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Calibration and Traceability of ILX Lightwave Optical Power Meters

APPLICATION NOTE

ILX Lightwave®
A Newport Corporation Brand

Calibration and Traceability of ILX Lightwave Optical Power Meters

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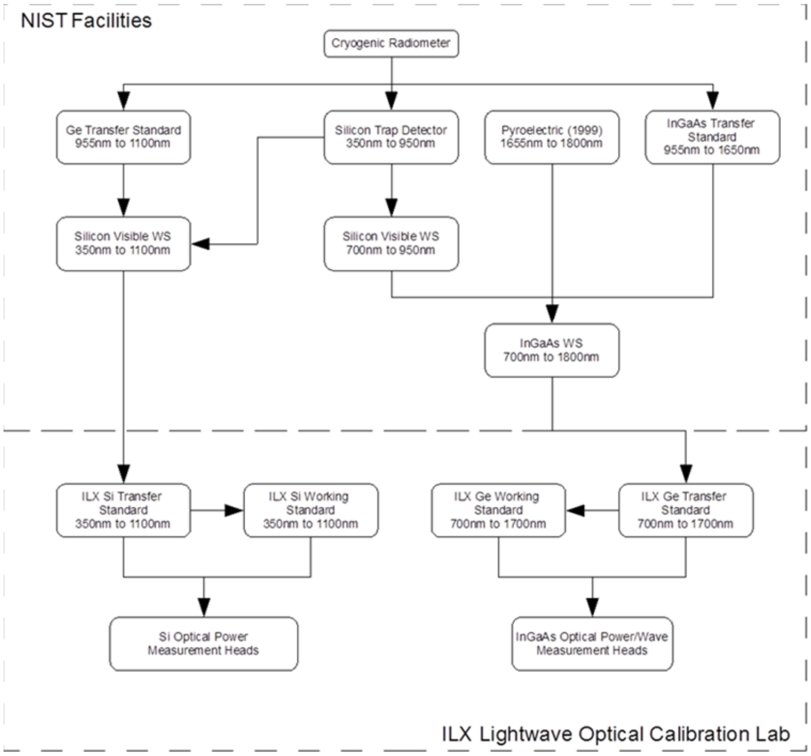
Background

"Many Federal regulations and contracts require organizations or contractees to verify that the measurements they make are "traceable" and to support the claim of traceability by auditing records for equipment used in the calibration process. This regulatory requirement implies the ability to relate individual measurement results through an unbroken chain of calibrations to a common source, usually U.S. national standards as maintained by the National Institute of Standards and Technology (NIST), or intrinsic standards based on fundamental constants of nature with values assigned or accepted by NIST. To adequately establish an audit trail for traceability, a proper calibration result should include: the assigned value, a stated uncertainty, identification of the standard used in the calibration and the specification of any environmental conditions of the calibration where correction factors should be applied if the standard or equipment were to be used under different environmental conditions." [1]

Introduction

End users of measurement instrumentation are interested in accuracy. They want the instrument to be predictable and consistent during measurements, and they need measurement assurance. High quality instrumentation provides assurance of predictable and consistent measurements through a robust quality system of calibration and traceability. ILX Lightwave has taken these concerns to heart in the development of our optical power meters by implementing a rigorous quality system in our calibration facility. This Application Note contains a map of our optical calibration traceability to NIST (Figure 1), describes our quality system, and some important issues regarding optical power meter calibrations.

Figure 1 - Traceability map for the spectral responsivity standards (below)



Traceability

Traceability refers to an unbroken chain of calibration transfers from a known standard to the instrument in question. At ILX Lightwave, this chain of traceability begins with the primary cryogenic radiometer standards maintained by the Optical Technology Division at NIST, and continues unbroken to the optical power heads produced by ILX Lightwave.

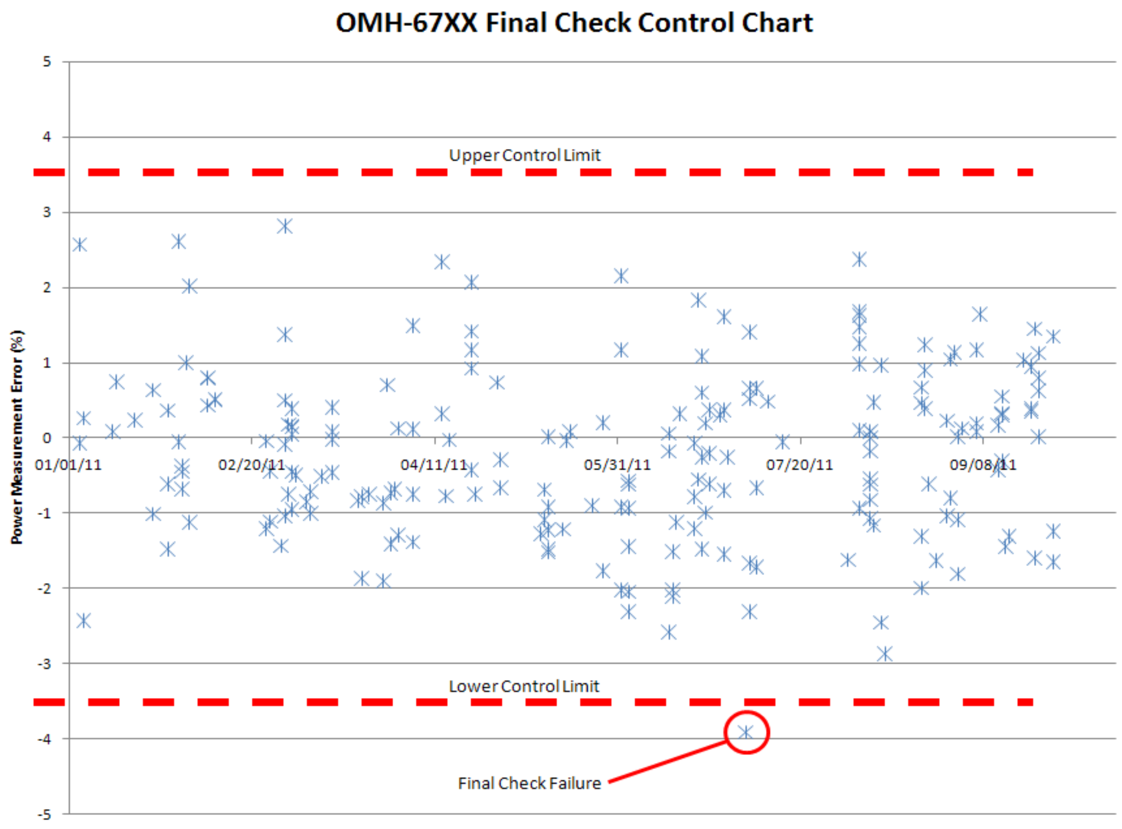
Once a traceability path has been established, it is necessary to have a well-documented quality system in place to ensure continuous traceability. Quality system standards stipulate that all procedures be well documented, including the maintenance and calibration of measurement standards, and measurement and test equipment (M&TE). In addition, recommended practices are published for reference such as NCSL's RP-7, *Laboratory Design, and RP-11, Reports and Certificates of Calibration.*

In addition to building and maintaining a path of traceability for the spectral responsivity standards, each instrument in the calibration apparatus is calibrated to either a NIST traceable standard or a recognized physical constant. For instruments such as picoammeters and DMMs, this calibration is contracted out to a NVLAP accredited calibration service. The monochromator wavelength is calibrated against the emission lines of a krypton calibration lamp.

Quality System

In 2001 ILX Lightwave was granted ISO 9001 certification. Since then, ILX has maintained and improved its ISO quality system. ISO 9001 certification has stipulations which govern the maintenance of calibration artifacts and that the maintenance procedures be documented.

Figure 2 – Example control chart for statistical tracking of calibration quality (below)



According to the Handbook of Statistical methods [2], all calibration systems should have some method of feedback in place to monitor the system and determine if it is functioning within controlled parameters.

In this vein the optical calibration laboratory maintains quality tracking measures intended to drive out deviations, errors, and problems within the calibration system. The three classes of parameters that are tracked are environmental conditions, quality of calibrations, and condition of the calibration apparatus.

Calibration lab temperature and humidity are tracked on a continuous basis. In order to achieve the stated calibration uncertainty for each head, temperature must be in the range of 21°C ± 3°C, and relative humidity must be between 15% and 85%. Both parameters are measured and recorded automatically with a thermo-hygrometer that is calibrated to NIST traceable standards.

For real-time feedback about calibration quality, each calibration that occurs in the calibration lab is compared to “Gold” standards that are maintained by the optical calibration lab (Figure 2). In these comparisons, the output of a small set of laser diode modules is measured with one of the gold standards as well as the unit under test. The reported results are compared and recorded, and measurement errors that fall outside of the calibration uncertainty of the instrument prompt an investigation into the source of the error, as shown in the data point outside the limits in Figure 2.

The gold reference standards are periodically recalibrated. The purpose of these recalibrations is to provide feedback about the relative stability of the calibration apparatus over time. These reference standards cover an appropriate range of wavelengths and power levels to meet the needs of the various heads offered by ILX Lightwave. The gold reference standards receive a full calibration on an annual basis. They then undergo periodic measurements of responsivity, or re-calibrations. The initial calibration provides a snapshot of the calibration lab performance. Subsequent measurements provide snapshots of performance relative to that initial calibration. The frequency of these subsequent measurements is a function of the stability of the measured calibration data; when significant changes from reference standard calibrations occur, the frequency of the checks is increased.

Measurement Theory

The substitution method of calibration is a method of transferring the calibration of a known instrument to an unknown instrument. It involves comparison of the response of the two instruments to identical (or nearly identical) signals. By comparing in this fashion, the calibration of the known instrument can be transferred to that of the unknown. In the case of spectral responsivity calibration, the method consists of measuring the optical power emitted by a source, with a calibrated optical power meter, substituting an unknown power meter in place of the known instrument, and measuring its response to the same optical signal. The final step is to calculate the responsivity of the unknown instrument from these two measured quantities. The calibration factor for the unit under test is then:

$$R_t = I_t / \mathrm{P_s}$$

where R_t is the spectral responsivity of the test detector, I_t is the electrical response of the UUT to the optical input, and P_t is the power of the optical signal as measured by the transfer standard.

Accuracy vs. Uncertainty

The transfer of calibration from one instrument to another must be accompanied by a statement of uncertainty, otherwise the calibration is meaningless. The statement of uncertainty establishes boundaries to the range over which a user can expect the value of a measurement to differ from the true value of the input. It is important to distinguish between uncertainty and error/accuracy. The result of a measurement may be quite close to the actual value and have a very low error or very high degree of accuracy; however, the uncertainty prevents that from being known.

It is common for instrumentation manufacturers to use the terms accuracy and uncertainty interchangeably [3]. While they are not strictly interchangeable, it is common enough that ILX has chosen to refer to calibration uncertainty as accuracy in specification documents. Consequently, the specified "accuracy" of an ILX Lightwave optical power meter refers to the "calibration uncertainty".

Calculating Uncertainty

ILX Lightwave follows NIST guidelines for evaluating and expressing spectral response calibration and measurement uncertainty. Accordingly, ILX Lightwave's published specifications state the expended uncertainty as defined in the NIST guidelines. This is the range in which the actual power is asserted to lie with a confidence level of 95%.

The actual uncertainty depends on several factors and is different for each product so each type of instrument must be characterized to determine its sensitivity to each source of uncertainty.

NIST guidelines specify two types of measurement uncertainty – Type A uncertainty is evaluated by statistical analysis of a series of observations; and Type B uncertainty is evaluated by means other than statistical analysis. For example, it is acceptable to estimate an instrument's contribution to measurement uncertainty using the specifications stated in the manual. Frequently, there is insufficient data to calculate a standard deviation, or the data does not follow a normal (Gaussian) distribution. In these cases, it is best to calculate the standard deviation from the maximum and minimum observed value; then convert this peak-to-peak error to an equivalent standard deviation by assuming either a uniform (rectangular) or a triangular distribution, and applying the appropriate factor. This has the added benefit of providing a conservative estimate of the uncertainty contribution, reducing the risk of under estimating the overall calibration uncertainty.

The expanded uncertainty is 2 x U_c for a 95% confidence level. This is the number that is usually used to determine the uncertainty at reference conditions that is conditions approaching those present at calibration. This is the number that is most often quoted in instrument specification.

Uncertainty Sources

Uncertainty arises from a wide variety of factors. This section discusses a number of common uncertainty sources that must be accounted for in optical power meters.

- **Calibration uncertainty of the parent transfer standard (U1)** – Refers to the stated calibration uncertainty that accompanies the NIST calibration. This is a type B uncertainty component with a normal distribution.

- **Temperature coefficient of the transfer standard (U_2)** – The temperature of the calibration lab is controlled to 21°C ± 3°C. Given that calibration events can take as long as one hour, and that the temperature of the calibration lab can be anywhere within the stated temperature range, the temperature coefficient of the transfer standard and the UUT must be evaluated over this range. This is a type A uncertainty component with an assumed rectangular distribution.

- **Current measurement accuracy of the picoammeter (U_3)** – Refers to the stated calibration uncertainty of the digital multi-meters and ammeters used to measure the response of the transfer standards and the UUTs. This is a type B uncertainty component with an assumed normal distribution.

- **Uniformity of the transfer standard responsivity (U_4)** – Refers to the spatial uniformity of responsivity of a typical photodiode in conjunction with the uncertainty in position and geometry of the optical output of the monochromator source. This is a type A uncertainty component with an assumed rectangular distribution

- **Non-linearity of responsivity (U_5)** – By calibrating spectral responsivity at a single power level for each wavelength, ILX is assuming that the responsivity of the photodiode is linear. In fact responsivity is not perfectly linear, and this component accounts for errors associated with the assumption of linearity. This is a type A uncertainty component with an assumed rectangular distribution.

- **Wavelength calibration of the monochromator (U_6)** – Given that photodiode responsivity is largely dependent upon wavelength, errors between the set point wavelength and the true wavelength can result in significant errors in spectral responsivity calibration. This is a type A uncertainty component with an assumed rectangular distribution.

- **Stray light contributions (U_7)** – Accounts for spectral stray light contributions due to imperfections in the monochromator system. This is a type A uncertainty component with an assumed rectangular distribution.

- **Long term stability of the transfer standard calibration (U_8)** – The transfer standards are on a 12 month calibration cycle. This contribution is evaluated by statistical analysis of the calibration of each transfer standard over the life of the transfer standard. This is a type A uncertainty component with an assumed rectangular distribution.

- **Band pass effect (U_9)** – The bandpass of a monochromator based spectral responsivity calibration apparatus can introduce calibration errors in wavelength ranges where the spectral responsivity is non-linear as a function of wavelength. Rather than calculate and compensate for band pass with each calibration, ILX Lightwave includes the effect of band pass in the uncertainty analysis. This is a type A uncertainty component with an assumed rectangular distribution.

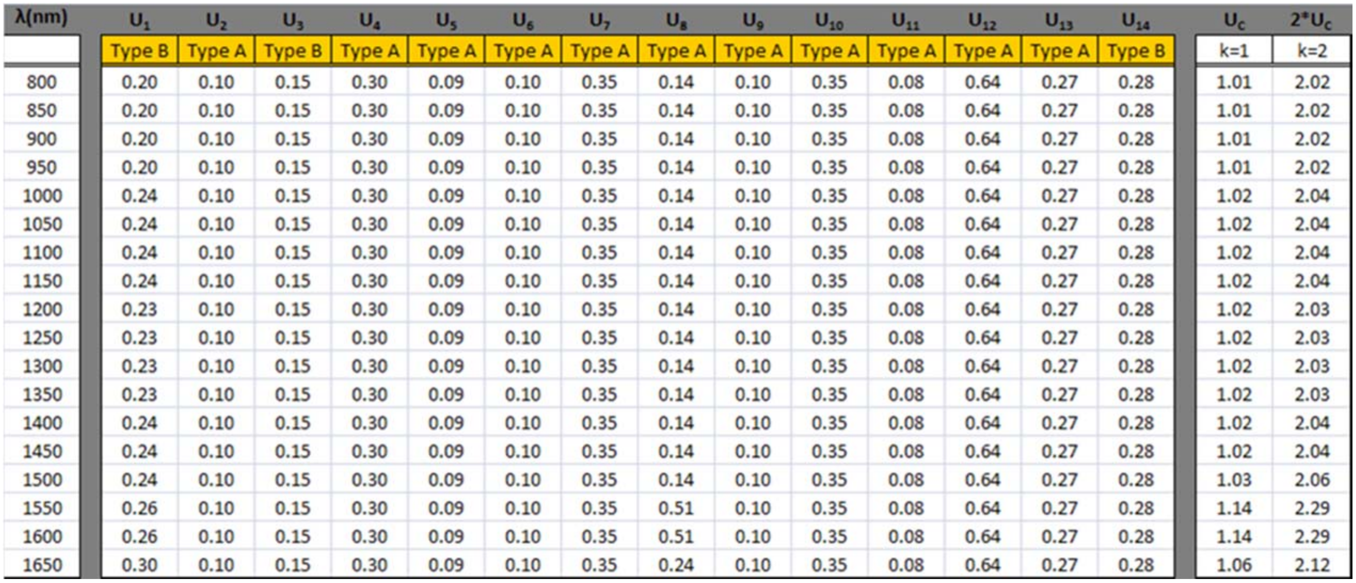
- **Temperature coefficients of the UUT (U_{10})** – This component accounts for the effect that cal lab temperature variations have on the UUT. This is a type A uncertainty component with an assumed rectangular distribution.

- **Polarization dependent response (U_{11})** – Refers to the effect that varying polarization states have on responsivity of an optical power meter. This is a type A uncertainty component with an assumed rectangular distribution.

- **Port effect (U_{12})** – Describes the situation where the power reported by an integrating sphere based optical power measurement head varies as a function of the reflectivity of the material filling the input port. This is a type A uncertainty component with an assumed rectangular distribution.

- **Linearity of responsivity of the UUT (U_{13})** – This component accounts for the non-linearity of responsivity of the UUT over the reference condition power range. This is a type A uncertainty component with an assumed rectangular distribution.

- **Additional contributions (U_{14})** – Accounts for UUT dependent contributions which are either insignificant when listed by themselves, or are specific to a particular power measurement head configuration.



λ(nm)	U_1	U_2	U_3	U_4	U_5	U_6	U_7	U_8	U_9	U_{10}	U_{11}	U_{12}	U_{13}	U_{14}	U_C	2^*U_C
	Type B	Type A	Type B	Type A	Type A	Type A	Type A	Type A	Type A	Type A	Type A	Type A	Type A	Type B	k=1	k=2
800	0.20	0.10	0.15	0.30	0.09	0.10	0.35	0.14	0.10	0.35	0.08	0.64	0.27	0.28	1.01	2.02
850	0.20	0.10	0.15	0.30	0.09	0.10	0.35	0.14	0.10	0.35	0.08	0.64	0.27	0.28	1.01	2.02
900	0.20	0.10	0.15	0.30	0.09	0.10	0.35	0.14	0.10	0.35	0.08	0.64	0.27	0.28	1.01	2.02
950	0.20	0.10	0.15	0.30	0.09	0.10	0.35	0.14	0.10	0.35	0.08	0.64	0.27	0.28	1.01	2.02
1000	0.24	0.10	0.15	0.30	0.09	0.10	0.35	0.14	0.10	0.35	0.08	0.64	0.27	0.28	1.02	2.04
1050	0.24	0.10	0.15	0.30	0.09	0.10	0.35	0.14	0.10	0.35	0.08	0.64	0.27	0.28	1.02	2.04
1100	0.24	0.10	0.15	0.30	0.09	0.10	0.35	0.14	0.10	0.35	0.08	0.64	0.27	0.28	1.02	2.04
1150	0.24	0.10	0.15	0.30	0.09	0.10	0.35	0.14	0.10	0.35	0.08	0.64	0.27	0.28	1.02	2.04
1200	0.23	0.10	0.15	0.30	0.09	0.10	0.35	0.14	0.10	0.35	0.08	0.64	0.27	0.28	1.02	2.03
1250	0.23	0.10	0.15	0.30	0.09	0.10	0.35	0.14	0.10	0.35	0.08	0.64	0.27	0.28	1.02	2.03
1300	0.23	0.10	0.15	0.30	0.09	0.10	0.35	0.14	0.10	0.35	0.08	0.64	0.27	0.28	1.02	2.03
1350	0.23	0.10	0.15	0.30	0.09	0.10	0.35	0.14	0.10	0.35	0.08	0.64	0.27	0.28	1.02	2.03
1400	0.24	0.10	0.15	0.30	0.09	0.10	0.35	0.14	0.10	0.35	0.08	0.64	0.27	0.28	1.02	2.04
1450	0.24	0.10	0.15	0.30	0.09	0.10	0.35	0.14	0.10	0.35	0.08	0.64	0.27	0.28	1.02	2.04
1500	0.24	0.10	0.15	0.30	0.09	0.10	0.35	0.14	0.10	0.35	0.08	0.64	0.27	0.28	1.03	2.06
1550	0.26	0.10	0.15	0.30	0.09	0.10	0.35	0.51	0.10	0.35	0.08	0.64	0.27	0.28	1.14	2.29
1600	0.26	0.10	0.15	0.30	0.09	0.10	0.35	0.51	0.10	0.35	0.08	0.64	0.27	0.28	1.14	2.29
1650	0.30	0.10	0.15	0.30	0.09	0.10	0.35	0.24	0.10	0.35	0.08	0.64	0.27	0.28	1.06	2.12

Figure 3 - Example uncertainty analysis for InGaAs power measurement head

Spectral responsivity calibration of the optical power measurement heads accounts for the largest contribution to calibration uncertainty, though it is by no means the only contribution. Calibration of the measurement channels of the OMM-6810B and the FPM-8220 also contributes, though typically these uncertainties are insignificant in comparison to the optical components.

ILX Lightwave calibrates the current and voltage measurement channels of its optical power meters against a set of current and voltage sources that are themselves traceable to NIST primary standards. The sources are calibrated by an ISO/IEC 17025:2005 accredited outside laboratory on an annual basis. Typical calibration uncertainty for the measurement channels of these instruments is less than ±0.15%.

Working Standard Used at ILX

The detectors used for working standards at ILX Lightwave are chosen for their high linearity (Figure 4), stability, and spatial uniformity of responsivity. Presently, ILX Lightwave uses two types of detectors for working standards: the Hamamatsu S1337-1010BQ silicon photodetector for 350 to 1100 nm band, and the EG&G Judson J16TE2-HSA2-R05M-SC germanium photodiode for the 800 to 1650 nm band. These working standards are calibrated at NIST on a regular documented schedule, establishing the primary link in the traceability chain. These are the same photodiodes used at NIST as in-house transfer standards.

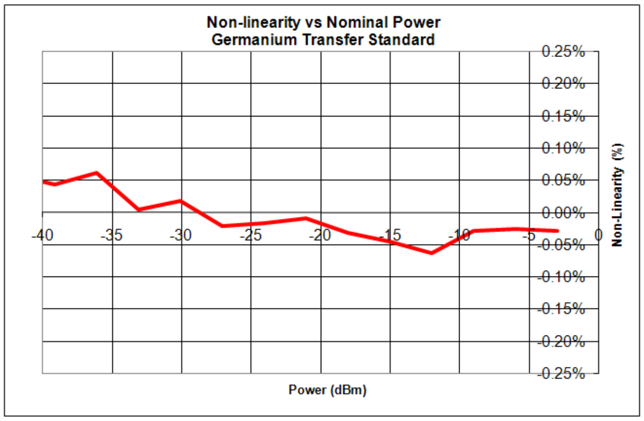


Figure 4 - Linearity of responsivity for the germanium transfer standard

Apparatus

ILX Lightwave uses two calibration systems within the optical calibration laboratory. The systems are used in the calibration of wavelength measurement heads. The systems consist of:

- Light Source
- Order Sorting Filter Wheel
- Monochromator
- System Optics
- Beamsplitter
- Transfer Standard Photodiode
- Monitor Photodiode
- Test Photodiode (UUT)
- Picoammeter/DMM
- OMM-6810B Power and Wavelength Meter
- Temperature / Humidity Monitor
- System Computer and Software

A continuous spectrum of light from UV to NIR is passed from the tungsten halogen bulb through the order sorting filter wheel. These filters are selected such that they prevent unwanted light from entering the monochromator, thereby eliminating the presence of overlapping grating modes. The pre-filtered light then enters the monochromator where narrow-band wavelength selection occurs. Typical band-pass from the monochromator is between 6 and 14nm. From the monochromator, the filtered light is directed on to a wedged beam sampler. The reflected light is dumped onto a monitor photodiode. The transmitted light is focused on the detector plane. (Figure 5)

Transfer standards and UUTs are manually placed at the detector plane. Each transfer standard has a custom kinematic mount for repeatable placement. Likewise, there are a series of custom kinematic mounts for each style of optical power measurement head.

The response of the transfer standards and the monitor detectors is measured with precision picoammeters. The response of the UUT's is measured with an ILX Lightwave OMM-6810B. Temperature of the UUTs is measured with a precision DMM.

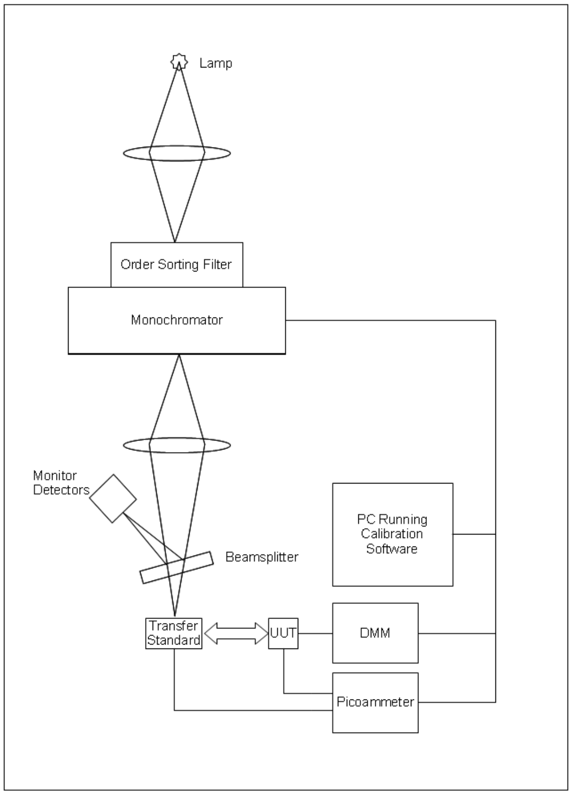


Figure 5 - First generation spectral responsivity calibration apparatus

The second generation calibration system has been in operation since 2011, and consists of many of the same basic elements. Like the first generation system, a continuous spectrum of light from a tungsten halogen lamp is pre-filtered by an order sorting filter wheel prior to entering the monochromator. Narrow-band wavelength-selected light is then passed through a wedged beam sampler. The reflected light is dumped onto the monitor detectors, and the transmitted light is focused on the detector plane. (Figure 7)

Where the second generation system differs from the first generation system is in the placement of the transfer standards and the UUTs. The second generation system uses a stepper motor driven rotation stage to place the standards and UUT's into the optical path.

This allows the operator to calibrate as many as five heads at a time, thereby reducing the level of operator interaction and increasing system throughput. It also improves repeatability of placement of the standards and UUT's (Figure 6), which in turn reduces the uncertainty due to non-uniformity of responsivity of the transfer standard.

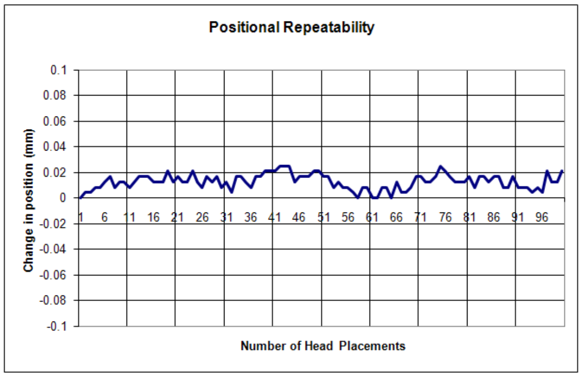


Figure 6 - Positional repeatability for the second generation spectral responsivity calibration apparatus

The response of the transfer standards, monitor detectors, and UUT's are all measured with precision picoammeters. For the FMH-8700 series of Fiber Optic Measurement Heads, the output is a voltage rather than a current, and their response is measured with a digital volt meter (DVM). UUT temperature is also monitored by a DMM.

Both calibration systems use PC based software applications to measure, record, coordinate, and control the calibrations. In addition to these basic functions, the calibration software monitors the environmental conditions during calibration. If at any point, the temperature or humidity deviates from the acceptable ranges, the calibration is aborted until the deviation is corrected.

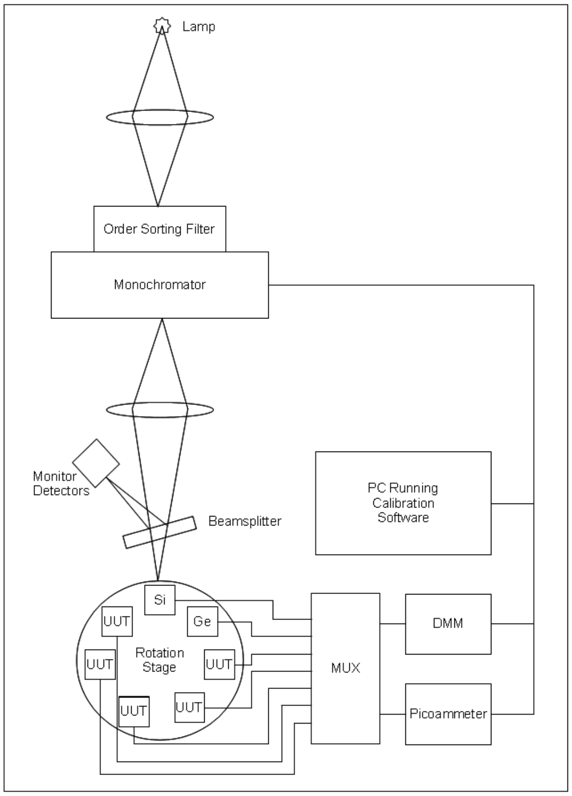


Figure 7 - Second generation spectral responsivity calibration apparatus

Calibration Process

Transferring calibration from one detector to another is a straight forward process. The monochromator is first set to the desired wavelength, and the standard detector is placed in the system. The photocurrent (I_s) produced by the standard (Amps) is:

$$I_s = \alpha * P * R_s \qquad (1)$$

where P is the power (W) incident on the beam splitter, α (unitless) is the fraction of light transmitted by the beam splitter, and R_s if the detector responsivity (A/W). The photocurrent produced by the monitor photodiode is:

$$I_{m1} = (1 - \alpha) * P * R_m \qquad (2)$$

where (1-α) is the fraction of light reflected by the beam splitter, and R_m is the monitor photodiode responsivity (A/W). The monitor photocurrent is indexed as it may change due to fluctuations in source brightness. Note that the ratio of these currents,

$$\frac{I_s}{I_{m1}} = \frac{R_s}{R_m} * \frac{\alpha}{(1-\alpha)} \qquad (3)$$

is independent of the monochromator power and is recorded for later use.

Next, the test detector is placed in the calibration system. In a similar fashion, the ratio of the test detector current I_t to the monitor current I_{m2} is:

$$\frac{I_t}{I_{m2}} = \frac{R_t}{R_m} * \frac{\alpha}{(1-\alpha)} \qquad (4)$$

From equations (3) and (4), it follows that the test detector responsivity is:

$$R_t = R_s * \frac{I_t/I_{m2}}{I_s/I_{m1}} \qquad (5)$$

The standard detector's responsivity is known (recorded on a NIST calibration report), so R_t is completely determined.

In practice, the transfer standard detector's response is measured in 10 nm steps over the wavelength range, and the quantity I_s / I_{m1} is recorded at each point. Then the test detector's response is measured at the same wavelengths, and the quantity I_t / I_{m2} is recorded. After measuring the response of both detectors, the responsivity of the test detector is calculated according to Equation (5) and recorded in a data file. Over the several minutes it takes to measure the standard detector's response at all wavelengths, the monochromator power may drift slightly. Now the role of the monitor photodiode becomes clear: by recording the ratios given by Equations (3) and (4), no error due to monochromator power drift is introduced.

Conclusion

When selecting an optical power meter vendor, you should ensure a sound quality system and calibration system is in place. The calibration should be traceable back to a national standard such as NIST. At ILX Lightwave, where accuracy and traceability are our primary concerns, we have instituted an ISO 9001 standard and NIST traceable calibration. Whether your application requires "free space" or fiber optic power measurements, our quality system for calibration guarantees a traceable measurement every time.

References

1. *National Institute of Standards and Technology Handbook 150, 2006 Edition*
2. *NIST/SEMATECH e-Handbook of Statistical Methods, www.itl.nist.gov/div898/handbook/, 2011*
3. *JCGM 100-:2008. Evaluation of Measurement Data – Guide to the Expression of Uncertainty in Measurement, Joint Committee for Guides in Metrology.*

The following publications are available for download at www.ilxlightwave.com.

White Papers

- A Standard for Measuring Transient Suppression of Laser Diode Drivers
- Degree of Polarization vs. Poincaré Sphere Coverage
- Improving Splice Loss Measurement Repeatability
- Laser Diode Burn-In and Reliability Testing
- Power Supplies: Performance Factors Characterize High Power Laser Diode Drivers
- Reliability Counts for Laser Diodes
- Reducing the Cost of Test in Laser Diode Manufacturing

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- Bandwidth of OMM-6810B Optical Multimeter Analog Output
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- Clamping Limit of a LDX-3525 Precision Current Source
- Control Capability of the LDC-3916371 Fine Temperature Resolution Module
- Current Draw of the LDC-3926 16-Channel High Power Laser Diode Controller
- Determining the Polarization Dependent Response of the FPM-8210 Power Meter
- Four-Wire TEC Voltage Measurement with the LDT-5900 Series Temperature Controllers
- Guide to Selecting a Bias-T Laser Diode Mount
- High Power Linearity of the OMM-6810B and OMH-6780/6790/6795B Detector Heads
- Large-Signal Frequency Response of the 3916338 Current Source Module
- Laser Wavelength Measuring Using a Colored Glass Filter
- Long-Term Output Drift of a LDX-3620 Ultra Low-Noise Laser Diode Current Source
- Long-Term Output Stability of a LDX-3525 Precision Current Source
- Long-Term Stability of an MPS-8033/55 ASE Source
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- Measuring the Sensitivity of the OMH-6709B Optical Measurement Head
- Measuring the Wavelength of Noisy Sources Using the OMM-6810B Optical Multimeter
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- Power and Wavelength Stability of the MPS-8000 Series Fiber Optic Sources
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- Temperature Controlled Mini-DIL Mount
- Temperature Stability Using the LDT-5948
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- Typical Long-Term Temperature Stability of a LDT-5525 TEC
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- Typical Output Stability of the LDC-3724B
- Typical Output Stability of a LDX-3100 Board-Level Current Source
- Typical Pulse Overshoot of the LDP-3840/03 Precision Pulse Current Source
- Typical Temperature Stability of a LDT-5412 Low-Cost Temperature Controller
- Using Three-Wire RTDs with the LDT-5900 Series Temperature Controllers
- Voltage Drop Across High Current Laser Interconnect Cable
- Voltage Drop Across High Current TEC Interconnect Cable
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- Wavelength Accuracy of the 79800 DFB Source Module

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- App Note 29: Accelerated Aging Test of 1310 nm Laser Diodes
- App Note 30: Measuring High Power Laser Diode Junction Temperature and Package Thermal Impedance
- App Note 31: Mounting Considerations for High Power Laser Diodes
- App Note 32: Using a Power / Wavehead for Emitter Level Screening of High Power Laser Diode Bars

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