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# High Power RF Photodiodes

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**Introduction:** For both analog and digital optical transmission systems, high-power photodetectors are becoming increasingly important. Analog communications systems for antenna remoting, phased array antennas, and photonic analog-to-digital converter systems require high fidelity with large dynamic range. To build optical links for these systems means that the optical to electrical converters (i.e., the photodetectors) must be able to operate at high photocurrent levels to minimize noise figure while providing the required dynamic range. In the digital domain, fiber optic systems are rapidly being developed for next-generation ethernet and secure communication systems. One approach to producing high-performance systems is to increase the optical power incident on the wide-bandwidth photodetectors so that the photogenerated RF output power (voltage swing) can directly drive the digital logic circuits. This approach eliminates the complications and expense of postdetection, wide-bandwidth, flat-phase RF amplifiers but requires higher performance photodiodes.

Two factors limit a photodiode's output power: space-charge screening of the intrinsic region electric field, and thermal considerations.[1] Space charge screening arises from the spatial distribution of photogenerated carriers as they transit the photodetectors depletion region. These charge carriers create an electric field that opposes the external-bias electric field. At sufficiently high optical power levels, the space-charge-induced electric field is strong enough to collapse the bias electric field, resulting in loss of the RF signal. Thermal limitations are the result of the geometry and thermal conductivity of the photodiode layers.

Traditional high-speed p-i-n photodiodes are made of an InGaAs optically absorbing layer grown on a lattice-matched InP substrate, with the composition and thickness of the various layers carefully chosen to balance the trade-offs between the power handling and frequency response for the photodiodes. We describe a new photodiode structure, jointly developed through a collaboration between the University of Texas–Austin and the Optical Sciences Division of NRL. These photodiodes use a partially depleted absorbing (PDA) layer to balance intrinsic-layer space charge effects and minimize thermal heat loading.[2] These devices have improved previous results by generating 10 times higher photocurrents than contemporary commercially available devices.

**Partially Depleted Absorber (PDA) Photodiodes:** Figure 1 shows the structure of the PDA photodiode. In a conventional semiconductor p-i-n photodiode, light generates electron and hole pairs in the optically absorbing intrinsic region (*i*-region) and they then travel in opposite directions to the contact layers. In both the InGaAs and InP semiconductor material systems, the velocity of electrons is higher than that of the holes, so the depletion region charge is dominated by slow moving holes. This velocity mismatch leads to a charge imbalance within the depletion region leading to space charge effects. In the PDA photodiode, charge

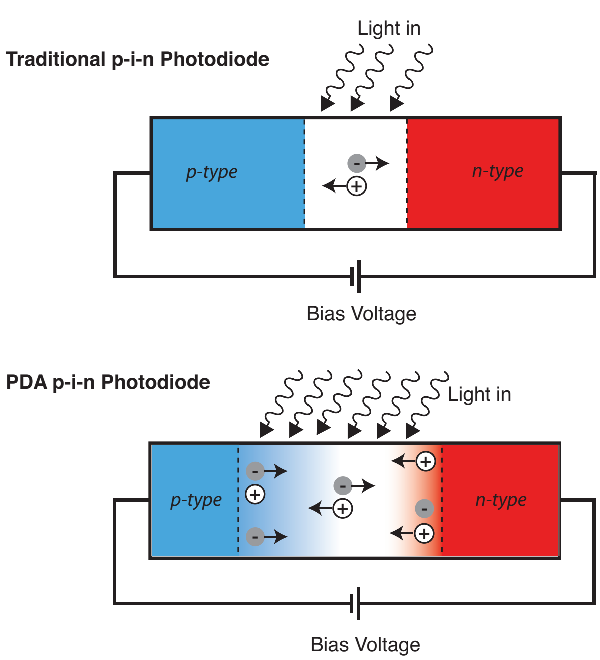


**FIGURE 1**
Schematic layer structure diagram comparing a traditional p-i-n photodiode to a partially depleted absorber (PDA) photodiode.

balance is accomplished by the *p*-doped and *n*-doped optical absorbers on each side of the *i*-region. The *p*-doped absorber injects electrons into the *i*-region while the *n*-doped absorber injects holes. In this implementation, electron injection is stronger than that of holes due to the different thicknesses of the absorbers on each side of the *i*-layer. Furthermore, the design of these diodes includes a thinned *i*-layer to further reduce space-charge effects and minimize thermal loading of the depletion layer. However, thinning the optically absorbing *i*-layer has the deleterious effect of lowering the optical responsivity. This limitation is mitigated in the PDA photodiode design by using a graded doping of the optically absorbing regions on either side of the *i*-layer to increase optical absorption.

**Performance Results:** Figure 2 shows a summary of the saturated photocurrent as a function of bias voltage at several different RF frequencies. The saturated photocurrent is detected by measuring a 1 dB (20%) drop in RF signal response at a specified frequency while a separate continuous wave (CW) unmodulated optical signal is applied to the photodiode. For a 100-μm diameter diode, measured at 300 MHz, the peak saturation photocurrent observed was 500 mA. For a 34-μm diameter diode, the peak saturation photocurrent observed was 153 mA at 5 GHz and 107 mA at 10 GHz. These photocurrents are five to ten times higher than commercially available detectors at these frequencies. For the case of the 100-μm diode, the initial slope of the saturation current with applied voltage fits a straight line with a slope of ~189 mA/V. This initial slope corresponds to a reversed bias series resistance of 5.3 Ω. We believe the extremely large photocurrents generated by these detectors are a direct result of the low series resistance of these photodiodes. Above a bias of 1-2 V, Joule heating ($I^2R$) limits the saturated photocurrent.

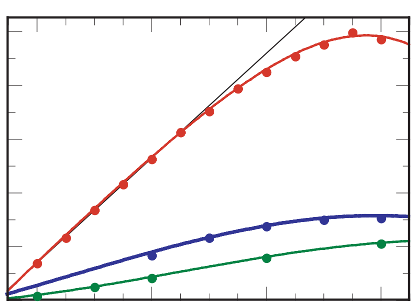

**FIGURE 2**
Saturated photocurrent as a function of bias voltage for a 100 μm diameter PDA photodiode measured at 300 MHz, and a 34-μm diameter PDA photodiode measured at 5 and 10 GHz. The straight line indicates an initial slope of 189 mA/V = 1/(5.3 Ω).

Figure 3 shows the RF power generated by a 100 MHz 100% amplitude modulation depth, 150 mW optical beam incident on a 100-μm diameter PDA photodiode with a fixed average photocurrent of 130 mA as a function of applied voltage. At low applied voltages, the external bias limits the possible output voltage swing (and maximum output RF power) due to the large signal I × V loading from the output impedance. This condition causes the photodiode terminal voltage to decrease to near zero (i.e., clipping behavior). At higher applied voltages, the output RF power exceeds 25 dBm until it begins to saturate above 6 V bias. When 2 GHz amplitude-modulated light is incident on a 34-μm diameter photodiode, 130 mA of photocurrent is able to generate upwards of 24.5 dBm of RF power to a 50 Ω load. With 6 GHz amplitude-modulated light incident upon a 34-μm PDA photodiode, the diode is slightly RF response limited due to its 3 dB bandwidth of 7 GHz. However, it is still able to generate upwards of 23.5 dBm at this frequency. These are the highest reported output RF powers directly generated from a photodetector.[2]

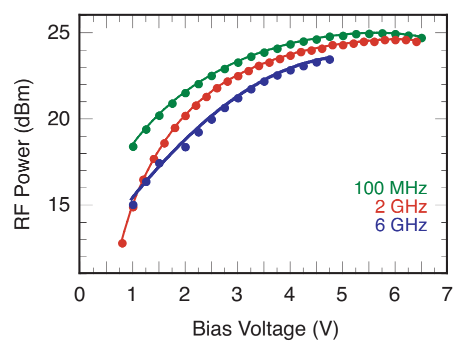


**FIGURE 3**
Peak RF power generated from a 100% amplitude modulation depth optical source as a function of bias voltage from a 100-μm diameter PDA photodiode at 100 MHz and from a 34-μm diameter PDA photodiode at 2 and 6 GHz.

**Summary:** We have described high-saturation-current, wide-bandwidth photodiodes. The partially depleted-absorber photodiode has achieved record high current (bandwidth) outputs of 500 mA (300 MHz), 153 mA (5 GHz), and 107 mA (10 GHz). The maximum RF output power generated from these partially depleted-absorber photodiodes exceeds +23.5 dBm from DC to 6 GHz.

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