A self-validated detector for characterization of quantum network components

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Abstract: We are developing a nearly polarization-independent, low-cost optical trap detector between 1000 nm and 1550 nm for optical power measurements. A NIST-traceable optical power calibration of this trap detector showed a promising result.

1. Introduction

We report on our progress towards developing a relatively low-cost trap detector with the ultimate aim of achieving 1 % uncertainty at near infrared between 1000 and 1550 nm for optical power measurements with minimal polarization sensitivity. Quantum networks will use single photons in the telecom band around 1550 nm and 1310 nm [1], and therefore single-photon detectors (SPDs) and sources are required at these wavelengths. While single-photon sources and detectors exist, their calibration and accurate characterization remains difficult and costly. One route is to calibrate and characterize an SPD accurately and use it to characterize compatible single-photon sources. One common method of calibrating an SPD is by using an attenuated laser source [2]. This method requires accurate knowledge of the laser power at nanowatt levels, attainable by using a calibrated optical power meter traceable to a primary standard such as a cryogenic radiometer [3-5]. However, such a calibration and recalibration of transfer or laboratory-standard detectors is a costly and time-consuming process and therefore not available to many users. Our trap detector should enable self-testing that minimizes the need for a frequent recurring calibration service.

2. Design description

Our system employs an optical trap configuration consisting of two commercial InGaAs photodiodes 5 mm in diameter and a flat mirror (Fig. 1). The photodiodes and mirror are contained in a small metallic package that can accept FC optical fiber connectors. When assuming that the internal quantum efficiency of the InGaAs photodiode is 100 % between 1000 nm and 1550 nm, the loss of each diode should only be due to the Fresnel reflection from its surface. The optical path was designed such that the two photodiodes and the mirror ‘trap’ the light beam inside the structure, where the first photodiode is oriented at 45° relative to the incident beam and the second photodiode is oriented at 45° relative to the beam reflected off the first diode, but out of plane to minimize polarization-dependent Fresnel losses. The mirror is perpendicular to its incident beam and thus reflects any remaining light back through the trap along the same path. Also, the two photodiodes, the mirror and the FC-connector should be as close as possible to one another, minimizing the total optical path length, to avoid losses due to beam divergence from a single-mode optical fiber.

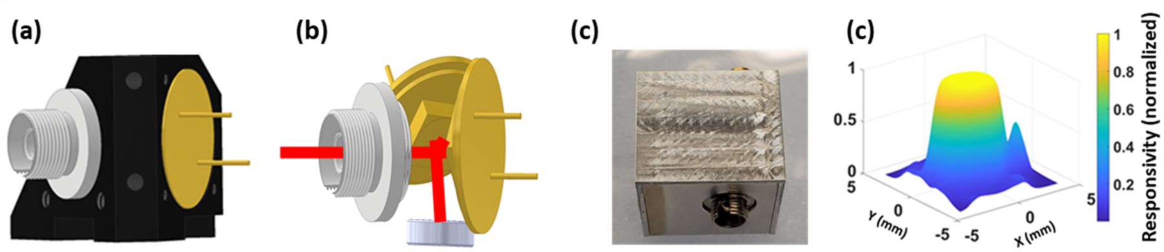

Figure 1: **(a)**, Prototype trap detector design. **(b)**, 3D design illustration with housing removed where the InGaAs photodiode (PDs) are shown in yellow and the flat mirror is on the underside. Light enters the trap through the FC optical fiber connector. **(c)**, Photo of the prototype trap detector with housing, the FC-connector is visible in the front, **(d)** Spatial uniformity of the InGaAs trap detector measured at 1540 nm with the fiber receptacle removed.

3. Characterization Results

We first characterized our trap detector using a collimated 1540 nm laser beam with a full width at half maximum (FWHM) beam diameter of 200 μm. As shown in Fig. 2, the spatial non-uniformity of the trap’s responsivity is less than 0.1 % (1-σ) across the active area. The responsivity has minimal variation with polarization, *i.e.* the maximum polarization-dependent loss is ~0.3 %. We validated that at least 99 % of the incoming light is lost inside the trap by measuring the light exiting at the mirror location, and thereby estimated its inefficiency (*i.e.*, reflectance loss). Knowledge of the reflected light exiting the trap detector and comparing it to the incoming light is in principle a straightforward method to validate its efficiency and can be performed in most laboratory settings by removing the mirror and measuring the amount of light at that output. Our overall estimated uncertainty for verifying the trap's efficiency (including random measurement errors, polarization dependence and spatial non-uniformity) is ~1 %. When using the trap detector with a single-mode fiber, an additional loss due to the divergence of the beam exiting the fiber needs to be taken into account. We have calculated that the maximum loss due to this divergence is less than 1 % and can be avoided by using a curved mirror instead of the flat mirror.

To verify our measurements and assumptions, we also performed an absolute calibration of our trap detector (Fig. 2(b), showing an external quantum efficiency (EQE) of more than 98% between 1000 nm and 1300 nm, which agrees with our measurements as described above. However, the EQE gradually decreases for wavelengths greater than 1300 nm. At 1540 nm the efficiency is 94.5 %, which does not agree with our measurements based on the simple transmission measurements as described above. We speculate that at 1540 nm, we are approaching the InGaAs bandgap and therefore probing a reduced quantum efficiency and that the InGaAs photodiode's absorptance region is too thin for all light to be absorbed. We will explore thicker photodiodes for this application.

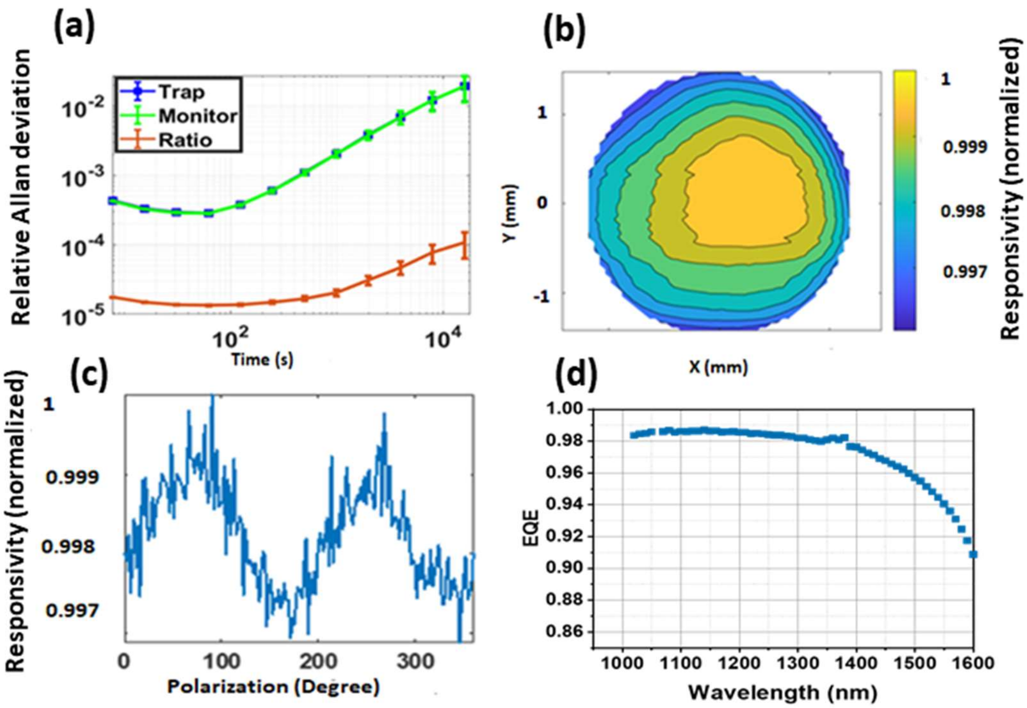

Figure 2: **(a)**, Relative Allan deviation of the trap responsivity over 24 hours. (**b**), Spatial uniformity at 1540 nm of the central region of the sensitive area of the trap detector. The calculated non-uniformity for this area is less than 0.1 % (1-σ). **(c)**, Polarization dependence of trap detector, the maximum polarization dependent loss is about 0.3%. and **(d)**, NIST absolute calibration: External Quantum Efficiency vs wavelength.

4. References

[1] Chapuran, T. E., et al. "*Optical networking for quantum key distribution and quantum communications.*" New Journal of Physics 11.10 (2009): 105001.
[2] Gerrits, Thomas, et al. "*Calibration of free-space and fiber-coupled single-photon detectors.*" Metrologia 57.1 (2019): 015002.
[3] Livigni, D. J. *"High accuracy laser power and energy meter calibration service."* NIST Special Publication 250 (2003): 62.
[4]: Houston, J. M., and Rice, J. P. "*NIST reference cryogenic radiometer designed for versatile performance.*" Metrologia 43.2 (2006): S31.