OPTICAL FIBER POWER MEASUREMENTS

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Abstract
We describe NIST measurement services for the calibration of optical fiber power meters. To augment the absolute power measurements NIST provides nonlinearity, spectral responsivity, and uniformity measurements. We explain the measurement standards, systems, methods, and uncertainties related to the NIST calibration services for optical fiber power meter. Fiber connector issues are briefly described.

Key words: calibration; cryogenic radiometer; fiber; linearity; measurement service; nonlinearity; optical fiber; optical power; optical power meter; spectral responsivity; tunable laser diode; uncertainty; uniformity.

1. Introduction

Since optical fiber power meters (OFPMs) are a very common type of optical test equipment, NIST has developed and implemented measurement services to help characterize these instruments.[1] These measurement services consist of absolute power calibrations using either parallel-beam or optical fiber/connector configurations. In addition, NIST provides measurements of nonlinearity, spectral responsivity (based both on tunable lasers and white-light sources), and uniformity. Calibrations are available at the three principal wavelength regions used by the optical fiber telecommunications industry, 850, 1300, and 1550 nm. Other optical power meter users (e.g., compact-disc player manufacturers and users of erbium-doped fiber amplifiers) are additionally interested in 670, 780, and 980 nm. We have also incorporated these wavelengths into our absolute power calibration program as well.

Most OFPMs are based on diode sensors made of either silicon (Si), germanium (Ge), or indium gallium arsenide (InGaAs). These detectors, which are spectrally sensitive, can produce different outputs when exposed to equal powers from different wavelengths. Both the spectral responsivity of the detector and the spectral pattern of the radiation emitted by a laser source should be measured.

As shown in NIST studies,[2,3] optical fiber power meters when connected to fibers can exhibit significant errors when measuring absolute power. This effect is predominately due to the radiation that is reflected from the diode and window surfaces back onto the fiber/connector assembly and then reflected back onto the detector. This reflected energy causes the optical power meter to read higher than it would for an equal power incident on the detector without a fiber attached. The magnitude of this effect is a function of both wavelength and connector type, and, as a result, the optical power meter should be calibrated with the same fiber, connector and connector adapter with which it is to be used.

Figure 1 depicts NIST optical power measurement traceability which is based on Electrical Standards (SI units) and Laser Optimized Cryogenic Radiometer (LOCR).

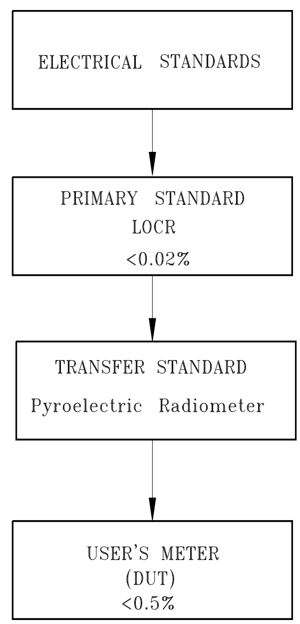

Figure 1. Traceability chart.

2. Laser Optimized Cryogenic Radiometer

To meet the accuracy needs of the optoelectronics community, we have established a new laser power and energy measurement system (Figure 2), based on a commercial cryogenic radiometer designated the Laser Optimized Cryogenic Radiometer (LOCR). The system provides laser power measurements with a combined standard uncertainty of 0.02 % or less.

In the LOCR, a copper optical receiver cavity is attached by a stainless-steel heat link to a copper heat sink, which is attached to the base plate of the liquid-helium reservoir by another stainless-steel heat link. The inside of the receiver cavity is painted black to maximize the absorption of optical power. Optical power enters the radiometer through a Brewster's angle window, which transmits the polarized laser beam with little attenuation. Two digital temperature controllers are used. The first controller regulates the heat-sink temperature, and the other regulates the receiver cavity temperature. Both temperature controllers maintain a constant temperature by applying electrical heating. The cavity temperature is measured using Ge resistance thermometers; heat is applied through thin-film heaters with superconducting leads. The electrical substitution occurs when optical power enters the receiver and is converted to thermal energy. The reduction in electrical power required to maintain the same receiver temperature is equivalent to the amount of optical power.

3. Laboratory standard

The laboratory standard for the NIST optical fiber power measurements is a commercially available, electrically calibrated pyroelectric radiometer (ECPR) which is calibrated against the LOCR. The laboratory standard is a thermal detector which has a black, highly absorbent coating and has, accordingly, an output that is spectrally insensitive over the wavelength regions of interest (600-1650 nm) for optical fiber power meter calibrations. The low-reflectance surface of the laboratory standard allows it to be used for both collimated beam and connectorized fiber measurements. This laboratory standard is used with a system comprised of laser diodes, fibers, connectors, fiber splitters, monitors, and lenses to calibrate optical fiber power meters. The measurement system can accommodate most commonly used types of connectors and fibers.

The pyroelectric sensor of the ECPR is made of lithium tantalate that is covered with a gold-black coating on one side. The gold-black coating (approximately 1 μm thick) is pure gold, which has been evaporated, and then deposited under specific temperature and pressure conditions onto the lithium tantalate surface.[4] Gold black is highly absorbent[5] in the visible and near-infrared regions.

Before the ECPR is used as a laboratory standard, it is first calibrated against the LOCR at several wavelengths (633, 1319 and 1550 nm) by use of the system shown in Figure 2.

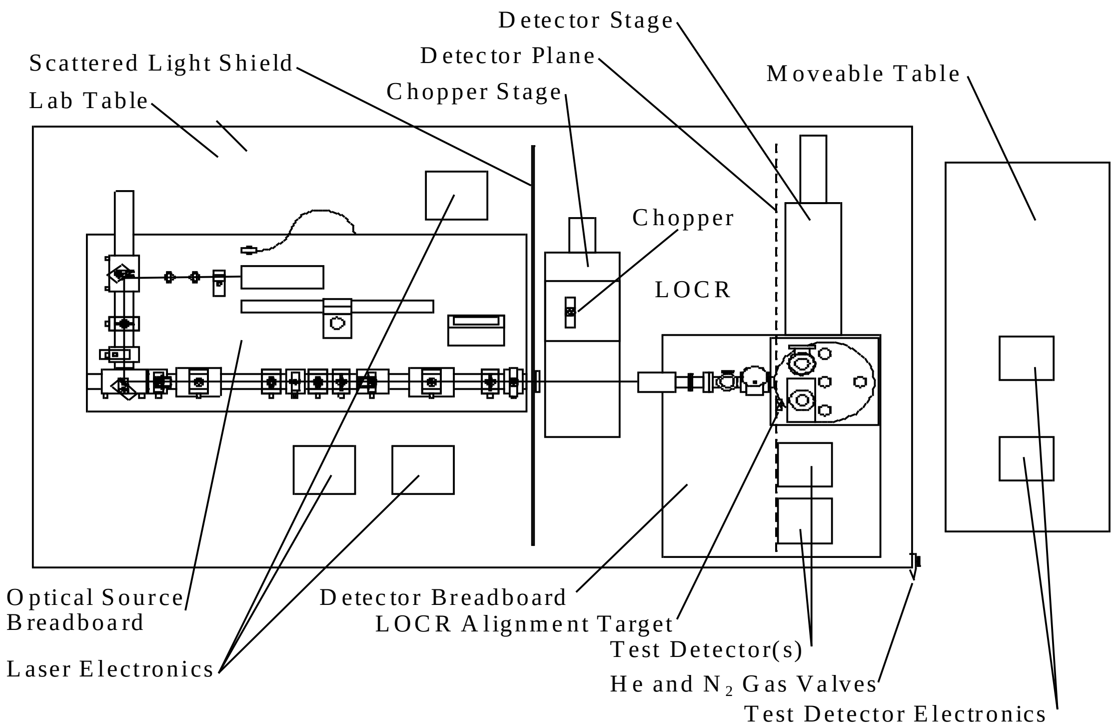

Figure 2. Measurement configuration for ECPR calibration.

4. Optical fiber power meter calibrations

Figure 3 depicts the measurement system configuration used for collimated-beam and optical fiber/connector measurements during the calibration of optical fiber power meters. The ECPR laboratory standard is used as the reference for these calibrations. The system contains several laser source plates, a connector converter stage (for connectorized measurements), lens assembly (for collimated-beam measurements), and a positioning stage for comparing the ECPR and the test meter that is being calibrated.

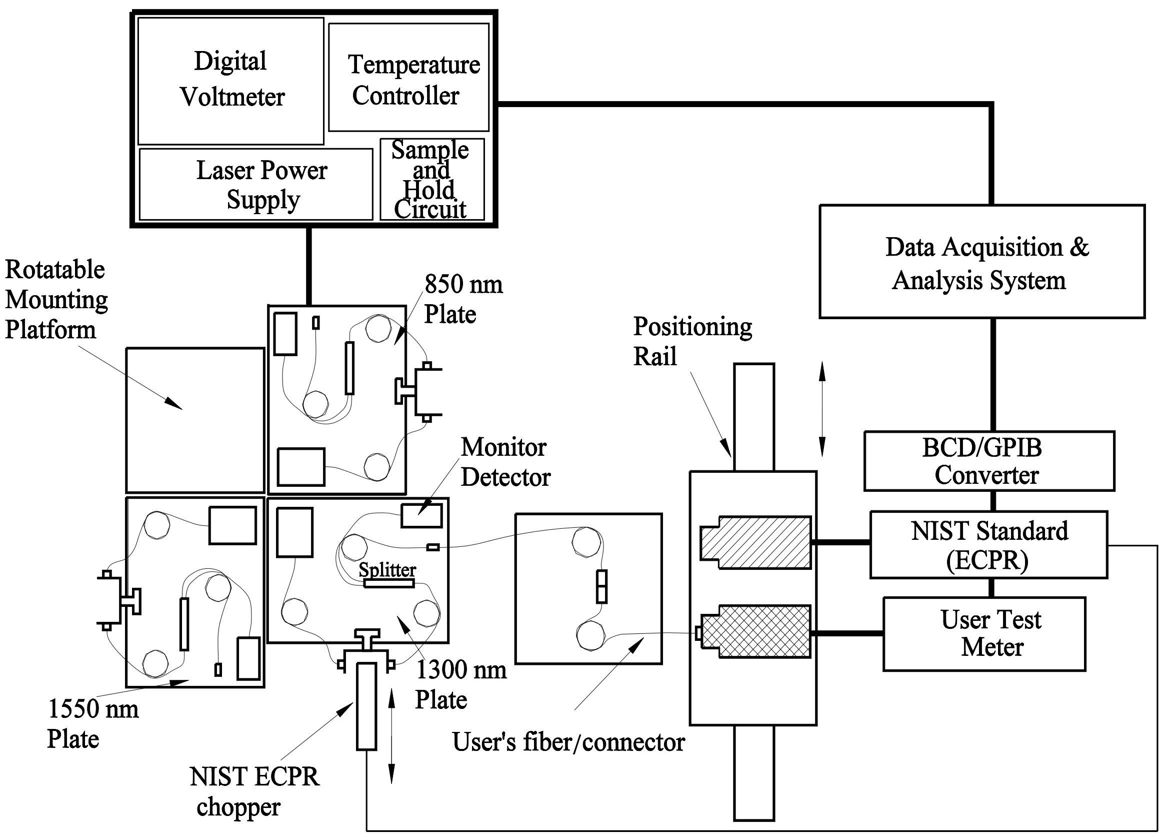

Figure 3. Optical power calibration system.

All system optical fibers are single-mode. Each laser source plate contains a laser diode whose output is transmitted through a fiber to a fiber splitter from which about 1% of the energy travels through a fiber to a monitor detector. The remaining 99 % of the energy is transmitted through another fiber, directing the energy to the meter being calibrated. Loose fibers throughout the system are wrapped on 5-cm diameter spools to minimize transient microbend losses. Also, all fibers are securely fixed so that they cannot move during the measurements.

As shown in Figure 3, a U-shaped collimator fixture is positioned in the propagation path following each diode laser. This fixture contains two lenses, which provide a collimated beam incident on the ECPR chopper wheel. When measuring with the ECPR, the chopper wheel is inserted into the space provided by this fixture; a chopped beam is then incident on the detectors (i.e., the monitor and the ECPR). The monitor detector is connected to a special current-to-voltage converter, which is used to provide an equivalency between powers in CW and chopped beams. This converter utilizes a capacitor that stores the peak voltage reading from the chopped signal until the digital voltmeter takes a reading. The chopper is removed for measurements not involving the ECPR).

For collimated-beam measurements, a lens at the end of the fiber path provides a collimated beam to the ECPR and test meter. For connectorized measurements, the customer's fiber is connected to the measurement system.

5. Measurement Assurance Program

NIST maintains a set of calibrated transfer power meters that are available for a Measurement Assurance Program (MAP) comparison of optical fiber power meters. These transfer standards are calibrated using the optical fiber power meter calibration system. First, NIST calibrates an appropriate transfer standard using the MAP participant's fiber cable, then the meter and the fiber cable are sent to the MAP participant, who compares the NIST transfer standard to his/her laboratory standard. The participant fills out a sample data sheet with his/her measurements, and returns the meter to NIST with the data sheet. NIST measures the MAP meter again. The results of the two sets of NIST measurements are averaged and then compared to the participant's results. The MAP calibration report then summarizes the results of this comparison including an assessment of the associated uncertainties.

6. Calibrations using tunable laser diodes

NIST provides services for optical fiber power meter calibrations at fixed wavelengths using both collimated beam and fiber/connector configurations. However, most users have laser sources whose center wavelengths differ from those used by NIST. To apply NIST's calibration results to the test meter, the meter user must know the spectral responsivity of the detector and the source wavelength. Thus, if the user's source wavelength is different from the wavelength used by NIST during the calibration, the calibration results must be adjusted appropriately. Therefore, it is important either to calibrate an optical fiber power meter at the user's laser source wavelength, or to provide the user with spectral-responsivity information for the detector used in the optical fiber power meter.[6]

For the tunable laser calibrations, NIST has developed a measurement system to calibrate optical fiber power meters using either collimated-beam or optical fiber/connector configurations. This calibration system uses power-stabilized tunable laser diodes that operate in the three optical fiber windows of 850 (±15) nm, 1300 (±30) nm, and 1550 (±30) nm. The lasers include optical isolators to decrease feedback reflections and improve stability.

For example, Figure 4 depicts the measured responsivity of a typical Ge detector in the 1550 nm region using the NIST tunable laser system. Five data points were taken and averaged for each wavelength point on the graph. A typical expanded uncertainty value for optical fiber power meters calibrated using tunable laser diodes is approximately ±0.5 %.

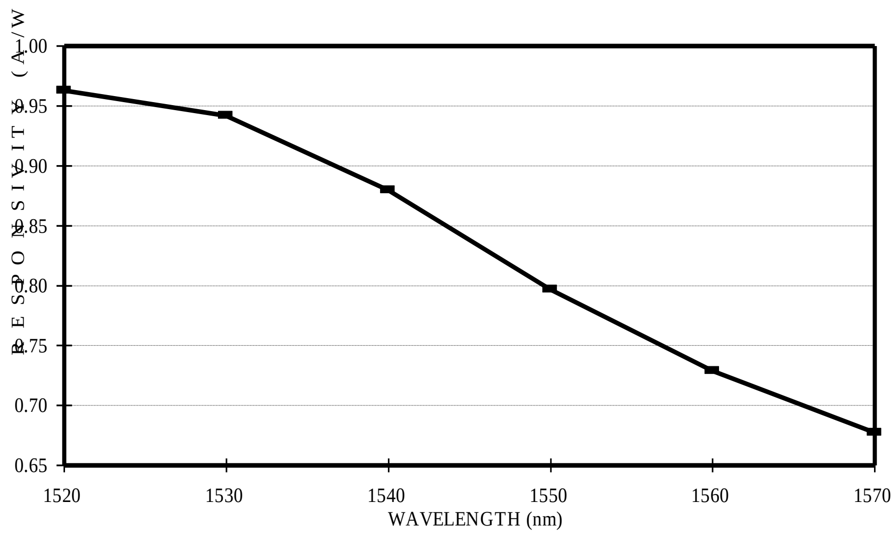

Figure 4. Typical Ge detector responsivity curve using 1550 nm tunable laser diode.

7. Nonlinearity

Using computer modeling[7,8] and experimental tests, we have developed a system for measuring the nonlinearity of optical fiber power meters over a wide dynamic range at telecommunication wavelengths.[9,10] The system utilizes optical fiber components and is designed to accommodate common optical power meters. The system also measures the range discontinuity between neighboring power ranges or scale settings of the optical power meter. Measurements with this system yield correction factors for powers in all ranges. The measurement system is capable of producing results that have standard deviations as low as 0.01 %. NIST's linearity system is capable of measuring the nonlinearity of optical power meters over a dynamic range of more than 60 dB at the three nominal telecommunication wavelengths: 850, 1300, and 1550 nm.

The NIST system for measuring optical fiber power meter linearity is depicted in Figure 5. We use high-power single-mode fiber-pigtailed lasers, which are temperature-controlled for power and wavelength stability. An external optical attenuator with a dynamic range of 60 dB is used to provide variable optical power. The output of the attenuator is divided into two approximately equal parts by introducing a 3 dB fiber splitter; one of the splitter arms has an additional length of fiber (approximately 100 m) to avoid interference. A computer-controlled shutter is inserted into a collimated beam in each arm. Both signals are combined in a 3 dB fiber coupler, which has a FC/APC connector (angled) at the output to decrease reflection effects back to the laser and other components of the measurement system. We use single-mode fiber components such as splitters and couplers.

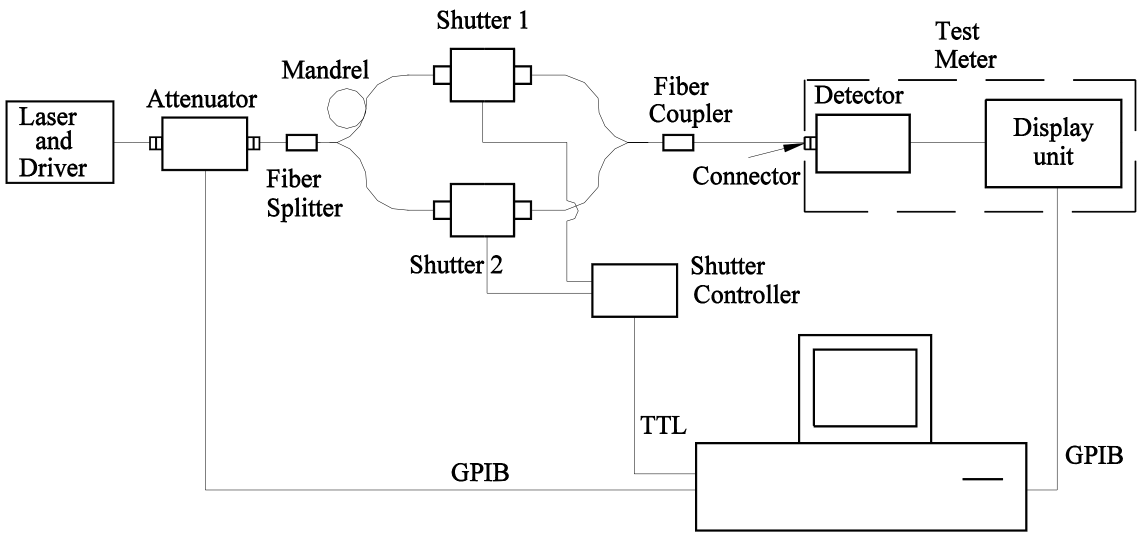

Figure 5. Linearity measurement system.

The data are acquired using the triplet superposition method, in which the measurements are performed by taking sets of three power readings from the test meter: (1) when shutter 1 is open and shutter 2 is closed, (2) when shutter 1 is closed and shutter 2 is open, and (3) when both shutters are open. This sequence is then repeated at different powers. The optical power meter is considered to be linear when the sum of the two individual power readings is equal to the combined power reading.

8. Spatial uniformity

The NIST spatial uniformity measurement system[11] has been very useful in evaluating various calibration problems. A nonuniform detector can give different results depending on a beam's intensity profile and the location of where the beam strikes the detector. Calibrating a nonuniform detector or using it to measure the power in a beam can be difficult because the detector's responsivity can change whenever the detector is realigned. This system is also helpful in determining which detectors are suitable for use as transfer standards. The system directly measures the responsivity of the detector at sample points across the detector surface by measuring the detector's output when illuminated by a power-stabilized beam. The system uses semiconductor laser sources (850, 1300, and 1550 nm). The detector being tested remains stationary while the laser sources are moved by a high-resolution positioning system. High-quality amplifiers and voltmeters are used to accurately measure the detector's responsivity and computer software controls the scan and processes the data.

9. Fiber connector effects

We showed previously[2,3] that the detector responsivity could vary dramatically when using various types of connectors or even connectors of the same type but from different vendors. We investigated the magnitude of this connector-induced variation by calibrating several types of optical fiber power meters at three telecommunication wavelengths of 850, 1310, and 1550 nm. In these measurements we varied the connector type and connector vendor and observed the resulting offsets in calibration results.

When optical fiber power is measured, radiation is transmitted to an optical fiber power meter through a fiber attached to a detector by a fiber connector and adapter. The proximity of a fiber connector to a detector and its associated window provide an opportunity for reflections to introduce errors in the power readings. Even though the measurements using connectors are generally repeatable, the connectors can skew the measurement results. We selected six common connector types: FC/PC, FC/APC, ST, biconic, SC, and SMA from four vendors chosen randomly. Calibrations were performed on four types of power meters at three telecommunication wavelengths: 850, 1310, and 1550 nm.

We found significant measurement offsets (of more than 10 %) resulting from the use of various connectors and a variability (also, of more than 10 %) within a single type of connector obtained from different vendors. Thus, errors could likely occur when changing types of connectors or connector vendors on fibers connected to optical fiber power meters. A laboratory standard, whose output is insensitive to the connector types such as a thermal device, is a useful tool when determining effects due to various connectors.

The magnitude of the errors is wavelength-dependent, but the offset is small if the connector, window, and sensor surfaces all have low reflectivities. Reflectivity problems can be minimized with absorbent or antireflection coatings. Also, tilting the detector can reduce this effect. It is very important to calibrate an optical fiber power meter with the same type of connector and connector adapter used in the actual measurement.

10. Uncertainty assessment

The uncertainty estimates for the NIST optical fiber power measurements are described and combined using the following guidelines.[12] To establish the uncertainty limits, the uncertainty sources are separated into (1) Type A components, whose magnitudes are obtained statistically from a series of measurements and (2) Type B components, whose magnitudes are determined by subjective judgement.

The combined uncertainty is determined by combining the Type A and Type B standard deviations in quadrature and then the expanded uncertainty is obtained by multiplying this result by a coverage factor of 2. A typical expanded uncertainty value for optical fiber power meters calibrated at NIST is approximately 0.5 %.

11. Acknowledgments

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