High-Power Highly Linear Photodiodes for High Dynamic Range LADARs

Shubhashish Datta and Abhay Joshi
Discovery Semiconductors, Inc.
119 Silvia Street, Ewing, New Jersey 08628, USA
sdatta@discoverysemi.com

Abstract: High power, highly linear photodiodes enhance the overall dynamic range of LADAR systems in two ways: faithfully transferring optical return signal into RF domain with high coherent gain and minimal non-linear distortions, and generating low-phase photonic microwave clocks. Large power handling capability of the photodiodes also reduces the requirement of signal amplification by RF amplifiers, which further improves the dynamic range. We present a 10 GHz bandwidth InGaAs p-i-n photodiode that generates broadband linear RF signal with peak-to-peak output amplitude up to 4 V and power-to-phase conversion factor <4 rad/W. The photodiode's performance is reported with pulsed stimulus, for repetition rates varying from 1 GHz to 10 GHz, as well as continuous wave signals. At higher power levels, these photodiodes produce compressed signals up to 6 V peak-to-peak output. In the compressed regime the power-to-phase conversion factor approaches zero for selected operating conditions, which is useful for generating precision clocks.

Keywords: highly linear photodiode, high power photodiode, high dynamic range, low phase noise, photonic clock.

1. Introduction

Coherent laser detection and ranging systems (LADAR) systems can significantly benefit from utilizing high power, highly linear photodiodes (HLPD) in both signal and clock paths, as shown in Fig. 1. Such photodiodes not only generate minimal non-linear inter-modulation distortions, but also improve the coherent gain through increased optical local oscillator power levels. The consequent reduction or elimination of RF amplification in the system further improves the noise figure and dynamic range of the system [1].

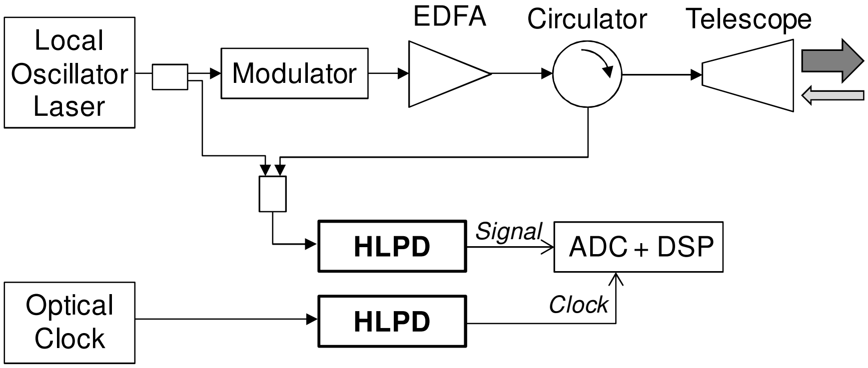

Figure 1. Block diagram of a coherent laser radar that incorporates high power, highly linear photodiodes (HLPD) for providing both signal and clock to the back-end electronics.

The overall dynamic range may also be limited by the clock jitter in the digitizer circuits. Feasibility of generating optical pulses with frequency instability of the order of 10^{-18} has made photonically generated clocks an attractive alternative to traditional microwave clock sources, especially in distributed systems with multiple telescope apertures [2, 3]. Highly linear photodiodes having negligible power-to-phase conversion (PPC) are needed to faithfully transfer the precision optical clock into the RF domain [4-7].

We present a 10 GHz bandwidth InGaAs p-i-n photodiode that generates broadband linear RF signal with peak-to-peak output amplitude up to 4 V, i.e. +16 dBm CW RF power, and PPC <4 rad/W. The photodiode's performance is reported with pulsed stimulus, for repetition rates varying from 1 GHz to 10 GHz, as well as continuous wave signals that satisfy the diverse requirements of LADAR systems.

2. Device Description

A top-illuminated dual-depletion region photodiode with optimized illumination profile was used for this work [1, 4]. The photodiode's RF output did not contain any internal resistive termination to maximize the transfer of RF power to the external 50 Ω load. A photodiode's power handling and linearity, which are limited by the collapse of applied electric field due to photo-generated space charge, increase monotonically with its reverse bias. The combination of high operating bias and the high photocurrent levels can correspond up to 1 W of power dissipation. The consequent heat generation in the InGaAs/InP photodiode chip can significantly increase its temperature and lead to thermally induced device failure. The photodiode chip was integrated with a thermo-electric cooler (TEC) and temperature sensor and assembled in a compact 8-pin microwave package, as shown in Fig. 2a, to extract the heat from the photodiode chip and ensure long-term reliable operation. The TEC and the temperature sensor were electrically isolated from the photodiode chip to minimize noise, crosstalk, and possibility of ground loops. The packaged photodiode module demonstrated a responsivity of 0.65 A/W at 1550 nm wavelength and a -3 dB bandwidth of 10 GHz, as shown in Fig. 2b.

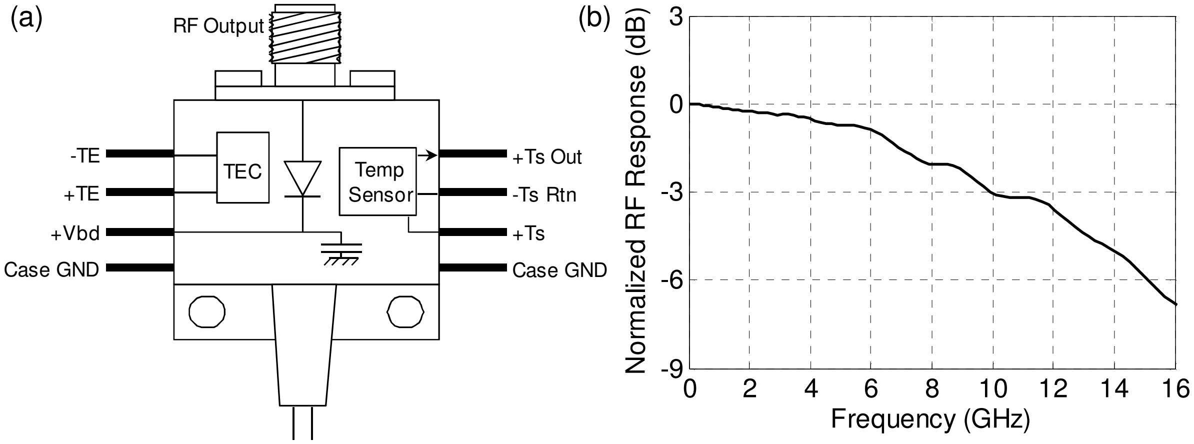

Figure 2. (a) Schematic and (b) RF response of open-terminated photodiode integrated with a thermo-electric cooler and a temperature sensor in a compact microwave package.

3. Amplitude and Phase Linearity with Pulsed Stimulus

The nonlinear transfer function of a photodiode manifests itself as amplitude compression as well as temporal distortions arising from RF pulse broadening at high optical power levels. These distortions were quantified by using the impulse response test setup shown in Fig. 3. This setup utilized a 1550 nm wavelength mode locked laser that emits 2.5 ps wide optical pulses. The optical pulse repetition rate of the laser was defined by its trigger frequency and was varied from 1 GHz to 10 GHz. The laser output was amplified using an Erbium Doped Fiber Amplifier (EDFA) and fed to the photodiode module through a variable optical attenuator (VOA). The integrated TEC of the photodiode module was driven to maintain the photodiode chip at a constant temperature of 15 °C. The module's case temperature was kept below 30 °C with appropriate heat sinking. The RF response was recorded at different reverse bias and average optical power levels using a 50 GHz sampling oscilloscope.

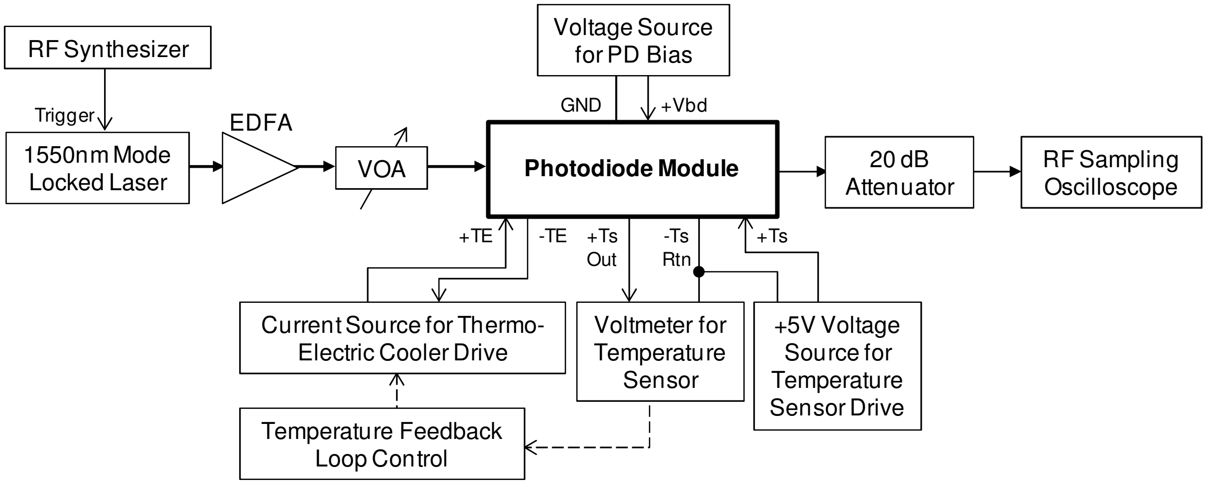

Figure 3. Test setup for characterizing the linearity of the photodiode module with pulsed stimulus.

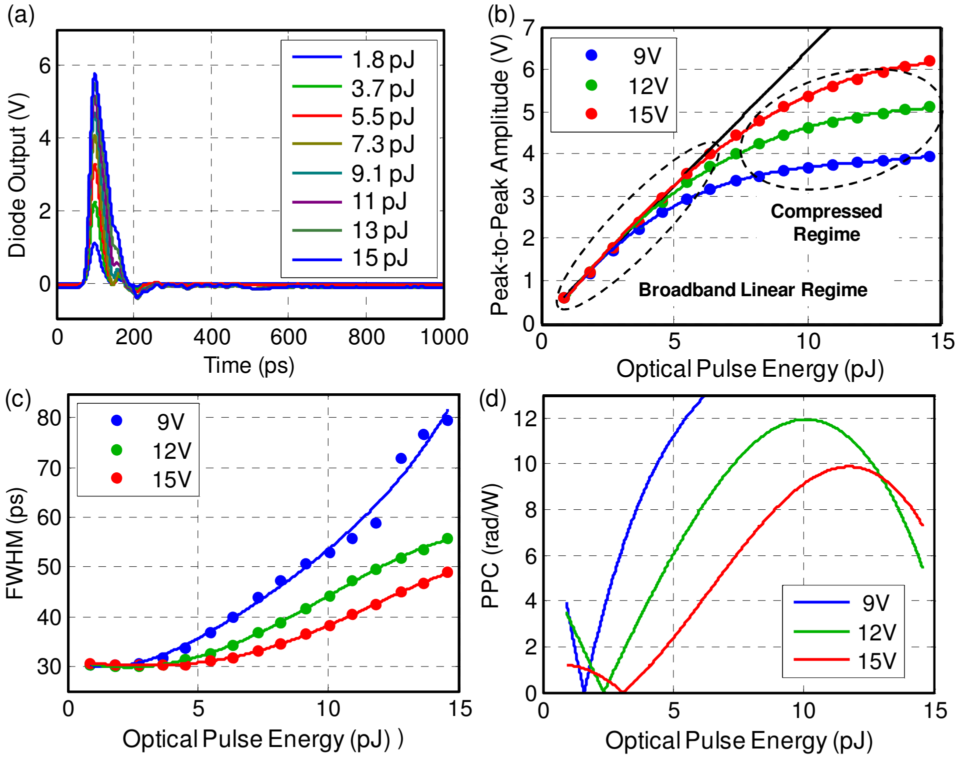

Figure 4. Impulse response of photodiode at 15 V reverse bias for various optical pulse energy levels at 1 GHz pulse repetition rate. (b) Peak-to-peak RF output amplitude, (c) full-width half maximum of the photodiode's output pulse, and (d) power-to-phase conversion of the photodiode at various reverse biases.

The RF impulse response results of the photodiode module at 1 GHz pulse repetition rate are summarized in Fig. 4. In the broadband linear regime, the photodiode's RF output amplitude scales linearly with the input optical pulse energy with negligible change in RF pulse shape. This regime can be extended to higher optical pulse energy levels by increasing the photodiode's reverse bias. The results shown in Figs. 4b and 4c displays a linear amplitude response and minimal pulse broadening up to 4 V peak-to-peak output at 15 V reverse bias. The phase nonlinearity, characterized by the power-to-phase conversion, was computed from the RF impulse response waveforms and was found to be <4 rad/W in this operating regime (see Fig. 4d).

While the broadband linear regime is ideal for detecting the optical return signal in a LADAR, the compressed regime may be preferable for generating low-phase noise clocks to trigger the digitizer. Photonic clock generation involves illuminating a photodiode with a high-power optical pulse train and filtering out a desired harmonic of the fundamental pulse repetition rate to extract a continuous wave RF clock. A photodiode's phase nonlinearity may vanish for specific sets of frequency, photodiode bias, and optical power levels in the compressed domain [6]. The photodiode's phase nonlinearity, expressed as picosecond per fractional input optical power, and the frequency dependent null points are shown in Fig. 5 at a reduced bias of 9 V.

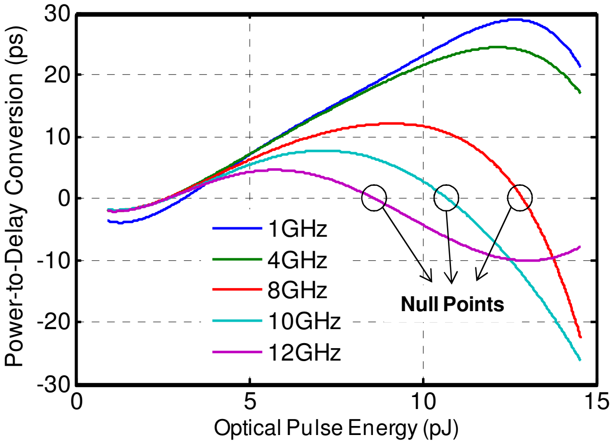

Figure 5. Power-to-delay conversion at 9 V bias illustrating the existence of frequency dependent null points in the compressed regime.

The second source of RF phase noise, namely shot noise, solely depends on the RF power of the filtered clock harmonic. As shown in Fig. 6, the peak-to-peak output amplitude of the photodiode is independent of the pulse repetition rate in both broadband linear and compressed regime, as long as the fundamental frequency is well within the -3 dB bandwidth of the photodiode. In other words, the RF amplitude at the filtered harmonic frequency scales linearly with the repetition rate. Therefore, increasing the pulse repetition rate allows generating a targeted clock harmonic power at a lower reverse bias, and improves the reliability of the photodiode.

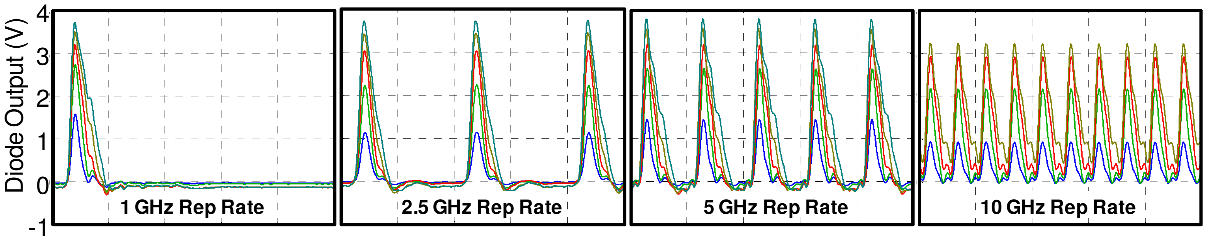

Figure 6. Impulse response of photodiode at 9 V reverse bias for different optical pulse repetition rates.

4. Power Handling with Continuous Wave Stimulus

Suppressing a photodiode's amplitude & phase nonlinearity simultaneously results in high power handling capability. The power handling test setup utilizes a Mach-Zehnder Modulator (MZM) to impose a sinusoidal RF modulation with ~100% modulation depth on a 1550 nm wavelength CW laser. The modulator output is amplified using an EDFA and fed to the photodiode module through a variable optical attenuator. The photodiode's output power is measured at different optical power levels by using an RF power meter. As shown in Fig. 7, RF output power of +16 dBm (4 Vpp) is achievable at 11 V photodiode reverse bias. Such signal level is sufficient for maximizing the effective number of bits (ENOBs) of typical digitizer circuits without requiring any RF amplification.

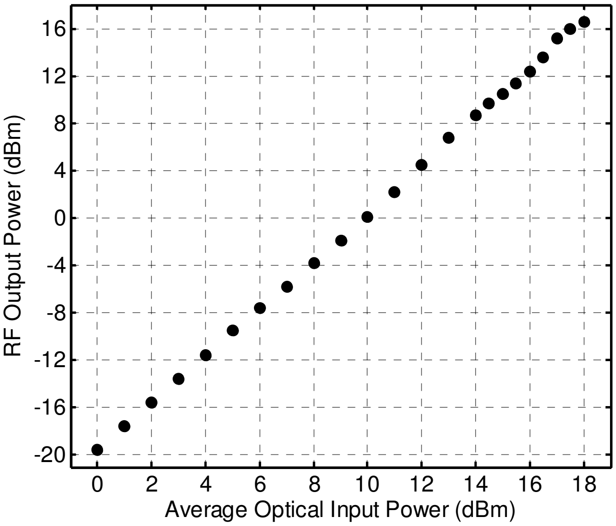

Figure 7. RF output power of the photodiode module at ~100% modulation depth as a function of average optical input power at 11 V reverse bias.

5. Conclusion

In summary, we have demonstrated a 10 GHz bandwidth high power, highly linear photodiode in a thermo-electrically cooled module that can reliably generate broadband linear RF signal with peak-to-peak output amplitude up to 4 V (+16 dBm CW RF power) with power-to-phase conversion factor <4 rad/W. The same device can be used in a compressed regime to photonically generate clocks having extremely low phase noise. These photodiodes can be incorporated in both signal and clock paths of the LADAR systems to increase their dynamic range.

6. References

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