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Research article

Photodiode quantum efficiency for 2-µm light in the signal band of gravitational wave detectors

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Abstract. Quantum technologies with quantum correlated light require photodiodes with near-perfect 'true' quantum efficiency, the definition of which adequately accounts for the photodiode dark noise. Future squeezed-light-enhanced gravitational wave detectors could in principle achieve higher sensitivities with a longer laser wavelength around 2 µm. Photodiodes made of extended InGaAs are available for this range, but the true quantum efficiency at room temperature and the low frequency band of gravitational waves is strongly reduced by dark noise. Here we characterize the change in performance of a commercial extended-InGaAs photodiode versus temperature. While the dark noise decreases as expected with decreasing temperature, the detection efficiency unfortunately also decreases monotonically. Our results indicate the need for a dedicated new design of photodiodes for gravitational wave detectors using 2-µm laser light.

Keywords. Quantum efficiency, photodiode, extended InGaAs.

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1. Introduction

The first detections of gravitational waves (GWs) since 2015 by LIGO and Virgo [1,2] have accelerated the development work for new generations of GW observatories such as the Einstein Telescope [3], LIGO Voyager [4] and Cosmic Explorer [5]. A fundamental source of noise in GW observatories is the thermally excited motion of the mirror surfaces. It leads to so-called thermal noise in the observatories' output light with contributions of various mechanisms. In future, the thermal noise is to be further reduced, also by cryogenic cooling of the mirrors, as is already the case at KAGRA [6]. Cryogenically cooled mirrors made of crystalline silicon with mirror coatings consisting of alternating layers of amorphous silicon and silicon nitride are very promising in this respect [7]. A side effect would be that instead of the current wavelength of 1064 nm, a wavelength about twice as long at around 2 μm would have to be used. A longer wavelength also has the advantage of reducing scattering caused by optical surface defects. GW observatories use quantum-correlated (squeezed) laser light [8–13], the advantage of which can only be utilized with photodiodes having very high detection efficiency combined with low dark noise [14].

Here we present the measurement of changes in quantum efficiency of a commercial extended-InGaAs photodiode when cooled from room temperature down to 4 K. The transimpedance amplifier and other electronic components were kept at room temperature. Our results show the expected decrease in photodiode dark noise. However, it turned out that the detection efficiency of the photodiode also decreased with decreasing temperature. This shows that cooling of current photodiodes alone is not sufficient to achieve ultra-high true quantum efficiency for 2 μm laser light.

The definition of the detection efficiency η_{DE} does not take into account photodiode dark noise. In the field of quantum technologies, which includes quantum sensing, quantum communication and quantum computing, electrons that are elevated into the conduction band with thermal energy are just as undesirable as undetected photons. We define the quantum efficiency η_{QE}, which takes photodiode dark noise into account. The following equations compare the two definitions:

$$\eta_{\mathrm{DE}} = \frac{U_{\mathrm{tot}} - U_{\mathrm{dark}}}{U_{\mathrm{perf}}}, \qquad \eta_{\mathrm{QE}} = \frac{U_{\mathrm{tot}} - U_{\mathrm{dark}}}{U_{\mathrm{perf}} + U_{\mathrm{dark}}}, \tag{1}$$

where the voltages U are transimpedance amplified photo currents measured on continuous-wave light. U_{tot} is the total measurement voltage, U_{dark} is the contribution with laser light switched off. U_{perf} is the perfect case, i.e. the usually unknown voltage that the measurement system would provide if every photon of the light beam (that is focussed on the photodiode surface) would be transferred into exactly one photo electron, combined with zero dark current. For the manufacturer of photodiodes, the detection efficiency η_{DE} is the relevant parameter because the problem of dark noise also depends on the light power used and the noise of the transimpedance amplifier. For the user of quantum technologies, on the other hand, η_{QE}, the quantum efficiency (of the entire measuring apparatus), is the relevant parameter. As an example, the quantum efficiency is correctly only 50% if an equally large dark current adds to that from perfect detection efficiency. In the literature, the term quantum efficiency is often used as a synonym for detection efficiency.

We carried out all measurements with continuous-wave laser light with 2128 nm wavelength. This particular wavelength is a promising candidate for future GW detectors, as it can be produced by degenerate optical parametric oscillation (DOPO) from the existing ultra-stable laser light at 1064 nm. Corresponding evidence has already been provided [15–17]. Squeezed light can be produced at this wavelength [18]. Other wavelengths in the 2 μm range have also been researched [19–21].

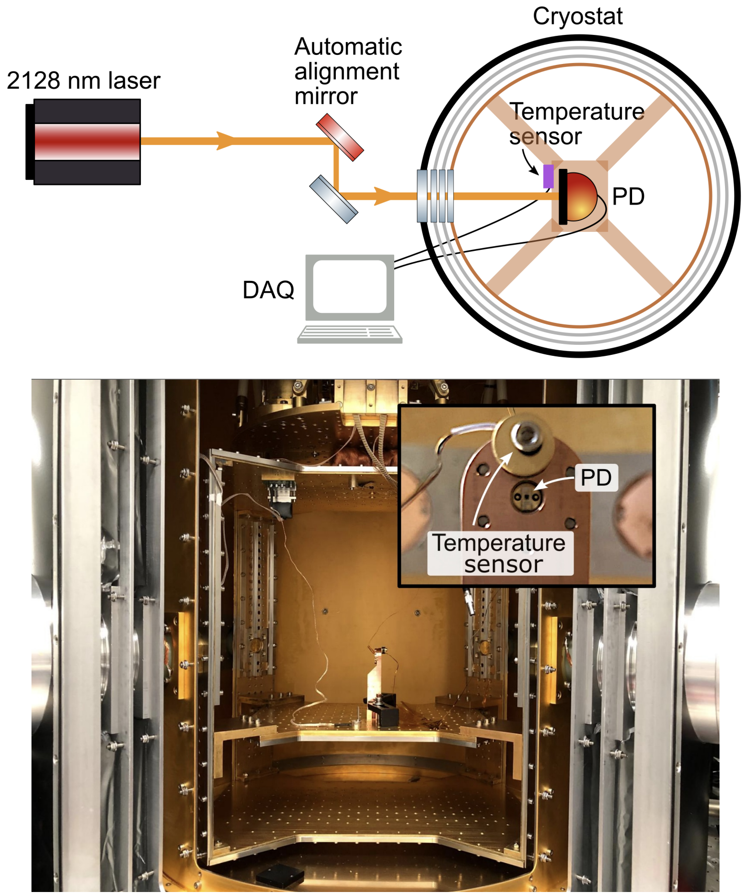
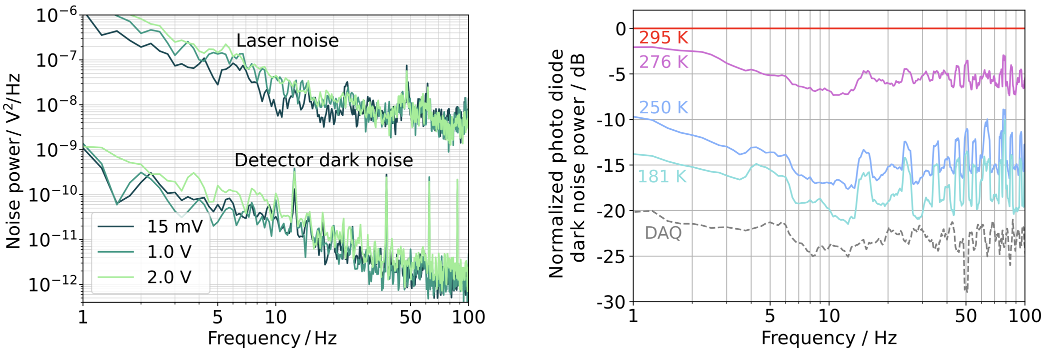


Figure 1. A Thorlabs FD05D photodiode (PD) was placed in a helium cryostat and cooled down to 4 K within 48 h. The photo current was converted to a voltage by a high-gain self-built transimpedance amplifier located in room temperature environment. During cool-down and warm-up, the laser light on the photodiode was switched on and off every 5 minutes and the photo voltage values were continuously sampled and stored at a rate of 1 kHz. This measurement data provided dark current, total photo current and their spectral densities. In parallel, the temperature of the photodiode was measured with a sensor in a common copper block. The stability of the light power on the photodiode was ensured by automatic beam centering and checked by a separate measurement on the input beam. DAQ: data acquisition system.

2. Experimental setup

Figure 1 shows the schematic of our experiment and a photograph of the photodiode inside our cryostat. Continuous-wave laser light of 0.1 mW at 2128 nm from a degenerate optical parametric oscillator [15] was directed onto the surface of the Thorlabs FD05D extended InGaAs photodiode (designed for the wavelength range of 0.9 to 2.6 µm; diameter of the active area: 0.5 mm. We removed the photodiode window before taking the measurements to avoid unnecessary photon losses (of approx. 3%). The remaining reflectivity was that at the semiconductor surface. We determined it to be approximately 0.8%. The incident light power was controlled and stable over the days when the measurements were performed. The cryostat was an Entropy closed-cycle helium cryostat with free-beam optical view ports with a clear aperture of 10 mm diameter. Three heat shield layers with anti-reflective coated windows provided shielding from thermal radiation. The cold experimentation chamber was mechanically decoupled from the vibrating cooler unit and mechanically connected to the optical table. One of the steering mirrors was actively controlled to keep the laser spot in the centre of the photodiode compensating movement due to thermal shrinking and expansions during cool-down and warm-up. We used a gradient descent with momentum algorithm [22], which steered every five minutes while not taking data the mirror for maximum power on the PD. This was achieved by iteratively checking the change in PD response and then moving the mirror based on the improvement in response to earlier measurements. The photodiode was mounted in a copper block with good thermal contact, as seen in the zoom in the photograph in Figure 1. A cernox temperature sensor from LAKESHORE was installed in the immediate vicinity. The self-built transimpedance amplifier (gain of 300 V/mA) of the photodiode was housed outside of the cryostat. Due to its high gain, the photodiode dark noise was significantly higher than other non-optical noise in our measurements. The optical signal of our detection efficiency measurements was broad-band optical power noise of the incident 2128 nm light of 0.1 mW, see Figure 2(a). The rather low power minimized heating of the photodiode.



(a) **(b)**

Figure 2. Noise power spectral densities from 1 to 100 Hz. (a) Comparison of laser power noise from 0.1 mW at 2128 nm and dark noise measured with the photodiode FD05D at 144 K for three bias voltages (the resolution bandwidth, RBW: 0.1 Hz, no averaging). (b) Photodiode dark-noise at four temperatures, normalized to that at room temperature. With decreasing temperature, detector dark noise strongly decreased as expected. The photodiode bias voltage was 0.39 V (RBW: 0.25 Hz, 50 times averaged).

3. Results

Figure 2(a) provides an overview of the spectral noise powers in our experiment for sideband frequencies that are relevant for future earth-based cooled GW detectors. The photodiode temperature here is exemplary at 144 K. The power noise of 0.1 mW of the 2128 nm light (our 'signal') is significantly higher than the dark noise of the FD05D photodiode.

Figure 2(b) shows measured dark noise power spectral densities of the photodiode at room temperature and three different lower temperatures. The lowest noise powers were already achieved at around 180 K with a reduction of more than 15 dB. At further reduced temperatures, the dark noise power did not drop any further, which was probably due to the dark noise of the room-temperature transimpedance amplifier stage. (The noise power of our data acquisition system (dashed) was approximately 5 dB below the lowest dark noise of the measurement system.)

The general reduction in dark noise with lower temperature is expected and well understood, as dark noise is essentially noise due to thermal energy. The thermal energy of the charge carriers

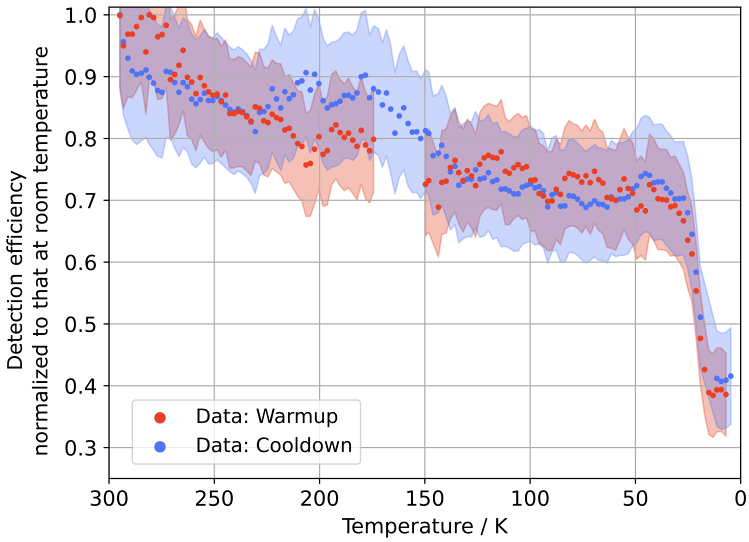


Figure 3. Change of the detection efficiency of PD FD05D with temperature, normalized to that at room temperature. The data was collected continuously over one full cooling cycle. Blue points were taken while cooling down over a time frame of 48 hours. Red points show the natural warming up over 16 days (cooling switched off, no heating). The missing data in the warm-up is due to a computer failure. A small hysteresis of the data was observed. The shaded areas indicate our estimation of systematic error bars due to fluctuations in the light power. All data was measured at a photodiode bias voltage of 0.39 V.

leads to a statistical probability of overcoming the band gap between the valence band and the conduction band even without light incidence. Our dark noise spectra show several peaks, which we were able to attribute to a 50 Hz ground loop of the mains and the temperature data recording at a rate of 5 Hz.

By cooling our extended InGaAs photodiode to temperatures below 200 K, we achieved a level of dark noise that was irrelevant when measuring laser power noise in the frequency band from 1 to 100 Hz (Figure 2). The detection efficiency largely approximated the quantum efficiency according to Eq. (1). However, the optimization of highly efficient photodiodes via cooling is only successful if the detection efficiency does not decrease as a result of cooling. The measurement results of this investigation on our FD05D photodiode are shown in Figure 3. The data was recorded over a cool-down period of 48 hours and a warm-up period of about 16 days. Measured was 0.1 mW stable laser light at 2128 nm with the noise power shown in Figure 2(a). The graph shows the *normalized* detection efficiency versus temperature. It was normalized to that at room temperature, i.e.

$$\eta_{\mathrm{DE,norm}}(T) = \frac{\eta_{\mathrm{DE}}(T)}{\eta_{\mathrm{DE}}(293\,\mathrm{K})} = \frac{U_{\mathrm{tot}}(T) - U_{\mathrm{dark}}(T)}{U_{\mathrm{tot}}(293\,\mathrm{K}) - U_{\mathrm{dark}}(293\,\mathrm{K})}. \tag{2}$$

The voltages (U) in Eq. (2) were measured every five minutes. The photo voltage was sampled for four seconds at a rate of 10 MHz when the laser light was either switched on (U_{tot}) or off (U_{dark}) and averaged to a single DC mean value. Values within the same 1-K temperature intervals were further combined to a unified DC mean value.

Figure 3 shows a continuously decreasing detection efficiency when cooling down from room temperature, which is an unfortunate result. At 250 K (where the dark noise drops to below 10%, see Figure 2(b)) the detection efficiency is reduced by 15%. Photodiodes for future gravitational wave detectors must have a detection efficiency (and quantum efficiency) of approximately 99% or better. A deterioration of 15% due to cooling would be unacceptable. A decrease in detection efficiency with decreasing temperature is not unknown and was recently also observed in [23, Figure 3] and [24, Figure 6]. Below 25 K our detection efficiency further dropped sharply and reached a value of approximately 40% at 10 K compared to that at room temperature. A sharp efficiency drop below a characteristic temperature is well-known and explained as the result of an enlarged band gap [24–26]. In principle, the viewport system of our cryostat could have led to a falsely exaggerated decrease in detection efficiency. However, the cryostat is specially designed to avoid this. The temperature-related shrinkage of the materials is compensated for in such a way that the free aperture does not decrease when the temperature changes. We checked this during the measurement and were unable to detect any scattered laser light at the apertures.

4. Conclusion

Quantum technologies require photodiodes with true quantum efficiencies close to one (> 99%), i.e. virtually perfect detection efficiencies with simultaneously negligible dark noise. For GW detectors, these properties must persist in the low-frequency signal band of the targeted GWs. For future terrestrial GW detectors with cryogenically-cooled mirrors, this applies to the sideband of approx. 1 to 100 Hz.

With this work, we have investigated the change of detection efficiency of a commercial extended-InGaAs photodiode for 2128 nm light and the change of dark noise at low sideband frequencies versus temperature. The photodiode was designed for high detection efficiency at room temperature for the wavelength range from 0.9 to 2.6 µm. With a hand-selected pair of the same photodiode model, we were able in the past to demonstrate a squeeze factor of 7 dB at a sideband frequency of 2 MHz, from which we concluded that the detection efficiency was approximately 93% at 2128 nm at room temperature [18].

The positive result of our measurements is that a temperature of approximately 200 K already reduces the photodiode dark noise in the mentioned low frequency band by more than 15 dB (Figure 2). Another positive result is that the photodiode showed no degradation of performance from being cooled down to 5 K four times and operated at bias voltages significantly higher than specified by the manufacturer.

The negative result of our measurement is that with cooling down to 200 K the detection efficiency of the same photodiode decreased by $(15 \pm 5)\%$ compared to that at room temperature. A concept for highly efficient photodiodes that requires cooling to reduce dark noise but loses detection efficiency at lower temperatures is not suitable for quantum technologies. For future cryogenic 2 µm-GW detectors targeting the scientifically interesting frequency range from 1 to 100 Hz, a new type of photodiode must be developed. The design must ensure quantum efficiency of more than 99% at these low frequencies with an active area diameter of approximately 3 mm, which is a typical size in GW detection.

Declaration of interests

The authors do not work for, advise, own shares in, or receive funds from any organization that could benefit from this article, and have declared no affiliations other than their research organizations.

Underlying data

Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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