High Power, Uncooled InGaAs Photodiodes with High Quantum Efficiency for 1.2 to 2.2 Micron Wavelength Coherent Lidars

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Abstract: Coherent lidars require photodiodes having high quantum efficiency (QE), which operate with a high local oscillator power for shot noise limited detection. We report an uncooled, lattice-mismatched InGaAs photodiode module for lidars operating at 1.2 \( \mu \text{m} \) to 2.2 \( \mu \text{m} \) wavelength. The photodiode is coupled to a 105 \( \mu \text{m} \) diameter core fiber to maximize its free-space coupling efficiency. The fiber-coupled module exhibits a responsivity of 1.0 A/W (80% QE) at 1550 nm wavelength and 1.2 A/W (73% QE) at 2050 nm wavelength. This device demonstrates a linear performance up to a photocurrent of 65 mA, and can deliver up to +14 dBm of continuous-wave RF output power, i.e. 3.1 V peak-to-peak amplitude. Thus, no further RF amplification is needed to maximize the effective number of bits for the backend digitizers. These photodiodes have a -3 dB bandwidth of 1.7 GHz and are adequate for frequency modulated continuous wave and nanosecond-scale pulsed lidars.

Keywords: extended InGaAs, high power, multimode

1. Introduction

Coherent lidars enabled by high power lasers promise better range and spatio-temporal resolution than their direct detection counterparts. These systems have leveraged Erbium doped fiber lasers and amplifiers, which were developed for 1550 nm wavelength telecom industry. Innovations in Thulium and Holmium doped high power lasers and optical amplifiers have opened up the 2 micron wavelength applications [1]. These lasers are available in both continuous wave (CW) and pulsed formats, and support a diversity of lidar designs [2 - 5]. Fully exploiting the coherent gain and speed afforded by these laser technologies requires a fast, high-power photodetector that demonstrates high quantum efficiency (QE) at these wavelengths.

An additional requirement for photodetectors used in lidar system is maximizing the optical collection area to boost the free-space coupling efficiency. Large-area photodiodes packaged with a free space optical interface have been historically used in such systems. These lidars require mechanically stabilized optical elements, including lenses and mirrors, to ensure a consistent optical coupling efficiency into the photodetector. The stability requirements are especially stringent when a symmetrical optical illumination profile is needed to boost the power handling and linearity of photodiodes [6, 7]. Photodiodes packaged with a large-core multimode fiber interface offer an attractive alternative by providing a consistent optical coupling efficiency and illumination profile without requiring stabilized free-space optical elements. The consequent reduction in the size and weight of the lidar is especially crucial for aerospace applications, which are not only sensitive to SWaP considerations, but also require sub-systems to withstand elevated levels of mechanical shock and vibration.

We report an uncooled, lattice-mismatched InGaAs photodiode module for lidars operating at 1.2 \( \mu \text{m} \) to 2.2 \( \mu \text{m} \) wavelength. The photodiode is coupled to a 105 \( \mu \text{m} \) diameter core multimode fiber to maximize its free-space coupling efficiency. The fiber-coupled module exhibits a responsivity of 1.0 A/W (80% QE) at 1550 nm wavelength and 1.2 A/W (73% QE) at 2050 nm wavelength, with a -3 dB bandwidth of 1.7 GHz. This device demonstrates a linear performance up to a photocurrent of 65 mA, and can deliver up to +14 dBm of continuous-wave RF output power. This device can also produce...
200 ps wide impulses that are linear up to 3.1 Vpp RF output, and thus enable both continuous wave and nanosecond-scale pulsed coherent lidars.

2. Device Description

Conventional InP / InGaAs photodiodes, commonly used in 1550 nm wavelength systems, utilize In₀.₅₃Ga₀.₄₇As absorber layer that is lattice-matched to the InP substrate (lattice constant = 5.87 Å). The cut-off wavelength of these devices is limited to 1650 nm by the bandgap of In₀.₅₃Ga₀.₄₇As material (Eg = 0.74 eV). In this work, we utilized a lower bandgap material, namely Indium-rich In₀.₇²Ga₀.₂₈As (Eg = 0.57 eV) as the absorber layer, to extend the photodiode’s cut-off wavelength to 2200 nm at ambient room temperature. The epitaxial structure of the lattice-mismatched In₀.₇²Ga₀.₂₈As / InP photodiode is compared with the conventional lattice-matched In₀.₅₃Ga₀.₄₇As / InP photodiode in Fig. 1.

The primary challenge in incorporating Indium-rich absorption layer is to minimize the dislocation defects that may arise from the lattice mismatch between In₀.₇²Ga₀.₂₈As (lattice constant = 5.94 Å) and the InP substrate. These defects act as generation-recombination centers and increase the photodiode’s dark current. Also, these defects may provide interstitial sites for material impurities and elevate unintentional background doping level in intrinsic In₀.₇²Ga₀.₂₈As absorption layer [8]. As a result, larger reverse bias is needed in a material with higher defect density to achieve a targeted depletion width and device capacitance for ultra-fast operation. The photodiode structure shown in Fig. 1a utilizes n-doped graded InAsₓP₁₋ₓ buffer layer that is lattice-matched to the (100) oriented, n⁺-doped InP substrate in the bottom and the In₀.₇²Ga₀.₂₈As absorber on the top. This buffer layer contains compositionally abrupt interfaces that minimize the propagation of lattice defects into the subsequently grown intrinsic In₀.₇²Ga₀.₂₈As absorption layer. We have previously reported uncooled photodiodes and photoreceivers having high QE in 1.2 μm to 2.2 μm wavelength range for ultra-fast applications [9].

Figure 1. Epitaxial structure of (a) lattice-mismatched In₀.₇²Ga₀.₂₈As / InP photodiode used in this work is compared with (b) conventional lattice-matched In₀.₅₃Ga₀.₄₇As / InP photodiode. (c) Bandgap and lattice constant of III-V semiconductors with materials of the two photodiode structures is annotated.
For this work, a 150 μm diameter In$_{0.72}$Ga$_{0.28}$As photodiode was terminated with an internal resistive 50 Ω load and assembled in a microwave package. The photodiode’s active area was optically coupled to a 1 m long multimode fiber pigtail having a 105 μm diameter core and a numerical aperture of 0.22. The packaged photodiode demonstrated a DC responsivity of 1.0 A/W at 1550 nm wavelength and 1.2 A/W at 2050 nm wavelength with a -3 dB bandwidth of 1.7 GHz, as shown in Fig. 2a. The optical propagation loss for the fiber pigtail was less than <0.2 dB over the photodiode’s spectral range, as shown in Fig. 2b.

3. Device Results

![Graph showing RF output power vs DC photocurrent](attachment:image.png)

Figure 3. RF output power of 100 μm diameter In$_{0.72}$Ga$_{0.28}$As photodiode for continuous-wave (CW) stimulus with 1 GHz sinusoidal modulation at 5 V and 7 V reverse bias. These results were obtained at an ambient room temperature of 20 °C without any active cooling.
The RF output power of the packaged 150 μm diameter In$_{0.72}$Ga$_{0.28}$As photodiode was measured at different optical power levels for a 1 GHz sinusoidally modulated, continuous wave (CW) signal. As shown in Fig. 3, the photodiode shows linear behavior up to a DC photocurrent of 52 mA at 5 V reverse bias. Increasing the photodiode's reverse bias to 7 V enhances the 1 dB compression point to 65 mA. It is noteworthy that the photodiode can reliably deliver RF output power of up to +14 dBm without requiring any active cooling.

The impulse response of the uncooled In$_{0.72}$Ga$_{0.28}$As photodiode was characterized using a 1550 nm wavelength, mode locked laser having a repetition rate of 1 GHz. The photodiode generated sharp RF pulses that are contained within a 200 ps temporal window, as illustrated in Fig. 4a. Nonlinear behavior of a photodiode is manifested simultaneously as amplitude compression and pulse broadening of its RF output. The pulse broadening also causes the RF output phase to vary with input optical power, and is characterized by the power-to-phase conversion (PPC) factor [7]. Excessive RF pulse broadening also introduces nonlinear crosstalk in time division multiplexed systems. The results shown in Fig. 4 demonstrate that this device can generate linear RF output up to 3.1 Vpp with a PPC <10 rad/W for input optical pulse energy up to 18 pJ.

![Graphs showing the impulse response, amplitude, FWHM, and PPC for different optical pulse energy levels.](image)

Figure 4. (a) Impulse response of uncooled, 150 μm diameter In$_{0.72}$Ga$_{0.28}$As photodiode at 9 V reverse bias for different optical pulse energy levels. (b) Peak-to-peak amplitude, (c) Full-Width Half Maximum (FWHM), and (d) Power-to-Phase Conversion (PPC) calculated from the impulse response.
4. Conclusion

In summary, we have demonstrated an uncooled, lattice-mismatched InGaAs photodiode module having high quantum efficiency at 1.2 \( \mu \)m to 2.2 \( \mu \)m wavelength range and a -3 dB bandwidth of 1.7 GHz. This device generates linear continuous-wave RF output up to +14 dBm, and RF pulses up to 3.1 Vpp. Such power handling not only ensures shot noise limited operation in coherent lidar, but also eliminates the need for any further RF amplification in back-end electronics. The utility of this photodiode in both CW and pulsed coherent lidars is further bolstered by its 105 \( \mu \)m diameter core, multimode fiber interface, which ensures consistent optical coupling without requiring mechanically stabilized free-space optical elements.

5. References


