Enhancing the quantum efficiency of an InGaAs photodiode by photon recycling

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Abstract

One of the performance indicators of a photodiode is the quantum efficiency. Since higher quantum efficiency produces larger signals, this becomes important when the signal-to-noise ratio is a crucial requirement, like in gravitational wave detectors. Also, the resulting lower optical loss is a critical requirement in some applications, like squeezed vacuum injection in advanced LIGO and other quantum optics experiments. One of the loss mechanisms of a photodiode is light reflected at the front surface. We have increased the quantum efficiency of an InGaAs photodiode at all angle of incidence by recycling the reflected light from the photodiode surface and have tested possible side effects due to backscattering. Our measurement demonstrated a 2~5% improvement in the quantum efficiency without additional scattered light, by introducing a transverse spot displacement of the recycled beam.

1. Introduction

The quantum efficiency defect of a photodiode can be classified in two categories: **Internal loss** and **external loss**

Internal loss: The loss mechanisms that occur to an incident photon absorbed by the detector which do not produce an electrical signal.

[Physical limiting processes]
- *Free carrier absorption:* The photon energy excites a free carrier, and an electron-hole pairs is not created.
- *Electron-hole pair recombination:* An electron-hole pair is created once, but recombines before being collected by the electrodes, due to high carrier density, incorrect location of the photon absorption, etc.

External loss: The loss mechanisms caused when an incident photon is not absorbed by or escapes from the detector.

[Physical limiting processes]
- *Reflection:* Since diodes are usually not coated for a specific wavelength, there is a finite reflectivity. Availability of specifically coated diodes are limited.
- *Scattering:* Surface roughness causes optical scattering. The surface roughness of photodiodes are not well known.

In this study, we tried to minimize the external loss by recycling of the reflected beam from a photodiode.

2. Method and setup

In our experiment, the primary reflection from an InGaAs 3mm photodiode (PD) C30665GH is reflected back to the PD by an HR mirror (Figs. 1 and 2). cf. Use of multiple PDs (aka photodiode trap) [1]

The incoming 1064nm beam from a single mode fiber is steered on the photodiode, nominally at an incident angle of 15deg. Note that the glass window of the PD has been removed. A curved mirror located at 20mm from the PD recycles the reflected light at the primary incidence. **The secondary beam is incident on the PD with 1.5mm displacement from the primary spot on the PD, resulting in 4.3deg misalignment from the primary beam axis.**

The beam parameters have been chosen to have a low modal coupling of the secondary beam into the incoming beam:

Waist size: 50um
Waist location: 20mm before PD

Spot sizes:
- primary beam: 230um
- secondary beam: 340um

Spots separation: 1.5mm

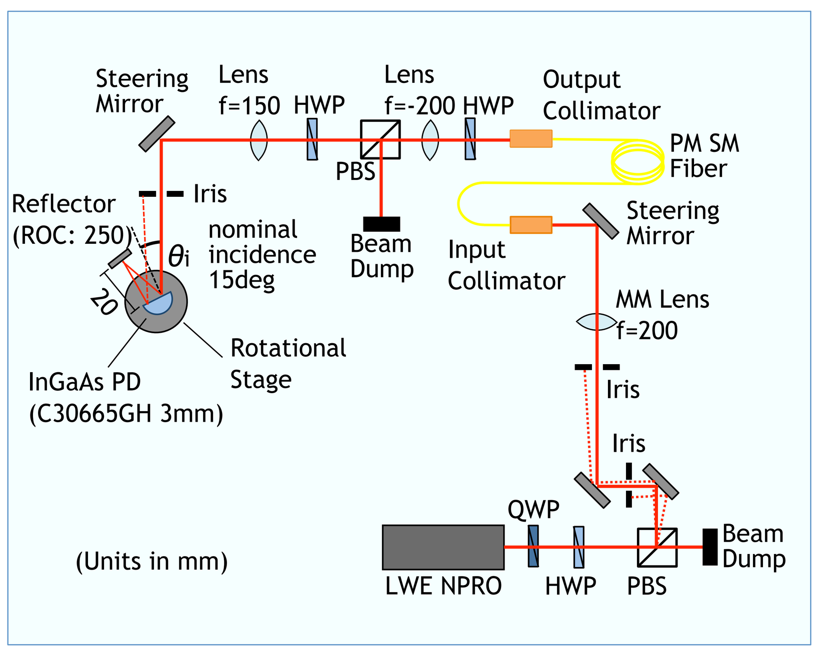

Fig. 1: Optical setup.

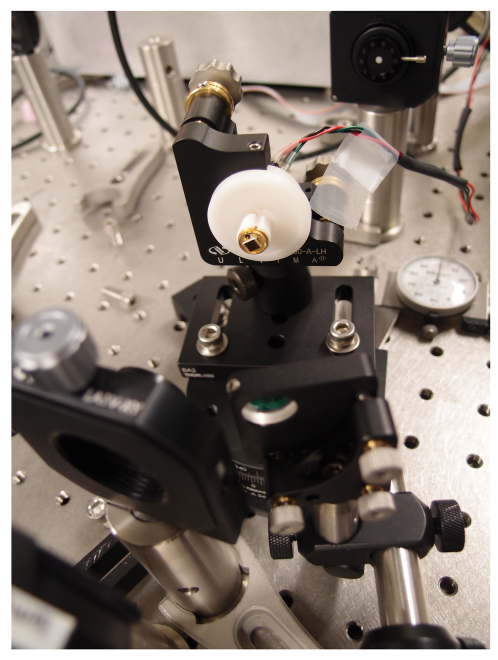

Fig. 2: Picture of the PD setup.

3.1. Result 1: Quantum efficiency enhancement

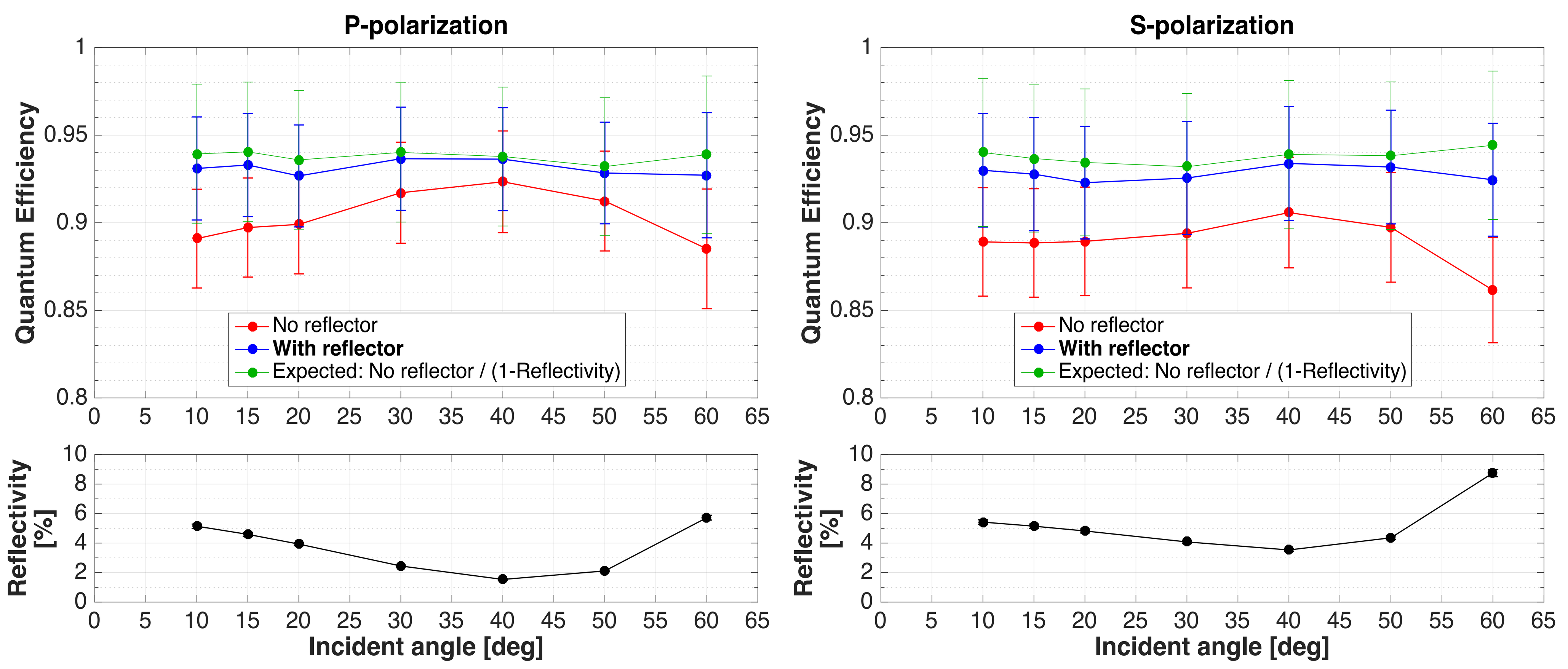

Fig. 3: Quantum efficiency and reflectivity. The left-hand side shows plots of the quantum efficiency (top) and the reflectivity (bottom) for p-polarized light at different incident angles. The right hand-side similarly shows plots for s-polarized light.

The quantum efficiency (QE) without the reflector (red curve) was measured to be dependent on the angle of incidence because of the reflectivity dependence of the PD on the angle of incidence (black curve). A minimum of the reflectivity for each polarization was observed at 40 degrees, which coincides with a maximum of the QE. In fact, the expected QE (green curve) for no external loss ignoring the scatter loss shows almost no angular dependence, indicating an angle independent internal loss.

When the reflected light was recycled, an enhancement of the QE was observed of 2% to 5% at any angle for both the p- and s-polarizations (blue curve). The enhanced QE was measured to be within ~1% of the expected QE.

Note that the absolute values are contingent on the accuracy of the power meter and that is the main source of the error bars.

3.2. Result 2: BRDF measurement

There are two backscattering processes involved in our technique: The backscattering from the primary and secondary incidences. They have been compared with the following measurements.

Indirect approach:
In order to estimate the contribution from each of these two processes, the Bi-directional Reflectance Distribution Function (BRDF) was measured (Figs. 4 and 5).

[Primary scattering]
BRDF(60deg) = 4 x 10^{-5} [1/sr]

[Secondary scattering]
R(15deg) = Reflectivity at 15deg = 0.05
BRDF(34.3deg)*R(15deg) = 9 x 10^{-6} [1/sr]

From this estimation, it is indicated that the secondary reflection has more than 4 times lower scattering than the primary reflection.

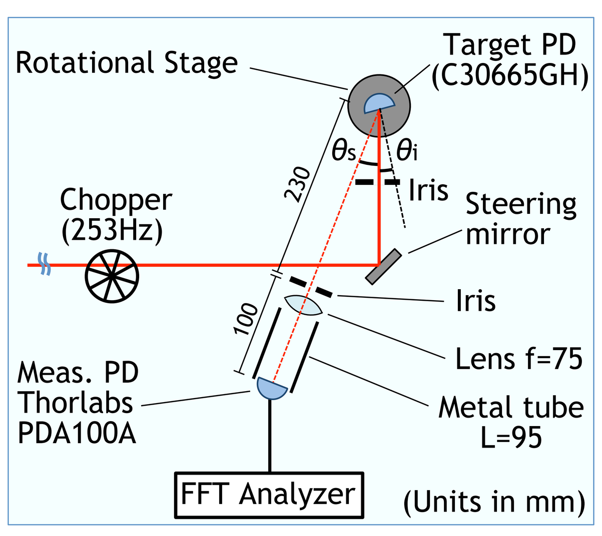

Fig. 4: BRDF measurement setup. The incident light was chopped at 253 Hz. The scattered light from the PD was collected by an iris and a lens into a Thorlabs PD.

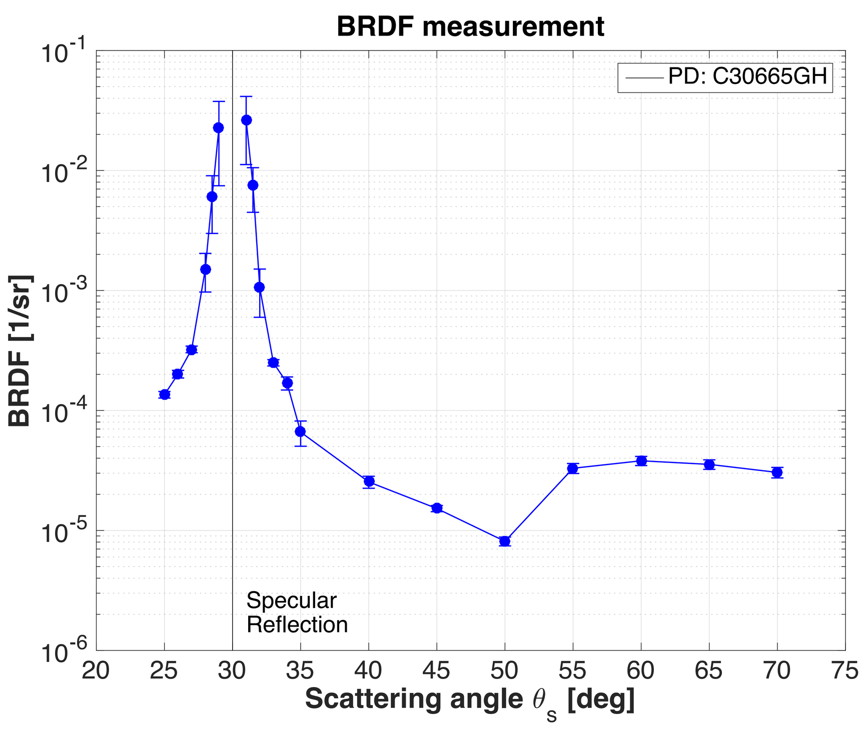

Fig. 5: Measured BRDF of the PD. The incident angle was fixed at 15deg and the PD specular reflection was dumped by a black glass beam dump. The scattering is high and symmetric around the the specular reflection at 30deg. It rapidly drops of orders of magnitude within 5 deg.

3.3. Result 3: Backreflection measurement

Direct approach:
We attempted to measure the backscattering by picking-off the backward beam along the incident beam path.

The measured increase of the BRDF was -1±8 x10^{-5} [1/sr]. **No significant increase of the backscattering was observed.**

When the reflector was placed at 50mm (1.7deg misalignment) from the PD, increase of the BRDF by 1.1±0.8 x10^{-4} [1/sr] was observed.

These results are consistent with the BRDF shown in Fig. 5.

Note that the primary scattering was measured to be 1x10^{-3} [1/sr] and is significantly higher than the one in Fig. 5. This is thought to be caused by an imperfect incident beam and input optics.

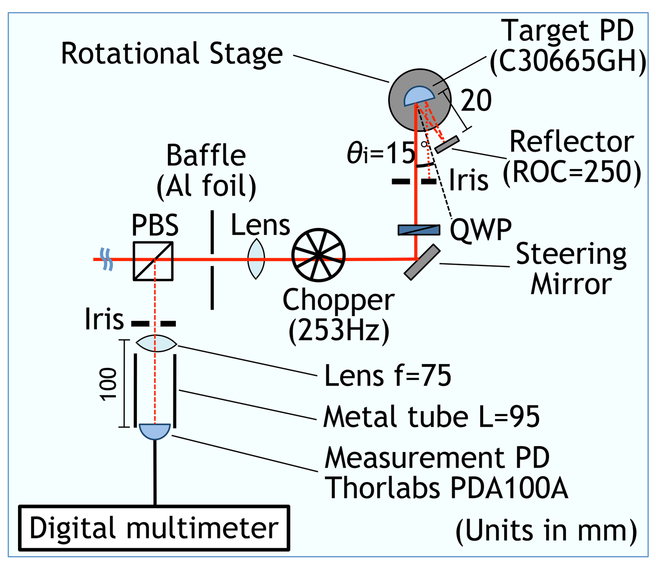

Fig. 6: BRDF measurement setup. The reflected light passes through an iris and focused with a lens into a Thorlabs PD. The lens and the PD are separated by a black tube.

4. Conclusion

The quantum efficiency of an InGaAs photodiode was enhanced by recycling the reflected light from the photodiode surface. As a result of the experiments at 1064nm, the improvement was observed to be about 4% at 15deg incident angle and 2%-5% in the whole range of considered angles. We also measured the BRDFs with and without recycling, hence proving that no dominant back scattering is introduced. This technique can be extended for other type of photodiodes and at other wavelengths. For visible wavelengths with Si photodiodes, this technique will offer a simple way to achieve high quantum efficiency as seen in [1]. For longer IR wavelengths, such as 1.5um and 2um, we are quite curious to see how low the internal loss of extended InGaAs photodiodes (such as [2]) is, in the context of third-generation gravitational wave detectors.

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Reference: [1] E. F. Zalewski and C. R. Duda, Applied Optics 22, 2867 (1983). [2] Laser Components Inc. Extended InGaAs PDs http://www.lasercomponents.com/uk/product/ingaas-500-2600-nm-1/