Towards 1 W, High Accuracy, Absolute Radiometer

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Emerging applications require a calibration at 1 W with greater accuracy than is currently available. Conventional free beam absolute electrical substitution radiometers (ESRs) operate at cryogenic conditions have historically provided the highest accuracy but operate at optical power levels < 2 mW. To improve the accuracy of calibrations at 1 W, we compare possible approaches to realize a primary standard for 1 W optical power measurements. We describe and evaluate two diverse concepts based on bolometer detectors: The first design is an adapted cryogenic approach while the second system is operating at room temperature (RT). With the proposed uncertainty budgets, we estimate an expanded uncertainty for the RT layout to be < 0.06 % (*k* = 2) while the cryogenic design approaches 0.02 % (*k* = 2).

INTRODUCTION

Historically absolute ESRs operate at cryogenic temperatures have provided the most accurate laser power calibrations, accepting optical input power levels of up to 1.4 mW [1]. These devices are built for free beam operation where the beam impinges on the absorber area via a Brewster window. Such equipment allows a combined standard uncertainty of < 0.01 %. For higher optical power calibrations, RT primary standards can be used to achieve power levels in the order of several watts but with uncertainty of 0.5 % – 1 % (*k* = 2) in best case. However, there exist applications with the need for lower uncertainties for a 1 W optical power calibration such as the photon calibrator system (P_{cal}) of the LIGO experiment. In that case, the optical calibration of their P_{cal} is directly proportional to the gravitational wave detection performance [2].

A cryogenic primary standard capable of measuring 1 W of optical power has not been demonstrated, and the thermal management challenges are significant. At the same time, there have been advances in room temperature bolometers at moderate optical powers [3,4] that suggest that high accuracy could be obtained at 1 W with a RT absolute radiometer. If possible, one could realize significant cost savings and possibly better portability over a cryogenic radiometer.

General requirements for a high accuracy 1 W radiometer include a nearly perfect absorber with a diameter > 8 mm to capture Gaussian beams up to 3 mm ($1/e^2$). A free beam operation in vacuum has to be ensured and thus a Brewster entrance window is used to transmit the beam to the absorber.

The aim of this work is to provide a first comparison of the predicted performance of a RT radiometer to a cryogenic version by theoretically estimating the uncertainties associated with new ways of implementing an absolute ESR for measuring 1 W optical power with planar bolometer detectors.

CRYOGENIC DESIGN

One of the major difficulties in a cryogenic high optical power approach is the dissipation of the heat generated by the absorber. We describe the design and modelled the performance of a heat link optimized for high laser powers. According to the heat map of a selected two stage mechanical cryocooler, powers > 2 W at temperatures above 5 K can be handled. We assume a cryocooler-stage plate with 1.4 Hz cyclic thermal fluctuation and an amplitude of ± 200 mK. For precise measurements a first 100× variation damping can be achieved with a thermal low-pass filter consisting of a beryllium copper ring dimensionally matching a readily available holmium copper ($HoCu_2$) element. With a temperature rise from 7.5 K to 9.5 K the integrated heat flow is 4 W and provides control power to handle 1 W optical power. A similar, size reduced second thermal low-pass filter (lead/$HoCu_2$) allows an amplitude modulation suppression to ± 12 µK at a detector stage temperature of 11 K. The screwed-on reference block is made of oxygen free cooper (OFC) with high thermal conductivity. A commercial resistance bridge is used to monitor the heat sink thermistor for feedback controlling the integrated cartridge heater. As a heat link (detector/reference block) an aluminium cylinder with a thermal conductance G = 1 W/K is mounted. For a seamless thermal contact, an OFC substrate is explosion bonded to the heat link prior to the spray-on carbon nanotube coating. A heater wire is wound around and is used as the electrical substitution heater for optical power measurements. The detector runs in an open loop where the temperature change is recorded in the centre of the OFC disk with a side mounted thin film resistor.

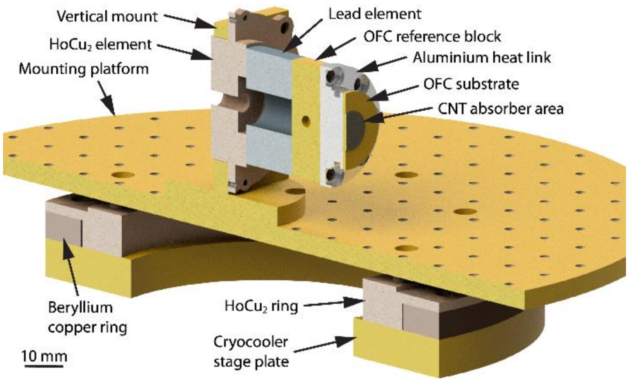

Figure 1. Concept of the cryogenic design

ROOM TEMPERATURE DESIGN

We investigated a design derived from a recently published RT operated compact total irradiance monitor [3] and a RT planar absolute radiometer capable of measuring laser powers up to 300 mW [4]. These differential radiometers are based on vertically aligned carbon nanotubes (VACNTs) grown on silicon substrate [5] and offers an expanded uncertainty of < 0.06 % ($k = 2$). The operation principle is based on a detector pair: one detector measures the laser power and the other compensates for ambient temperature fluctuations. To adapt the designs presented in Refs. [3,4] to 1 W optical power, we assumed a 1 mm thick and 24 mm diameter silicon substrate. A spiral tungsten heater centred on the back of the detector and four low-noise thermistors near the edges of the detector chip reduces the inequivalence between optical and electrical powers [4]. Temperatures of the two detector chips are matched by connecting thermistors in a custom-made AC driven Wheatstone bridge and varying the electrical power to the measuring detector chip [3,4]. A heat link thermal conductance is designed to keep the detector temperature constantly at 303 K with respect to the temperature controlled base plate at 293 K. The heat link consisting of three stainless steel cylinders transports the heat load to the reference block. The reference block is temperature controlled with a thermo-electric cooler and a thermistor providing a thermal stability < 500 µK.

UNCERTAINTY BUDGET

We estimate uncertainty budgets for both 1 W cryogenic and RT radiometers. The major contributions for the uncertainty budget originate from the bolometer. We have estimated expected electrical heating inequivalence, VACNT properties such as non-uniformity, polarization dependence, the absorber reflectance, and the uncertainty in the transmission of the Brewster window. In the electrical power measurement we summarize the uncertainties in the voltage measurements. The dominant electrical noise component originates for both designs from the commercial resistor bridge for the heat sink thermal loop. The radiative coupling at cryogenic temperatures can be neglected by using highly reflective gold-coated components. However, for the RT layout we estimated the ambient temperature coupling and contributions from the thermal fluctuation in the reference block and heat link. In addition to the uncertainties of the Brewster window transmittance correction, the laser power drift and variations, the laser pointing stability and the changes in background radiation are integrated in the optical contribution.

CONCLUSION

The two presented ESRs having a similar detecting principle but antipodal working conditions result in comparable combined standard uncertainties. A first analysis of a cryogenic design that can manage the thermal load of a 1 W laser beam is described. Such a cryogenic radiometer is estimated to achieve an expanded uncertainty of 0.02 % ($k = 2$), a factor of 3 better than the estimated expanded uncertainty of < 0.06 % ($k = 2$) for a RT design. Both designs show that better accuracy than is currently available is within reach.

REFERENCES

1. J. Martin, et al., A cryogenic radiometer for absolute radiometric measurements, Metrologia, 21, 1985
2. S. Karki, et al., The advanced LIGO photon calibrators, Review of Scientific Instruments, 87, 2016
3. D. Harber, et al., Compact total irradiance monitor: flight demonstration, Proc. Vol. 11131, 11310D, 2019
4. A. Vaskuri et al., Microfabricated bolometer based on a VACNT absorber, Proc. SPIE Vol. 11269, 2020, *Subm.*
5. N. Tomlin, et al. Planar electrical-substitution carbon nanotube cryogenic radiometer, Metrologia, 52, 2015