NIST Reference Cryogenic Radiometer Designed for Versatile Performance

J. Houston, and J. Rice

National Institute of Standards and Technology, Gaithersburg, MD, USA

Abstract. We describe the unique design concept of modularity and versatility in the construction of a new cryogenic radiometer developed at NIST. We address the benefits of the modular design in the construction and development and discuss some of the device characterizations and results of a cryogenic radiometer intercomparison.

Introduction

Cryogenic electrical substitution radiometers presently provide the basis for optical measurements in most national measurement institutes. The National Institute of Standards and Technology (NIST) required a new cryogenic radiometer that would provide the lowest possible uncertainty and yet would not become quickly obsolete. The new radiometer needed to have the versatility to grow with NIST's needs, to embrace new technologies, and most especially still be able to provide laser power measurements with uncertainties of 0.01% or better over a range of power levels from µW to mW. Additionally, the radiometer needed to have an improved thermal performance and the ability to calibrate a variety of different optical detectors.

Design

The cryogenic radiometer that was designed and built at NIST is called the Primary Optical Watt Radiometer (POWR), previously known as HACR 2. POWR has replaced the previous High Accuracy Cryogenic Radiometer (HACR). While POWR measures optical power responsivity of detectors using lasers, the unique element of the NIST design is the concept of modularity. The radiometer can be divided into three main sections: the cryostat, the detector module that consists of the receiver cavity, heat sink, and thermal anchor, and finally the optics section. Each of these three components has design elements that contribute to POWR's versatility. In the cryostat itself the base of the helium reservoir is a 381 mm diameter plate, called the cold plate, that contains a series of threaded holes. The critical experimental elements mount and are thermally anchored to the cold plate and are easily removed or replaced. A series of wiring paths that support the different types of four-wire heaters and thermometry and two-wire thermometry are connectorized inside the radiometer for ease of removal. One final element in the actual cryostat design is that it can be operated at two different temperatures, at 4.2 K for most measurements and at 2 K to reduce the thermal noise in the measurement of significantly lower optical powers.

The detector module design is critical in that the goal was to achieve laser power measurements with 0.01% uncertainty at the microwatt and milliwatt levels and yet achieve the modularity to exchange receiver cavities. The detector module design is comprised of four main elements: the cold block, the thermal anchor, the heat sink, and the receiver cavity. The receiver cavity and the thermal anchor were specifically designed to provide the expected radiometric performance of POWR, the ability to measure µW to mW optical power with 0.01% uncertainties or better. The heat sink design includes a place to mount the thermal anchor and a 20 mm diameter receiver cavity combination, and a limiting entrance aperture. Heaters and thermometers on the heat sink regulate its temperature to reduce the noise and uncertainty in the receiver cavity's measurements. The receiver cavity/heat sink module then mounts into the cold block. The main purpose of the cold block is to provide a helium temperature background that surrounds the receiver cavity. The cold block is the part of the detector module that attaches to the cold plate and is thermally anchored to the liquid helium reservoir.

The front optics section includes the window section. Besides the Brewster angle window, this front optics section design provides the opportunity to measure the window transmittance in-situ. Attached between the window and the cryostat is a large, five-way cross. This cross is the location for a trap detector to be inserted to measure the transmittance of an installed window.

Construction

The cryostat is designed and tested for improved thermal and mechanical performance. The helium reservoir holds almost 100 L of liquid helium to provide a measured hold time of 14 days for normal operation. An annular reservoir of liquid nitrogen surrounds the helium reservoir for thermal insulation. The base of the helium reservoir is 304 stainless steel with helicoils for longterm mechanical performance (Figure 1). The wiring for the thermometry is phosphor bronze.

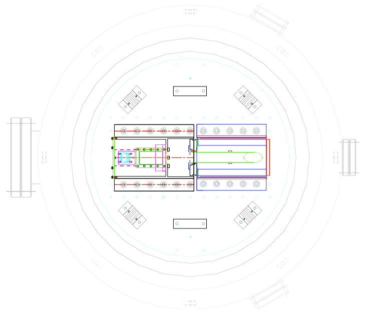

Figure 1. POWR's cold plate provides a series of threaded holes to mount all critical experimental components. The Detector Module and baffle section are mounted from right to left onto the cold plate. The laser beam enters from the left through the baffle section into the receiver cavity. Four thermal anchors for the wiring and two thermal anchors for the wire connectors are on the perimeter of the cold plate.

The detector module itself was initially built and tested with the following elements (Figure 2). The receiver cavity is an electroformed copper cylinder, 20 mm in diameter and 150 mm long. A 30-degree slant closes off the back end of the cavity. The cavity is coated with a specular black paint. One heater is noninductively wrapped on the closed end of the cavity, with another two chip heaters attached to the back slant. The germanium resistance thermometer is located on the cylinder barrel. All wiring from the detector module ends in connectors to provide easy detachment. A Kapton thermal anchor attaches the receiver cavity to the heat sink. Both the heat sink and the cold block are made of OFHC copper that is plated first with nickel and then gold. All surfaces are highly polished and reflective to reduce any radiative effects.

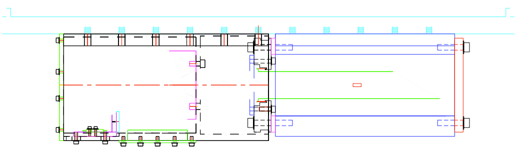

Figure 2. The Detector Module is on the right half with the receiving cavity mounted onto the heat sink and surrounded by the cold block. On the left side is the baffle section with the off axis parabolic mirror and silicon photodiode combination.

While the majority of the detector section itself remained unchanged, the receiver cavity and some thermometry evolved until POWR achieved the desired performance. The receiver cavity evolved until the performance was achieved in Detector Module 3. Additionally the wiring was changed to provide the capability for a feed-forward temperature control loop algorithm.

One element designed into the measurement is the determination of the light scatter magnitude. This was achieved by placing a baffle section attached to the cold block located directly in front of the detector module, and additional baffles along the interior optical path. The baffle section collects the scattered radiation with an off axis parabolic mirror that surrounds the laser beam and reflects the scattered radiation into a silicon photodiode for measurement.

The evolving detector module demonstrates the benefits of the modular design. While the construction and wiring of each detector module required days of work, the actual exchange of detector modules in the cryostat itself took less than one day. A connectorized detector module was easily replaced in the cryostat.

Measurements

The detector modules after being painted and built were measured outside the cryostat for reflectance (from which absorptance is inferred) at three different wavelengths. The measurements were done against NIST PTFE reflectance standards. The final cavity had absorptances of 0.999995 at 633 nm. Because the radiometer is versatile, the detector module can easily be removed and tested over time to see if the paint and absorptance is stable.

Once Detector Module 3 was installed into the cryostat two types of measurements commenced, first the characterization of the electrical to optical equivalence and second the calibration of traps. A full discussion of POWR’s characterization is to be discussed in a future paper. The calibration of the traps was performed in two different configurations, one with the traps on a separate translation stage in front of the window, and a second with the traps in the optical plane of the receiver cavity on the translation stage that moves the radiometer itself. In the end the second setup was used. The same traps measured by POWR were measured by other cryogenic radiometers at NIST and the calibrations agreed within 0.01% to 0.02% which is well within the three radiometers’ uncertainties (Table 1). A full discussion of this intercomparison will be published later.

Table 1. Results of a comparison of three cryogenic radiometers measuring trap detector, presented in terms of the difference from the POWR-measured responsivity of a silicon photodiode trap detector.

Cryogenic radiometer	488 nm	514 nm	633 nm
L1 ACR	-0.021%	-0.002%	-0.011%
LOCR	-0.005%	0.020%	0.001%

The radiometer Brewster-angle window was measured in-situ, but not in vacuum. The Brewster-angle window was optimized for 633 nm and maintained in that alignment for the calibrations. The transmittances at each wavelength were measured before and after the trap calibrations. For the window transmittance measurement the trap was inserted inside the five way cross and aligned to the laser beam. The trap was removed for POWR’s calibration cycles. A typical window transmittance was 0.999921 with an uncertainty of .0012% at 633 nm.

Conclusion

A new NIST reference cryogenic radiometer, POWR, has been developed. The goal in the development of the POWR was to have the versatility in design so that detector modules could be exchanged while providing optical power measurements at uncertainties of 0.01% or better. Final characterization measurements on Detector Module 3 (Rice, et al.) are soon to be completed, but the exchanging of the first three detector modules and the performance of the third module shows that POWR has achieved this goal. In the future, as technology changes or there are special requests for measurements at different power levels or wavelengths, POWR will be able to meet the needs.

Acknowledgements. We would like to thank Steven Lorentz and Joe O’Connell for their contributions in the construction of POWR. Responsivity measurements from the L1 ACR were provided by Steve Brown and Keith Lykke, and for the LOCR by David Livigni. We would like to thank Albert C. Parr, Chief of the Optical Technology Division at NIST, for his continued support of this project.