Low-Noise Large-Area Quad Photoreceivers Based on Low-Capacitance Quad InGaAs Photodiodes

Abhay Joshi, Jim Rue, and Shubhashish Datta

***Abstract*—We report a large-area quad photoreceiver (2×2 array) having an equivalent input current noise density of $<$3.2 pA/$\sqrt{}$Hz per quadrant up to a 3-dB bandwidth of $\sim$20 MHz. The low-noise photoreceiver performance is enabled by a 1-mm diameter quad p-i-n InGaAs photodiode having 2.5-pF capacitance per quadrant at 5-V reverse bias.**

***Index Terms*—Photodetectors, photodiodes.**

I. Introduction

QUAD photoreceivers, namely a 2×2 array of p-i-n photodiodes followed by a transimpedance amplifier (TIA) per diode, are required in several applications relying on free-space optical propagation with position and/or direction sensing capability, such as long baseline interferometry, free-space optical communication, missile guidance, and biomedical imaging and spectroscopy. It is desirable to increase the active area of quad photoreceivers (and photodiodes) to enhance the link gain, and therefore sensitivity, of the system. However, the resulting increase in the photodiode capacitance reduces the photoreceiver's bandwidth and adds to the equivalent input current noise, especially at high frequencies, for a given voltage noise level of the TIA [1]. In fact, a photodiode's capacitance, and the excess current noise arising from it, scales linearly as the device area, thereby negating the corresponding increase in the link gain. Owing to this contradiction, the sensitivity of the overall system may be limited by that of the front-end quad photoreceiver. An example of such an application is the Laser Interferometry Space Antenna (LISA), which proposes to detect gravity waves in space by measuring distance with $\sim$10 pm/$\sqrt{}$Hz accuracy over a baseline of five million kilometers [1].

In LISA, the optical local oscillator (LO) power incident on each photoreceiver quadrant will be restricted to 100 μW to minimize the power requirements and thermal fluctuations for high pathlength stability [1]. Assuming a photodiode responsivity of 0.7 A/W at 1064-nm wavelength, the desired shot noise-limited system operation requires the photoreceiver to display an equivalent input current noise density of $<$4.7 pA/$\sqrt{}$Hz per quadrant. For 0.9-A/W photodiode responsivity at 1550-nm wavelength, an equivalent input current noise density of $<$5.4 pA/$\sqrt{}$Hz is needed. Currently, LISA's sensitivity is restricted by the noise arising from 20- to 25-pF capacitance per quadrant demonstrated by typical 1-mm-diameter InGaAs quad photodiodes [1].

Manuscript received July 29, 2009. First published August 25, 2009; current version published October 09, 2009. This work was supported in part by the National Aeronautics and Space Administration.

The authors are with Discovery Semiconductors, Ewing, NJ 08628 USA (e-mail: abhay@chipsat.com).

Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LPT.2009.2030665

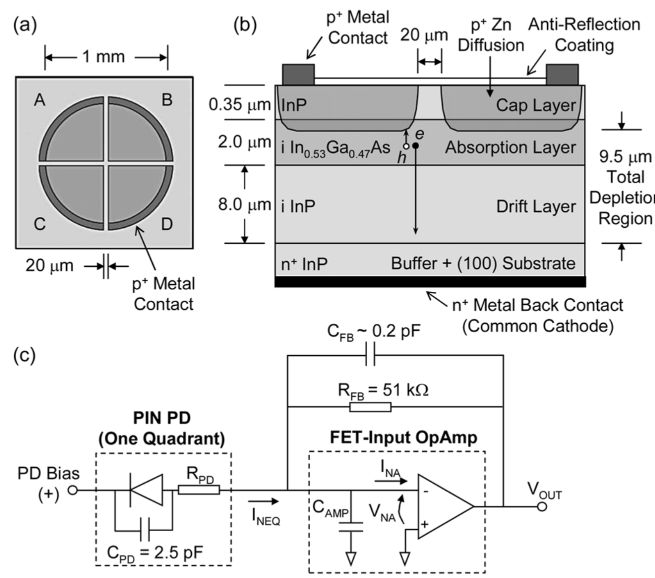

Fig. 1. (a) Top-view and (b) cross section of a top-illuminated DDR InGaAs quad photodiode having 1-mm active area diameter. Each quadrant is separated from its adjacent neighbor by 20 μm. (c) Schematic of the PIN-TIA circuit for one quadrant of the quad photoreceiver showing key design parameters for computing equivalent current noise.

In this work, we present a 1-mm-diameter InGaAs quad photodiode having 2.5-pF capacitance per quadrant. In conjunction with low-noise field effect transistor (FET)-input operational amplifiers, this low-capacitance quad photodiode is leveraged to demonstrate a quad photoreceiver having an equivalent input current noise density of $<$3.2 pA/$\sqrt{}$Hz per quadrant up to a 3-dB bandwidth of $\sim$20 MHz. This constitutes up to $\sim$17-dB improvement in sensitivity over a quad photodiode having 20-pF capacitance per quadrant.

II. Device Description

The schematic of the quad InGaAs photodiode structure, based on the top-illuminated dual-depletion region (DDR) design, is shown in Figs. 1(a) and (b). The DDR structure allows high-speed (i.e., low-capacitance) operation in a top-illuminated geometry by balancing the transit times of electrons and holes with the aid of an InP drift layer [2]. The epitaxial growth was carried out in a metal–organic chemical vapor deposition (MOCVD) reactor on an n^+-doped InP substrate. Standard planar processes were used to define the 1-mm-diameter quad active area with 20-μm separation between the adjacent quadrants. The photodiode structure contains a 2-μm-thick $In_{0.53}Ga_{0.47}As$ absorption layer, of which the top 0.5 μm was

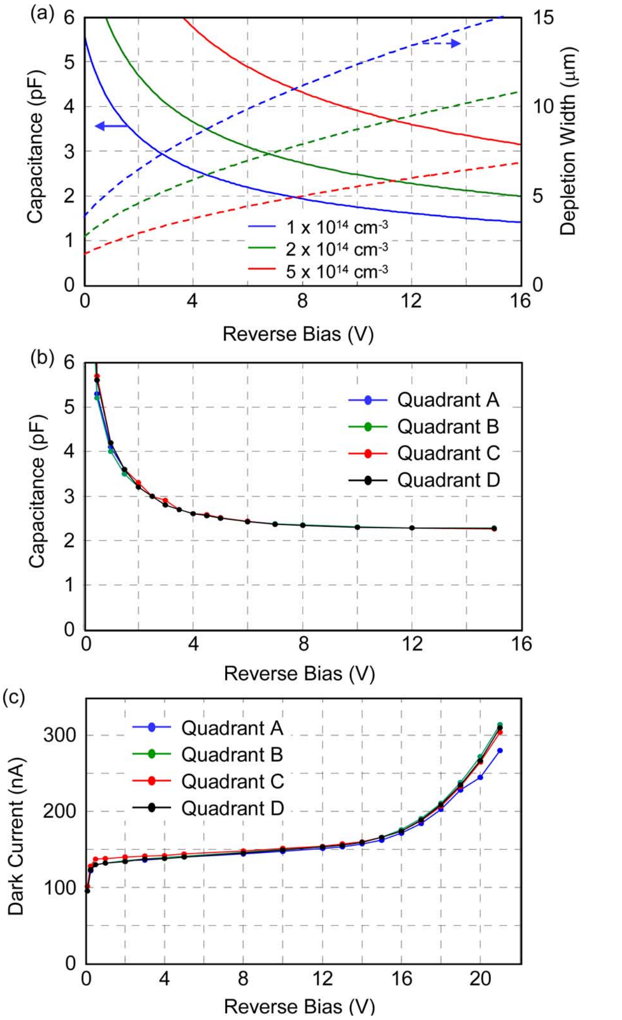

Fig. 2. (a) Calculated depletion width (dashed lines) and capacitance per quadrant (solid lines) of 1-mm-diameter quad photodiode as a function of reverse bias and n-type background doping. (b) Measured capacitance and (c) dark current per quadrant of 1-mm-diameter quad photodiode.

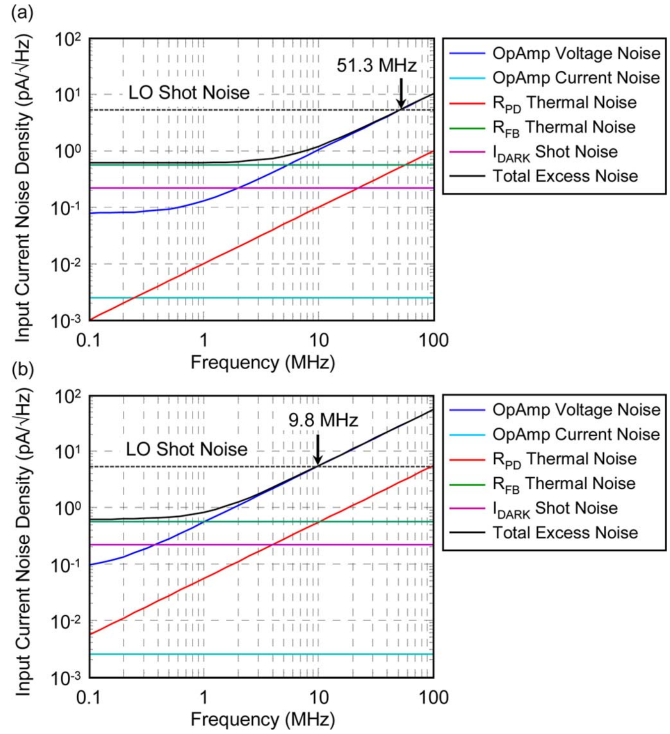

Fig. 3. Calculated equivalent input current noise density for a quad photoreceiver employing a quad photodiode having (a) 2.5- and (b) 20-pF capacitance per quadrant. Shot noise due to 100-μW optical LO power is also shown for 0.9-A/W photodiode responsivity at 1550-nm wavelength.

p-doped to an acceptor concentration of $\sim 1 \times 10^{18}$ cm^{-3} through Zn diffusion. Combined with the 8-μm-thick intrinsic InP drift region, a total depletion width of 9.5 μm can be achieved at high reverse bias.

Each individual quadrant of the quad photodiode was coupled to a separate PIN-TIA circuit, shown in Fig. 1(c), to realize the quad photoreceiver. The TIA employed a 51-k $\cdot\, \Omega$ feedback resistance $R_{\rm FB}$ and $\sim$0.2 pF of feedback capacitance $C_{\rm FB}$ in conjunction with Analog Devices' ADA4817 FET-input operational amplifier (OpAmp). The nominal OpAmp parameters, relevant for noise calculations, include input voltage noise density $V_{\rm NA} = 4$ nV/$\sqrt{}$Hz, input current noise density $I_{\rm NA} =$ 2.5 fA/$\sqrt{}$Hz, and input capacitance $C_{\rm AMP} = 1.4$ pF. The photodiode quadrant is characterized by its capacitance $C_{\rm PD}$ and series resistance $R_{\rm PD}$ ($\sim$10 Ω). The quad photoreceiver was assembled in a standard TO-3 package for device testing.

III. Measurement Setup

The dark current and the capacitance of each quadrant of the quad photodiode chip were measured using a precision source meter (Keithley 2400) and a capacitance–voltage (CV) meter (HP 4284A), respectively. Each quadrant of the packaged quad photoreceiver was characterized as follows. The center of the quadrant was illuminated with a single-tone modulated 1550-nm wavelength optical signal and its conversion gain was recorded using a 50-Ω radio-frequency (RF) spectrum analyzer (Agilent E4440A). To prevent the OpAmp from overloading, an additional 50-Ω series resistor was used between the photoreceiver quadrant output and the RF spectrum analyzer. The same spectrum analyzer was used to measure the photoreceiver quadrant's output voltage noise density. The equivalent input current noise density for each photoreceiver quadrant was computed from the corresponding output noise and conversion gain measurements. These measurements were performed at room temperature without any active cooling.

IV. Results and Discussion

For a given active area, a p-i-n photodiode's capacitance can be reduced by increasing the width of its depletion region. In a conventional InGaAs–InP photodiode structure, the entire depletion region is usually comprised of low bandgap $\rm In_{0.53}Ga_{0.47}As$ ($E_g = 0.74$ eV) absorbing material. However, the low bandgap material in the photodiode structure increases the dark current of the photodiode by enhancing the band-to-band tunneling and generation-recombination current. Consequently, such a design is not optimal for low-noise applications. In the DDR photodiode structure, shown in Fig. 1(b), the thickness of the intrinsic $\rm In_{0.53}Ga_{0.47}As$ absorption layer is dictated by the quantum efficiency requirements and is restricted to 1.5 μm. The majority of the intrinsic region is comprised of the 8-μm-thick high bandgap InP ($Eg = 1.35$ eV) drift layer, thereby minimizing the photodiode's dark current.

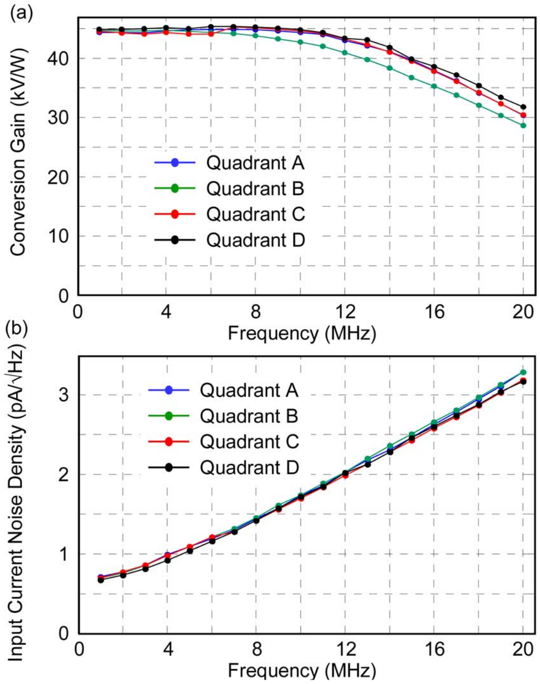

Fig. 4. (a) Conversion gain at 1550-nm wavelength and (b) equivalent input current noise density per quadrant of the 1-mm diameter quad photoreceiver.

It is also necessary to maintain a low unintentional background doping level to ensure that this intrinsic region is depleted at a reasonable photodiode bias. Fig. 2(a) demonstrates that a depletion width of 9.2 μm can be achieved at 5-V reverse bias for an n-type background doping concentration of 1×10^{14} cm^{-3}. Such a depletion width will result in 2.4-pF capacitance per quadrant (C_{PD}) in a 1-mm diameter quad photodiode. Achieving the same depletion width at elevated levels of background doping will require higher reverse bias voltage.

The quad photodiode reported here had $C_{\mathrm{PD}} = 2.5$ pF at 5-V reverse bias, as shown in Fig. 2(b), therefore implying an n-type background doping of $\sim 1 \times 10^{14}$ cm^{-3} in the intrinsic region. Each photodiode quadrant demonstrated a dark current, $I_{\mathrm{DARK}} = 140$ nA at 5 V reverse bias [see Fig. 2(c)]. Such dark current leads to a shot noise density of 0.2 pA/$\sqrt{}$Hz, which is negligible as compared to other noise sources discussed below.

The equivalent input current noise density I_{NEQ} in each quadrant of the quad photoreceiver, shown in Fig. 1(c), arises from a combination of the OpAmp's voltage noise, OpAmp's current noise, thermal noise from the photodiode's series resistance, thermal noise from the feedback resistance, and shot noise due to the photodiode's dark current. These noise sources are statistically independent and combine in quadrature as follows:

$$I_{\mathrm{NEQ}}(f) = \sqrt{\begin{array}{l} V_{\mathrm{NA}}^2\left(\frac{1}{R_{\mathrm{FB}}^2} + 4\pi^2 f^2 (C_{\mathrm{PD}} + C_{\mathrm{AMP}})^2\right) \\ +I_{\mathrm{NA}}^2 + \left[4\pi f (C_{\mathrm{PD}} + C_{\mathrm{AMP}})\sqrt{k_B T R_{\mathrm{PD}}}\right]^2 \\ +\frac{4k_B T}{R_{\mathrm{FB}}} + 2qI_{\mathrm{DARK}} \end{array}} \tag{1}$$

where T is the absolute temperature, k_B is the Boltzman's constant, and q is the charge of an electron (see Fig. 1(c) for other definitions). Fig. 3(a) displays these noise components and the resulting I_{NEQ} for $C_{\mathrm{PD}} = 2.5$ pF. The values of the other parameters used in these calculations have been given in Section II. The equivalent noise for $C_{\mathrm{PD}} = 20$ pF is also given in Fig. 3(b) for comparison. It is evident that I_{NEQ} is limited by the thermal noise from the feedback resistor at low frequencies (= 0.6 pA/$\sqrt{}$Hz for $R_{\mathrm{FB}} = 51$ kΩ at 300 K). At high frequencies, I_{NEQ} is dominated by the OpAmp's input voltage noise with $C_{\mathrm{PD}} + C_{\mathrm{AMP}}$ as the load. Therefore, reduction in the quad photodiode's capacitance leads to lower noise in the quad photoreceiver. Comparison of the photoreceivers' noise with the shot noise for 100-μW LO power and 0.9 A/W photodiode responsivity further demonstrates the relevance of low-capacitance quad photodiodes (see Fig. 3).

Owing to the 51-k $\cdot\, \Omega$ feedback resistance and the measured photodiode responsivity of 0.9 A/W at 1550-nm wavelength, each photoreceiver quadrant demonstrated a conversion gain of 45 kV/W with a 3-dB bandwidth of $\sim$20 MHz [see Fig. 4(a)]. The $\sim$0.5-dB discrepancy between the conversion gains of the four quadrants can be attributed to the device-to-device variations in the OpAmp parameters. All photoreceiver quadrants demonstrated an equivalent input current noise density of <3.2 pA/$\sqrt{}$Hz up to 20-MHz frequency, as shown in Fig. 4(b). The frequency dependence of the photoreceiver noise confirms the dominance of the OpAmp's voltage noise contribution. For a $C_{\mathrm{AMP}} = 1.4$ pF used in this work, the quad photodiode with $C_{\mathrm{PD}} = 2.5$ pF allows a 14.5-dB improvement in sensitivity over a quad photodiode having 20-pF capacitance per quadrant. This improvement can increase up to $\sim$17 dB as the OpAmp's input capacitance is further reduced to <0.5 pF.

V. Conclusion

We have demonstrated a 1-mm-diameter quad InGaAs photodiode having 2.5-pF capacitance per quadrant at 5-V reverse bias. This performance was enabled by the DDR photodiode structure. This quad photodiode was leveraged to develop a quad photoreceiver having an equivalent input current noise density of <3.2 pA/$\sqrt{}$Hz per quadrant up to a 3-dB bandwidth of $\sim$20 MHz.

Acknowledgment

The authors thank Dr. J. Livas, Dr. R. Silverberg, Dr. M. Jhabvala, and Dr. S. Babu at the NASA Goddard Space Flight Center for helpful discussions and support for this work. The authors also thank C. Nowacki and R. Pantaleone for assisting in device testing and assembling the quad photoreceiver.

References

[1] V. Wand *et al.*, "Noise sources in the LTP heterodyne interferometer," *Classical and Quantum Gravity*, vol. 23, pp. S159–S167, 2006.
[2] F. Effenberger and A. Joshi, "Ultrafast, dual-depletion region, InGaAs/InP p-i-n detector," *J. Lightw. Technol.*, vol. 14, no. 8, pp. 1859–1864, Aug. 1996.