream without additional electronic amplifiers.

2. DEVICE DESIGN AND FABRICATION

Figure 1(b) shows the MUTC PD layers that were grown as p-down structure lattice-matched on semi-insulating InP substrate. In this design the thicknesses of the InGaAs absorber layers were optimized to maximize the carrier transit time-limited bandwidth. To this end we calculated the frequency response of the sum of the three following current contributions: electron diffusion current, hole drift current, and electron drift current. They can be expressed as integral functions with respect to positions of carriers spanning the region from the absorber to the drift layer [10]. The ratio of depleted absorber and undepleted absorber was then chosen to maximize the carrier transit time-limited bandwidth of the photodiode. Figure 2a shows the calculation result using the parameters in table 1. With a fixed total absorber thickness of 250 nm, we found a maximum of 167 GHz for 50 nm undepleted absorber and 200 nm depleted absorber. A 50 nm cliff layer made of moderately n-type doped InP is added to reduce the space charge effect [11]. Since InGaAs and InP have a difference in band gap, InAlGaAs with 0.86 eV band gap was chosen as the bandgap-grading layer material. Grading layers on both n-side and p-side help carriers to overcome the band discontinuities.

As shown in Figure 1(a), and in contrast to our previous work [5], we designed a structure that results in n-down after bonding with the following benefits: the InP n-contact layer is

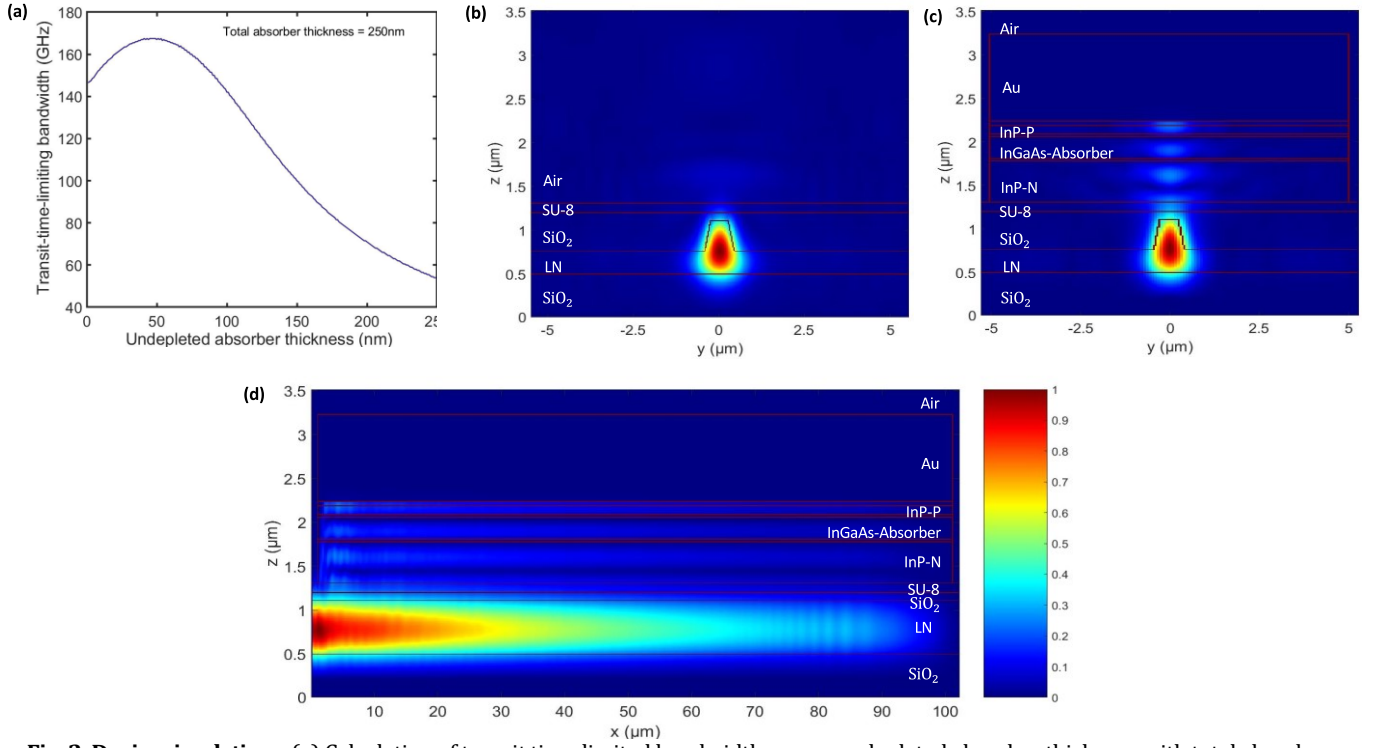


Fig. 2. Device simulations. (a) Calculation of transit time-limited bandwidth versus undepleted absorber thickness with total absorber thickness of 250 nm and a fixed drift layer thickness of 200 nm. Optical simulations of E-field magnitude, (b) yz cross-section at $x = 0 \mu\text{m}$ (passive waveguide), (b) yz cross-section at $x = 5 \mu\text{m}$ (PD), and (c) zx cross-section at $y = 0 \mu\text{m}$.

Table 1. Bandwidth Calculation Parameters

Thermionic emission velocity in InGaAs	$2.5 \times 10^5 \text{ m/s}$
Hole saturation velocity	$0.45 \times 10^5 \text{ m/s}$
Electron velocity in InGaAs and InP	$1 \times 10^5 \text{ m/s}$
Electron mobility in p-type InGaAs	$0.5 \text{ m}^2/\text{Vs}$
Electron diffusivity in p-type InGaAs	$1.3 \times 10^{-2} \text{ m}^2/\text{s}$
External load resistance	50Ω
Series resistance	5Ω

transparent at the operating wavelength 1550 nm; a low sheet resistance in the contact layer can be achieved since high n-type doping levels ($>10^{19} \text{ cm}^{-3}$) can easily be reached in InP together with high electron mobility; formation of n-metal contacts with low contact resistance; and keeping p-type InGaAs as the top contact layer without compromising the responsivity. Although the layer structure was specifically designed for 1550 nm, we expect that the PD has a broad working wavelength range that is ultimately limited by the bandgaps of the highly doped InP contact layer (920 nm) and the absorber InGaAs (1650 nm).

Figure 1(c) shows a schematic of the TFLN waveguide which was optimized for photodiode integration. The total thickness of LN is 600 nm with the waveguide height being 250 nm. We deposited

SiO_2 on top of the trench waveguides followed by chemical-mechanical polishing (CMP) to improve surface flatness. The total thickness of the SiO_2 layer after CMP is 100 nm on top of the waveguide which is optimal for both bonding and evanescent light input-coupling from the waveguide into the PD. With this standard TFLN platform, other optical devices like ring resonators and modulators can be simultaneously fabricated on the same chip as shown in Figure 1(e).

Photodiodes were fabricated by first bonding a $4 \text{ mm} \times 8 \text{ mm}$ InGaAs/InP MUTC wafer die on TFLN waveguides covering the area where PDs were then fabricated. With sufficient margins on all sides, the alignment accuracy for this step was $500 \mu\text{m}$. We used SU-8 as the adhesive bonding agent. The thickness of the SU-8 was controlled by spin coating speed and designed to be 100 nm for a high optical coupling efficiency. Figures 2(b-d) show a simulation of the light coupling from the LN waveguide into the photodiode. The SU-8 was both UV and high temperature cured to achieve higher stability. After a 40-minutes outgas, the PD epitaxial material die and the LNOI chip were brought in contact and cured at 130°C under 10 psi for 60 min. The InP substrate of the III-V photodiode die was removed after bonding using wet etch (HCl). For the n-mesa fabrication we used inductively coupled plasma reactive ion etching (Cl_2 and N_2) followed by a short selective wet etching (HCl) to expose the InP contact layer. The combination of the two methods allowed us to largely avoid undercut which can be detrimental for small mesa areas while ensuring to stop the etching above the InP. The p-mesa formation was done by wet etching (H_3PO_2 and HCl). We fabricated PDs with the following active areas (width in $y \times$ length in x): $10 \mu\text{m} \times 10 \mu\text{m}$, $20 \mu\text{m} \times 10 \mu\text{m}$, $15 \mu\text{m} \times 20 \mu\text{m}$, $20 \mu\text{m} \times 30 \mu\text{m}$, and $20 \mu\text{m} \times 50 \mu\text{m}$. Lithium niobate waveguides

outside the bonding area were protected by photoresist during the fabrication process. An air-bridge structure was adopted to connect the metal on top of n-mesa and p-mesa to the ground-signal-ground (GSG) radio frequency (RF) pads. Those RF pads were designed to yield a characteristic impedance of $50\ \Omega$.

3. DEVICE CHARACTERIZATION

A. DC measurements

Dark current is an important figure of merit for PDs, as it is one of the major sources for noise. The fact that the low dark current of our MUTC PD on TFLN of 3 nA (Fig. 3(a)) is comparable or lower than dark current from similar PDs on native substrate [12], indicates that the integration process did not degrade the performance.

The responsivity of the photodetectors was measured at 1550 nm by edge-coupling light into the TFLN waveguides. The external responsivity of the PDs were calculated by dividing the photocurrent by the optical power at the lensed fiber tip (measured by an optical power meter). For a $10\ \mu\text{m} \times 10\ \mu\text{m}$ sized photodiode, the external responsivity was 0.2 A/W. It should be mentioned that external responsivity is significantly affected by the fiber-to-waveguide coupling loss and does not reflect device performance well in this integration scheme. Thus, internal responsivity was

characterized by investigating the ratio of photocurrent and the light coupled into waveguides. The average fiber-to-waveguide coupling loss was 5 dB. The loss was measured on a straight waveguide with a visibly good facet on the same chip using a conventional fiber-to-waveguide-to-fiber setup. This coupling loss measurement also agrees with the simulation result using Lumerical FDE to calculate mode overlap between the fiber mode and the TE mode in the TFLN waveguide. It should be noted that we did not use an anti-reflection coating. With taking coupling loss into account, the internal responsivity of a $10\ \mu\text{m} \times 10\ \mu\text{m}$ device is 0.6 A/W which agrees with optical simulation using Lumerical FDTD module. The responsivities for PDs with areas of $20\ \mu\text{m} \times 10\ \mu\text{m}$, $15\ \mu\text{m} \times 20\ \mu\text{m}$, $20\ \mu\text{m} \times 30\ \mu\text{m}$, and $20\ \mu\text{m} \times 50\ \mu\text{m}$ are 0.17 A/W, 0.24 A/W, 0.52 A/W and 0.4 A/W, respectively. It should be mentioned that we diced the waveguide facets along the edge of the TFLN chip after photodiode integration and there was visible non-uniformity across different facets. The fact that facet loss varies across different waveguides can explain the spreading of the measured responsivity data.

We also measured photocurrent versus optical power on a $20\ \mu\text{m}$ wide and $30\ \mu\text{m}$ long PD. As shown in Figure 3(b), the photocurrent was linear for input powers as high as 20 dBm.

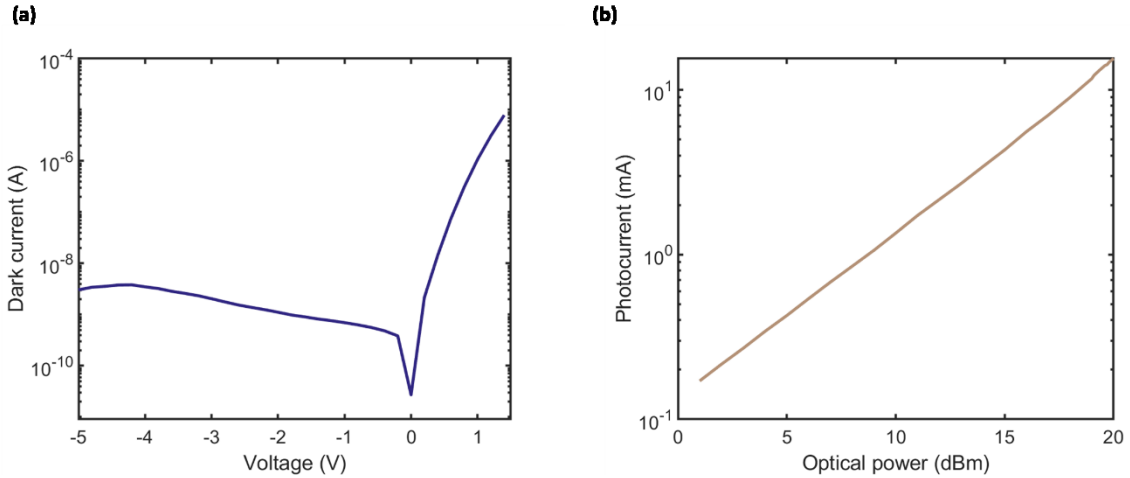


Fig. 3. DC measurements of MUTC photodiodes integrated on thin-film lithium niobate platform. (a) Dark current characteristics of a $1400\ \mu\text{m}^2$ device. (b) Measurement of photocurrent versus optical power (measured at fiber tip) of a $600\ \mu\text{m}^2$ device.

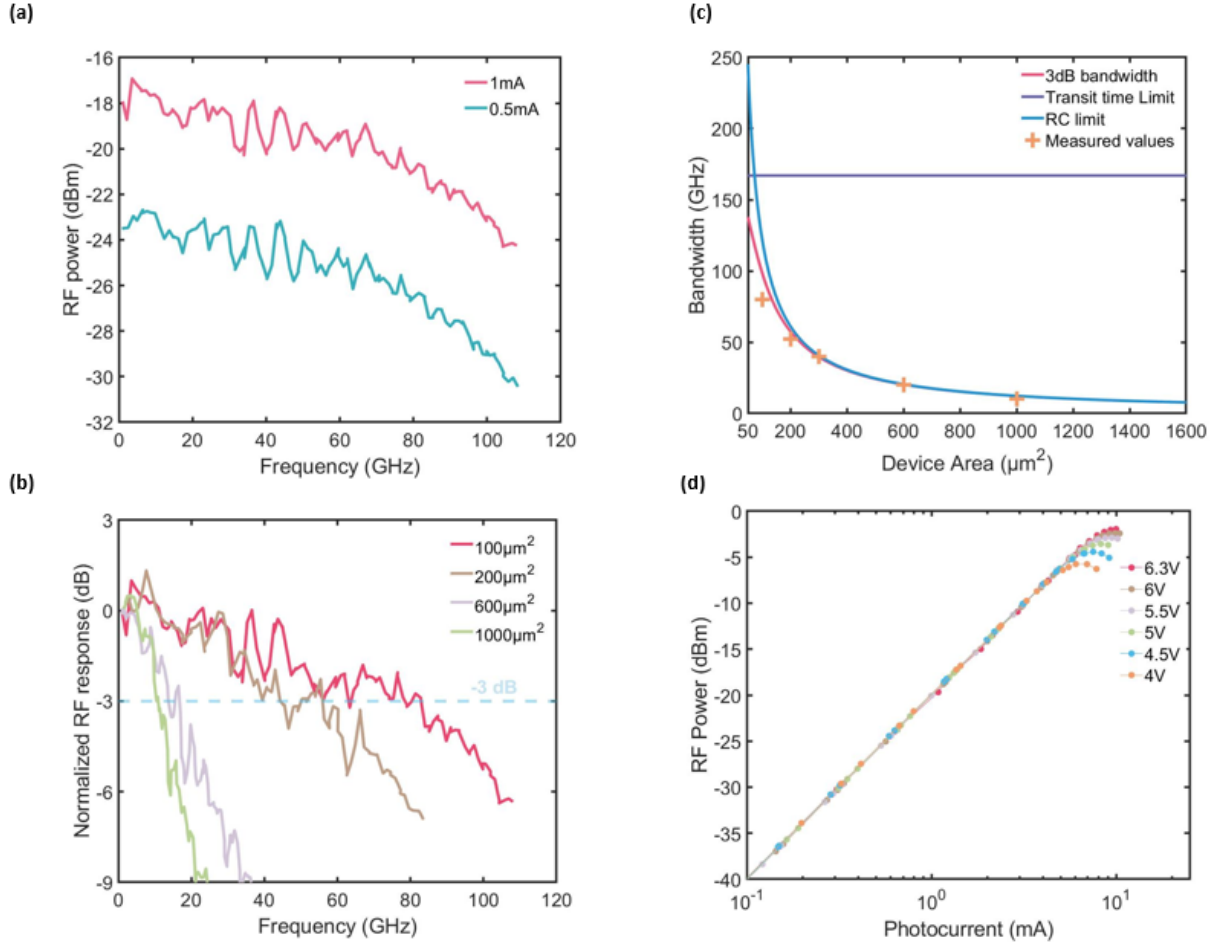


Fig. 4. AC measurements of MUTC photodiodes integrated on thin-film lithium niobate. (a) Frequency responses of a 100 μm^2 PD at different photocurrents. (b) Frequency responses of various sized photodiodes at 1 mA photocurrent and 3 V reverse bias. (c) Simulations and measurements of bandwidth for different device areas. (d) Measurement of RF power of a 300 μm^2 PD at 48 GHz at different reverse bias.

B. Frequency response

The 3 dB bandwidth was measured by a heterodyne setup. Two distributed feedback lasers with wavelengths near 1550 nm were used to generate a frequency tunable optical signal with near 100% modulation depth. The frequency of the beat signal is controlled by thermally tuning the wavelength of one laser while the other laser remains at one stable wavelength. This optical signal was then directed to an erbium-doped fiber amplifier (EDFA) followed by a variable optical attenuator to control the amplitude of the optical signal. A single-mode tapered fiber was used to couple light into the TFLN waveguide. The fiber to waveguide alignment was done using a 6-axial stage. A GSG RF probe was used to extract the photocurrent by probing at the designed RF metal pads (Fig.1(d)). A semi-rigid coaxial cable was used to connect the RF probe with the bias tee. The RF signal was detected using a calibrated 50 Ω RF power meter with frequency range from DC to 110 GHz. The losses of the RF probe, semi-rigid coaxial cable, and bias tee were determined with a 110 GHz network analyzer and then subtracted from the measured data.

Figure 4(a) shows the bandwidth measurements of a 100 μm^2 PD at photocurrents of 0.5 mA and 1 mA at the same 3 V reverse bias.

The 3 dB bandwidth of 80 GHz did not change with different photocurrents and the output RF power from the photodiode matches the expectation. Figure 4(b) shows the bandwidth measurement results of the photodetectors with 100 μm^2 , 200 μm^2 , 600 μm^2 , and 1000 μm^2 device areas. Photocurrent was kept the same during measurements by adjusting the fiber alignment and the polarization of the optical signal controlled by a fiber polarization controller. The highest 3 dB bandwidth of 80 GHz was achieved with the 100 μm^2 photodetector and the 3 dB bandwidth decreases as the device active area increases. If the PD is significantly shorter than the electrical signal wavelength, the photodetector can be treated as a lumped circuit element. Therefore, the resistance-capacitance (RC) time and carrier transit time are the two primary bandwidth limitations. Figure 4(c) shows the simulated transit time limit, RC limit and 3 dB bandwidth for this epitaxial structure and the measured bandwidth values agree well with the calculation. In this calculation, we use the calculated transit time-limited bandwidth of 167 GHz and a total resistance of 55 Ω (50 Ω external load and 5 Ω series resistance). Figure 4(d) shows the RF power at 48 GHz measured at different reverse bias. The maximum RF power was -1.9 dBm at 10 mA and 6.3 V. It should be mentioned that a higher reverse voltage led to PD failure at DC

dissipated power of >70 mW. We expect that the high-power performance of the PD on LNOI can be further improved by flattening the absorption profile to avoid localized saturation [13].

C. Eye Diagram

Digital data detection performance of the photodetectors was characterized by an eye diagram measurement. A non-return-to-zero on-off-keyed pseudo-random bit sequence (PRBS) data pattern was generated by a PRBS generator at 40 Gbit/s. Figure 5(a) illustrates our experimental setup. An external cavity laser provided the optical signal to a commercial 40 GHz modulator. The 550 mV peak-to-peak signal from the PRBS generator was fed into the modulator biased at its quadrature point. The optical signal then went through an EDFA, a variable optical attenuator (VOA), and an optical filter with 1 nm passband before being coupled into the TFLN waveguides. The electrical signal was extracted by a RF probe and went through a semi-rigid cable, a bias tee and a coaxial cable before entering the 50 GHz sampling oscilloscope for readout. It is worth mentioning that our PD can handle sufficient photocurrent and provided high signal-to-noise ratio to the oscilloscope so no

additional RF amplifier to boost up the electrical signal was necessary in the measurement.

We first measured the eye diagram of a commercial PD with 40 GHz bandwidth shown in Figure 5(b) as a reference. Figure 5(c) shows the measurement result of our $200\ \mu\text{m}^2$ PD with the measured 3 dB bandwidth of 52 GHz. It should be mentioned that the commercial PD was connected directly on the input port of the oscilloscope while the on-chip measurement of our photodetector required additional RF parts that were not calibrated out from the eye diagram. Even with the extra loss in the system, our photodetector performs similar to the commercial PD. The clear open eye diagram proves the high-speed performance of our photodetector and also demonstrates its capability for digital communication applications.

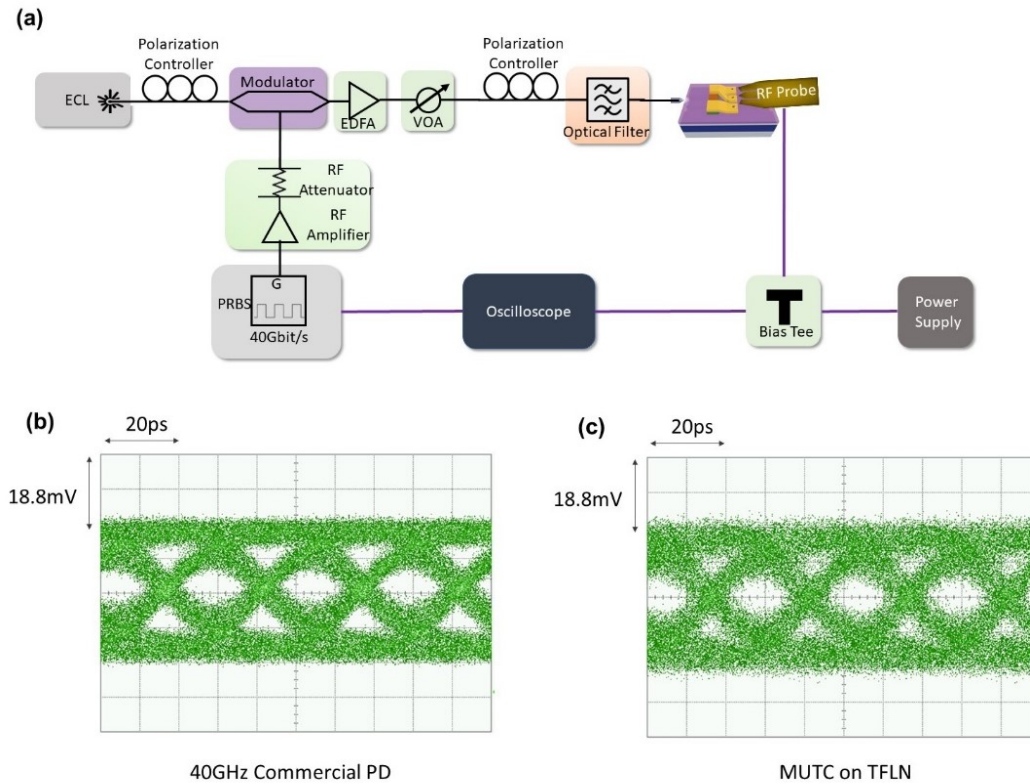


Fig. 5. Eye diagram measurement. (a) Measurement system setup. (b) Measured eye diagram for a commercial photodiode. (c) Measured eye diagram for a MUTC photodiode on TFLN with $200\ \mu\text{m}^2$ PD area.

4. Summary

In conclusion, we designed and fabricated MUTC photodiodes on TFLN waveguides. The internal responsivity for a high-speed photodiode with 80 GHz bandwidth is 0.6 A/W. The dark current is as low as 3 nA. The fabrication process of our MUTC photodiodes is fully compatible with modulators and ring resonators on the same wafer. With excellent performance, our integrated MUTC

photodiode can enable high-performance photonic integrated circuits on the LNOI platform.

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Disclosures. The authors declare no conflicts of interest.

Data availability. All relevant data are available from the corresponding author upon request.

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