Metrology for the Optoelectronics Industry*

G. W. Day
Optoelectronics Division
National Institute of Standards and Technology
325 Broadway
Boulder, CO 80305

ABSTRACT

The National Institute of Standards and Technology (NIST) provides measurement technology, standards, and traceability for much of the optoelectronics industry. This paper covers its support for two major industry segments, the laser industry and the optical communications industry.

Keywords: Lasers, Metrology, Optical communications, Optoelectronics

1. THE OPTOELECTRONICS INDUSTRY

Optoelectronics, or photonics, is not a precisely defined field, but generally encompasses those technologies and applications wherein both optics and electronics play essential roles. Many familiar and economically significant high technology products and processes are made possible by optoelectronic components—modern telephone systems, the Internet, compact disc storage, laser printers, fax machines, advanced manufacturing techniques, and new medical diagnostic and treatment procedures. More new, and equally revolutionary, applications based on optoelectronics can be expected.

According to the Optoelectronics Industry Development Association[1] (OIDA), the market for optoelectronic components grew to over $70 B in 2000, making it roughly one-third as large as the semiconductor electronics industry. And, like many other high technology fields, the optoelectronics industry has a strong need for reliable and cost effective metrology.[2] Between 10 % and 30 % of the cost of producing an optoelectronic component can typically be attributed to measurements, including both those that support the manufacturing process and those that support product specification.

Lasers are the essential component in enabling many of the products listed above. About 470 million lasers, worth over $8.8B were sold in 2000.[3] Over 400 million of them were semiconductor lasers and, of those, most are used in compact disc systems and bar-code readers. Another important application for semiconductor lasers is optical fiber communications, the fastest growing part of the optoelectronics industry. Today, optical fiber is being produced fast enough to go around the world more than seven times each day (110 M km/yr),[4] a production rate that increased by over 50 % last year. The market for other components of optical communications systems is growing even faster.

The National Institute of Standards and Technology has been providing measurement technology, standards, and traceability to these segments of the optoelectronics industry for several decades, and continues to improve that support as the industry grows and has new needs. This paper will describe some of that work from a historical perspective.

2. METROLOGY FOR THE CHARACTERIZATION OF LASERS

Experimentalists developing new lasers during the early- and mid-1960s quickly discovered the difficulties of quantitatively determining the output of a laser. Many of the early lasers operated as pulsed sources, often with a pulse energy of a joule or more and a peak power of tens of megawatts, easily saturating most detectors. Other lasers, for example CO_2 lasers, provided many watts of cw power, easily destroying conventional detectors. Polarization states varied with time, often within the duration of a single pulse. The high degree of spectral and spatial coherence led to interference effects that made it difficult to attenuate the laser output reliably. In most cases, conventional radiometric techniques, then mostly based on standard, incoherent sources, proved unsuitable for measuring the output of the new lasers. Many researchers, including those at NIST (then the National Bureau of Standards, NBS), turned to thermal detectors or calorimeters, calibrated by electrical substitution.

Figure 1 shows the heart of the first NBS primary standard for laser measurements,[5] developed by Don Jennings around 1965. It is a liquid cell calorimeter, in which the pulsed output of a ruby laser was absorbed in a cell containing an aqueous solution of $CuSO_4$. Thermocouples in the liquid measured the temperature rise resulting from the absorbed energy. The pulse energy could be calculated from the heat capacity of the cell, or determined by heating the liquid by an electrical pulse of known energy and comparing that with the laser-induced temperature rise. The two methods agreed within a few tenths of a percent, and the overall uncertainty was judged to be about 0.7 %. The limits of the calorimeter were about 30 J, or a peak power of about 200 MW. In 1967, NBS provided the first calibration of a customer's energy meter by comparing its response to that of a calorimeter similar to the one shown.

Figure 1. Liquid cell calorimeter; first primary standard for laser measurements developed at NBS.

The demand for laser calibration services grew substantially during the next few years, and around 1970 NBS began the development of a series of calorimeters based on isoperibol (constant temperature environment) calorimetry.[6] Dale West, who had long experience in calorimetry for other applications, led the effort. The first of the new calorimeters, known as the C-Series Calorimeter, was designed for measuring the output of cw lasers operating in the visible and near infrared at power levels in the 1 mW to 1 W range.[7-8] The basic construction of the calorimeter is shown in Figure 2. The heart of the calorimeter is an absorbing cavity, blackened to absorb most of the light on first incidence, and with an angled end, to direct power not initially absorbed to a second absorbing surface. Thermocouples measure the change in temperature during periods of heating and cooling. Dissipation of a known amount of electrical energy in a resistive heater provides a calibration and a direct link to electrical units. The cavity is surrounded by a temperature-controlled jacket, to provide the required isoperibolic environment. A window seals the vacuum region between the cavity and the jacket; the window is slightly wedged to eliminate interference effects from the coherent source. Figure 3 shows the completed standard.

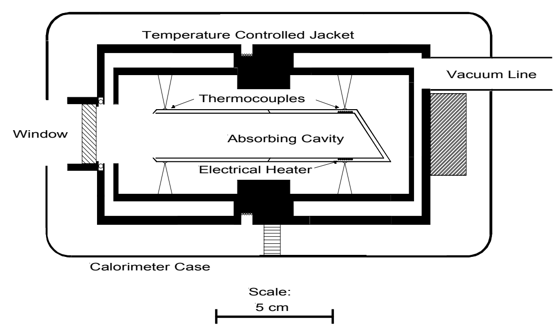

Figure 2. Internal design of the C-series calorimeter.

The C-Series Calorimeter continues to be used at NIST as a primary standard for detector calibrations within its range of operation, from about 50 μW to 1 W, and provides measurements with an uncertainty of about 0.25 %.

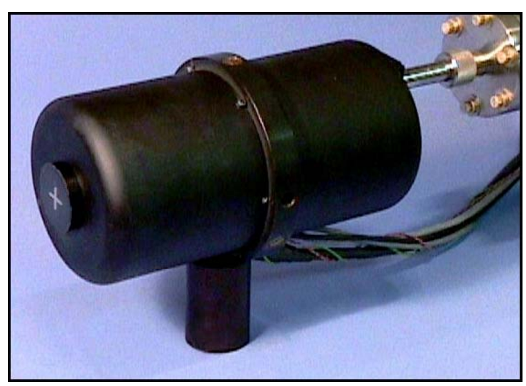

Figure 3. External view of the C-series calorimeter.

Other calorimeters were subsequently developed, using the same basic principles. The K-Series Calorimeter,[9] shown in Figure 4, was designed for much higher power levels, up to 1 kW cw, for calibrating power meters designed for Nd:YAG and CO_2 lasers used in cutting, welding, and other high power manufacturing applications. The Q-Series

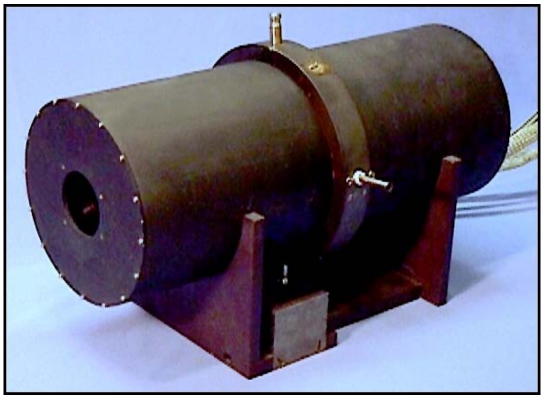

Figure 4. K-Series Calorimeter for high-power cw laser measurements.

Figure 5. Q-Series Calorimeter for pulsed-laser measurements.

Calorimeter, shown in Figure 5, was designed for calibrating instruments used with pulsed lasers, particularly Q-switched Nd:YAG lasers with pulse durations in the range of 20 ns.[10] Subsequently, modified versions of the Q-Series calorimeter have been developed for use with excimer lasers operating at 248 nm and 193 nm.[11-12]

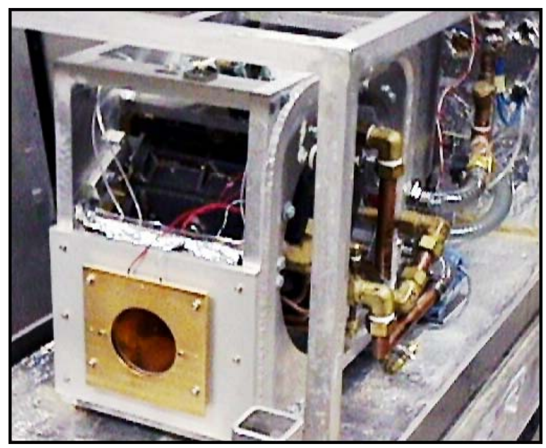

Figure 6. BB Calorimeter for measuring cw laser radiation at levels up to 100 kW.

For the highest-power lasers, of interest primarily to the Department of Defense, a water-cooled calorimeter was developed that can measure cw laser power up to 100 kW, or more.[13-14] That instrument, known as the BB Calorimeter, is shown in Figure 6.

In designing instruments for high power or energy, care must be taken to ensure that absorbing surfaces can withstand the radiation without damage. Volume absorbing materials can typically withstand more intense radiation than surface absorbing materials, and are used in several of the calorimeters described above. Reflective surfaces can typically withstand higher levels, still. Two reflectors, one convex and one diffuse, are used in the BB calorimeter to spread the radiation over a large area for absorption.

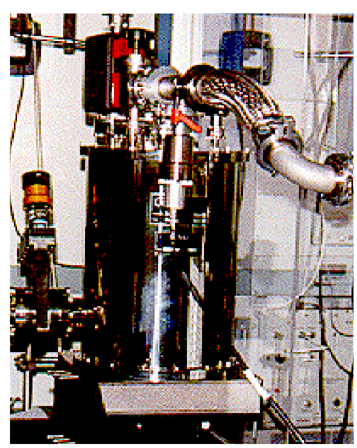

Figure 7. Laser-optimized cryogenic radiometer (LOCR).

Measurements of power or energy made by the calorimeters described above are traceable to SI units through the assumption that equal amounts of absorbed optical energy and dissipated electrical energy result in the same response. The uncertainty in this equivalence is often the principal limitation to their accuracy.

One means of improving the optical-electrical equivalence is to maintain the absorbing cavity at a cryogenic temperature where, among other considerations, the thermal diffusivity of the metals is substantially greater. This is the principle behind the cryogenic radiometers that are widely used in various areas of radiometry.

For measurements of low-power cw laser radiation, cryogenic radiometers provide the lowest uncertainties currently available (around 0.05 %). Figure 7 shows a commercial cryogenic radiometer, optimized at NIST, which is used for calibration of instruments that measure the output of lasers in the visible and near infrared at levels between 0.1 mW and 1 mW.[15]

NIST currently maintains a total of seven primary standards for laser power and energy, as shown in Figure 8.

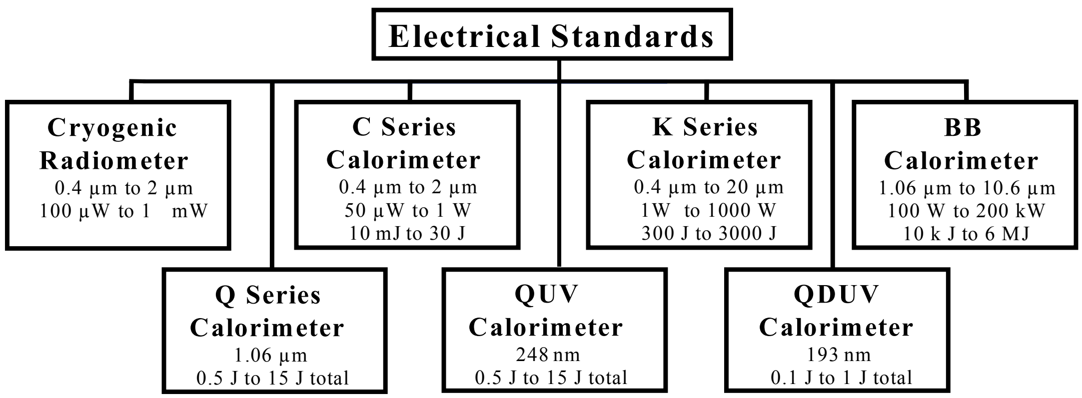

Figure 8. NIST primary standards for measurements of laser power and energy, with the approximate ranges of wavelength and power or energy for which they are used.

Detectors and power meters are often calibrated by direct comparison to one of these standards, using a slightly wedged beam splitter made from a high quality optical material appropriate for the wavelength of operation[16] (Figure 9.) Several distinct beams are generated by the wedged beamsplitter. Their relative magnitude compared to the incident beam can be readily calculated or measured (Figure 10) and the wedge also minimizes problems with coherent reflections. Several orders of magnitude of calibrated attenuation can be achieved in this way.

During calibration, the standard is typically placed in the transmitted beam (0-order) and the instrument to be calibrated is placed in one of the reflected, or higher order transmitted, beams. Alternatively, the instrument to be calibrated could be placed in the 0-order beam and the standard in one of the reflected or higher order transmitted beams. By using combinations of such possibilities, a detector can be calibrated over a range of power or energy substantially exceeding that suitable for the primary standard.

Another method of extending the range of these primary standards is the use of transfer standards. High quality transfer standards can be calibrated against a primary standard and are often used over ranges of parameters (power, energy, wavelength) that extend beyond those suitable for the primary standard.

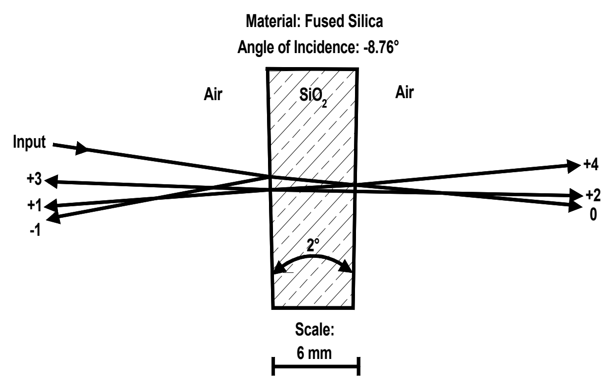

Figure 9. Wedged beamsplitter, showing various orders of reflected and transmitted beams. Angle of incidence specified is convenient for alignment.

Order	Attenuation Ratio
0	1.075
-1	26.08
+1	28.52
+2	8.222×10^2
+3	2.379×10^4
+4	6.864×10^5

Figure 10. Attenuation ratios for a fused silica beamsplitter: wedge angle = 2°; angle of incidence = 8.76°; wavelength = 633 nm; vertical polarization.

Transfer standards can also be useful when special geometric considerations are involved, such as the need to collect all of the power diverging from the end of an optical fiber. Other issues in the calibration of power meters used with fiber include coherent reflections in connectors and reflections from other surfaces around the detector. Generally these considerations are addressed with all-fiber calibration systems such as that shown in Figure 11. Currently, NIST offers absolute power calibrations[17] and linearity measurements[18] in the principal wavelength ranges of interest in communications.

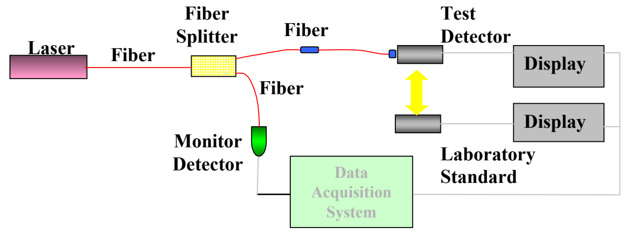

Figure 11. System for calibrating meters and detectors that accept power through an optical fiber connector.

One transfer standard, developed at NBS in the 1970s and manufactured commercially, is the Electrically Calibrated Pyroelectric Radiometer[19-21] or ECPR (Figure 12). Like the primary standards described above, the ECPR compares the temperature change (in this case in a pyroelectric material) resulting from absorbed optical power with that resulting from dissipated electrical power. To achieve a high degree of equivalence, the absorbing surface, a form of gold known as gold-black, is also used as the heating element.

Other types of transfer standards that are useful in extending the range of the laser primary standards are those based on various light-trap configurations, which collect radiation not absorbed on the first incidence, and direct it back to the same detector element, or to another one. Using a variety of such techniques—hemispherical reflectors, pairs of detectors positioned as the surface of a hollow wedge, and other multiple detector designs—virtually all of the light incident on the detector can be collected. Figure 13 shows several trap-detectors developed and used at NIST.[22-26]

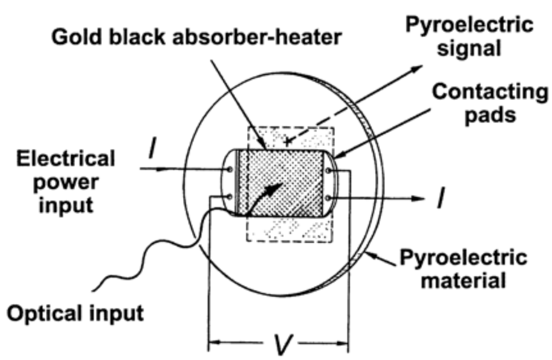

Figure 12. The detector element of an electrically calibrated pyroelectric radiometer.

Figure 13. Several light-trap detectors—transfer standards designed to collect and absorb virtually all of the light incident upon them.

Along with the standards and technologies described above, NIST maintains the capability of measuring a variety of other characteristics of lasers and associated detectors—relative intensity noise[27] (RIN), detector spatial,[28] spectral,[29] and angular uniformity, and laser beam profile,[30] among others.

3. METROLOGY FOR THE OPTICAL COMMUNICATIONS INDUSTRY

Work at NBS on the characterization of optical fiber began in 1976, at a time when telephone companies around the world were just beginning to test optical communications systems in the field. Most of the fiber then available was multimode fiber, in which several hundred optical modes propagate in a core that is typically 50 µm in diameter. The refractive index profile of the fiber core was shaped to minimize the differences in group velocity among the modes.

The operating wavelength was typically around 850 nm. Data rates were relatively low, often a few Mb/s. Costs were high, roughly $1/m, and product quality was uncertain. Specifications, and the underlying measurement methods, were not standardized, and a customer could expect significant differences between similarly specified fiber from different manufacturers. Very little commercial instrumentation was available to measure fiber properties.

Many of the early problems in optical fiber characterization related directly to multimode propagation in the fiber. Differences in attenuation among the modes led to variations in measured attenuation depending on how light was launched into the fiber and also led to a nonlinear variation of transmittance with length. The modulation bandwidth of a multimode fiber was limited by the degree to which the refractive index profile successfully equalized the group velocities of the modes. As with attenuation, bandwidth did not scale linearly with length but, in addition, compensation could occur when two or more fibers were joined together, and the prediction of bandwidth for many fibers spliced together was thus very difficult.

NBS work in those early years focused mostly on developing and evaluating fiber measurement techniques, describing them so that they could be replicated, and working with standards-developing organizations as they evolved into industry standards. Much of the early NBS work on multimode optical fiber measurements was published in a series of NBS Technical Notes, later collected in two volumes[31] called "Optical Fiber Characterization." NBS also conducted many interlaboratory comparisons within the industry, to quantify the need for particular standards and to verify the effectiveness of the standards adopted.[32]

One of the measurement methods which received considerable attention was Optical Time Domain Reflectometry[33-34] (OTDR), which involves transmitting an intense optical pulse through the fiber and observing the light returning toward the source due to Rayleigh scattering and reflections from imperfections in the fiber. It is a powerful, non-destructive, method of obtaining spatial-resolved information on fiber properties.

As commercial instrumentation for characterizing fiber increasingly became available, there emerged a demand for artifacts to calibrate that instrumentation. This was somewhat unlike the experience with laser radiometry, in which NIST provides traceability to national standards through calibration services. It probably results from the fact that instruments for characterizing fiber tend to be relatively large, are not particularly suitable for shipping and, in some cases, need relatively frequent calibration.

The first parameter for which an artifact standard was developed was the diameter of the fiber cladding—the outer diameter of the glass. Manufacturers needed to reduce their tolerances on diameter to ±1 μm to improve the performance of splices and connectors and, as a result, needed calibrations with an uncertainty of around 0.1 μm. Several methods for making the required measurements were studied and eventually a contact micrometer method was adopted.[35] At the required level of uncertainty, it was necessary to compensate for the deformation to the fiber caused by the force applied by the micrometer.

The resulting standard, NIST Standard Reference Material 2520 (Figure 14), is a short piece of fiber, selected to have a highly cylindrical cladding with a diameter of approximately 125 μm. Four different diameters at the same location, and their average, are specified to an expanded uncertainty of approximately ±40 nm (k=3). The fiber is mounted in a fixture that protects it and allows it to be inserted in typical instruments. To date, over 100 of the SRMs have been provided to, among others, most of the major fiber and instrument manufacturers, and thus most of the optical fiber produced in the world is tested on instruments traceable to NIST through this standard.

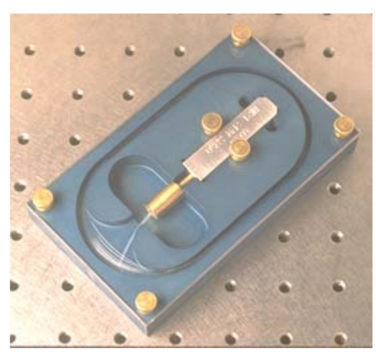

Figure 14. NIST Standard Reference Material 2520, Optical Fiber Cladding Diameter

The development of SRM 2520 was followed by the development of several other dimensional standards related to fiber—connector ferrule diameter (SRM 2523), pin gauges for sizing the inner diameter of ferrules (SRM 2522), fiber coating diameter (SRMs 2553, 2554, 2555),[36] and mode-field diameter (SRM 2513)[37]—and a study of fiber endface geometry.[32o]

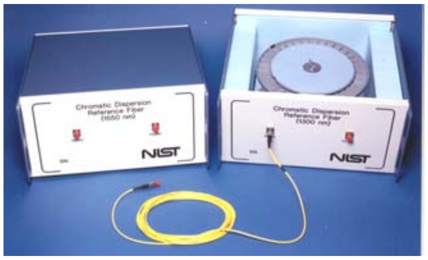

Figure 15. SRM 2524, Chromatic Dispersion Standard.

Figure 16. SRM 2518, Polarization Mode Dispersion Standard.

As data rates in optical communications systems became larger, dispersion became a greater concern, and a standard for chromatic dispersion (SRM 2524) was developed[38] (Figure 15). It consists of 10 km of dispersion-shifted fiber for which the wavelength of zero chromatic dispersion was determined to an expanded uncertainty of approximately 0.06 nm (k=2). At data rates of 10 to 40 Gb/s, now being used in high capacity systems, polarization mode dispersion (PMD) becomes a significant limitation to system performance, as well. PMD is particularly difficult to measure because, in a fiber, it changes with temperature and other environmental factors. To address this problem, NIST developed a device[39] that simulates the polarization properties of a fiber, but is small and stable (SRM 2518). It consists of a stack of 35 birefringent linear retarders (waveplates) of pseudo-random magnitudes and orientations (Figure 16).

Polarization measurements are of general importance in optical communications systems. To enable more accurate measurements of the linear retardance of waveplates and other components, NIST developed a standard linear retarder[40] (SRM 2525) with a retardance of approximately 90°. It consists of two Fresnel rhombs (Figure 17) made of a very low stress-optical coefficient glass, and is designed to have low variation of retardance with wavelength, angle of incidence, and temperature. The expanded uncertainty in retardance (k=2) is less than 0.1°.

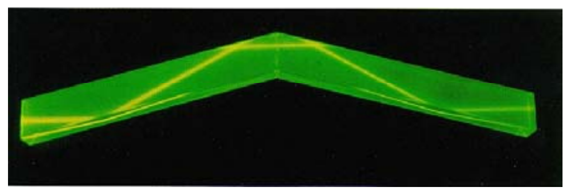

Figure 17. Optical elements of SRM 2525, Optical Retardance Standard

Perhaps the most dramatic development in the field of optical communications has been the emergence of dense wavelength-division multiplexing. Using several hundred lasers oscillating at frequencies spaced 50 GHz to 100 GHz apart, each transmitting data at up to 40 Gb/s, the demonstrated transmission capacity of a single fiber has risen to over 10 Tb/s. Extending the technology to the full transparency range of a fiber could add a factor of 5. Wavelength control is one of many issues involved in developing such systems.

To calibrate instruments used for measuring the spectral properties of components, NIST has developed a series of easy-to-use Standard Reference Materials, based on the absorption spectra of various molecular gasses. Appropriate gasses include acetylene[41] (SRM 2517a: 1510 to 1540 nm), hydrogen cyanide[42] (SRM 2519: 1530 to 1560 nm), and carbon monoxide[43] (SRM 2516: 1560 to 1595 nm). Figure 18 shows an absorption cell from one of the standards. Figure 19 shows the absorption spectra of acetylene at a pressure of 6.7 kPa. The principal uncertainty in the wavelengths of the absorption lines is the shift of line center with pressure, but this effect is generally

Figure 18. SRMs for wavelength calibration: absorption cell in front and packaged units in back

small. Most of the line centers in these gasses can be certified to within 0.6 pm.

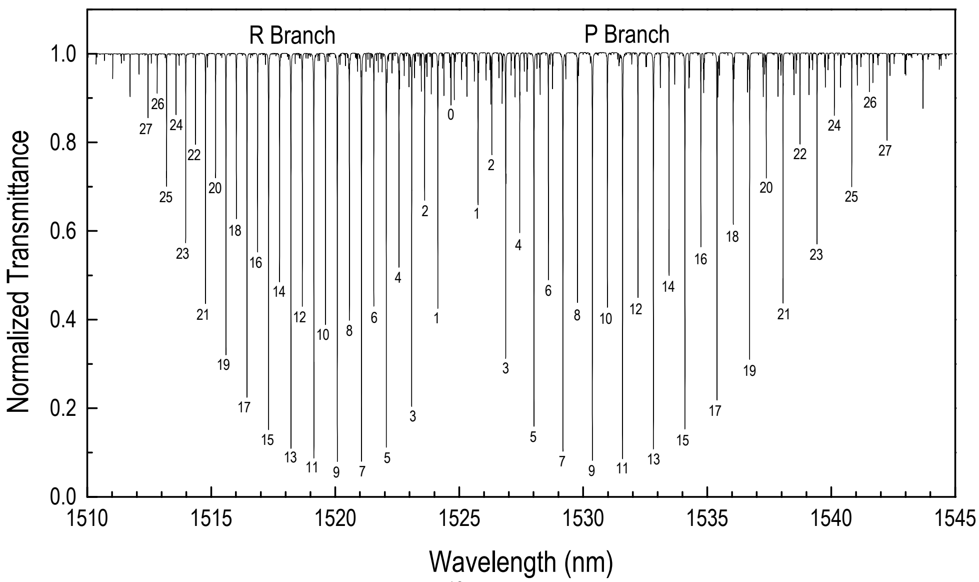

Figure 19. Absorption spectrum of acetylene ($^{12}C_2H_2$) at a pressure of 6.7 kPa (SRM 2517a) in which 15 lines are certified to an uncertainty of 0.1 pm, 39 lines to 0.3 pm, and 2 lines to 0.6 pm (expanded uncertainty, k=2).

The design of systems with higher data rates in each channel (wavelength) requires careful characterization of the detector or receiver performance. For measurements of the magnitude of the frequency response to frequencies to about 50 GHz, a heterodyne measurement method (Figure 20) is the basis for calibration services.[44] As data rates move to 40 Gb/s, measurements of both magnitude and phase response to at least 100 GHz will be required. To meet this demand, an electro-optical sampling system is being developed.[45]

Several new standards and measurement capabilities are under development to meet emerging needs of the optical communications industry: an SRM for polarization dependent loss[46] (PDL), a PMD standard suitable for use in measuring the PMD of discrete components, and new and improved methods of measuring dispersion of fiber and components, among others.[47]

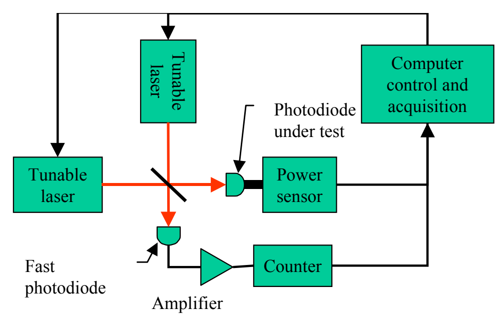

Figure 20. Heterodyne system for measuring the frequency response of optical detectors and receivers

4. SUMMARY

For over three decades, NIST has worked with the optoelectronics industry to provide the metrology that the industry needs to manufacture and specify an ever-expanding range of components. Today, NIST maintains the broadest range of measurement capabilities for optoelectronics of any national measurement laboratory—in some measurement areas, it is the only laboratory able to provide traceability, and makes those services available throughout the world. This paper describes some of those capabilities briefly, and provides a guide to detailed publications.

5. ACKNOWLEDGEMENT

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