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WAVELENGTH METERS

Solid-state etalons improve wavelength measurement

Novel wavelength measurement tools set new standards in terms of resolution, precision, and acquisition speed for tunable lasers

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Since the invention of the laser, wavelength measurement devices (WLMs) have been indispensable tools in research, production, and quality control of laser technology. The two most important output readings of a WLM are the wavelength and the linewidth of the laser being characterized. When the laser wavelength is measured under controlled optical conditions--that is, in a medium with known refractive index--the laser frequency and ultimately the photon energy can be calculated. Laser linewidth and line jitter, on the other hand, characterize the time coherence of the emitted laser light.

The measurement properties of WLMs are distinctly different from those of another common wavelength characterizing device--the spectrometer. A spectrometer utilizes the dispersion of a prism or a diffraction grating to spatially displace or split the spectral components of a light source. By detecting the position of the split components after some distance, the wavelength can be determined. The light source under investigation does not need to be coherent. In contrast, the detection principle of a WLM is based on the evaluation of an interference pattern and thus on the coherence of the laser.

Historically, spectrometers were already in use long before the invention of the laser and have recently received renewed attention in telecommunications as so-called optical spectrum analyzers (OSAs). Although technically obsolete for ultra-high-resolution measurements, spectrometers are still used, for example, in the characterization of broad area laser diodes, which exhibit little coherence in their output.

Wavelength measurement techniques

The early WLMs were based on Michelson interferometers with a variable optical path length in one of the interferometer arms. The unknown laser wavelength was measured by simultaneous recording with a well-characterized laser reference such as a Zeeman-stabilized HeNe laser. In order to achieve a sufficiently precise wavelength reading, the environment of both interferometer arms had to be well controlled and well characterized. During the last 30 years a plethora of postgraduate students has developed multiple derivates of this measurement principle for their own use.

The best-known commercial instrument today is the "wavemeter" device from EXFO Burleigh Products (Victor, NY), the roots of which can be traced back to work by John Hall and his colleagues at NIST.[1] The measurement rate is typically on the order of a few hertz and the minimum laser power required is in the milliwatt range. However, the moving components within the interferometer arm necessitated elaborate mechanical and optical isolation of the wavelengthmeter from the actual experiment.

More recently WLMs based on solid-state etalons have taken the technological lead in precision wavelength measurement. Highly precise WLMs consist of multiple etalons with wedged surfaces--so-called "Fizeau" interferometers. They can achieve wavelength resolution down to the 10-MHz level without any moving parts (see Fig. 1). For fast and highly accurate read-out of the interference pattern, state-of-the-art CCD detectors are used. These instruments allow data acquisition rates up to 400 Hz. Alternatively, by increasing the exposure time the minimum laser power requirements can be lowered to only 10 nW, an acceptable power loss for most experiments, even for continuous monitoring.

The solid-state etalon concept still relies on an accurate distance measurement in the first place--the distance between the mirror facets of the etalons has to be well characterized--yet the dependence of the measurement on the refractive index of the intermediate space is significantly reduced. The measurement block is manufactured from solid components with well-known optical properties and mounted within a thermal isolation housing. An internal sensor precisely records its temperature and the data reading is corrected accordingly by software.

The fast data acquisition rate guarantees not only a synchronous wavelength recording during a typical frequency scan of a laser, but also allows the WLM to be used for active wavelength control of the tunable laser source. A representative application is differential-absorption-lidar, a technique that compares the intensity of back-scattered laser light on and close to an atmospheric absorption line. Here, the wavelength meter itself can serve as a long-term reference, setting the wavelength of the lidar laser to "on-line" and "off-line" values, respectively.

Moreover, the measurement of pulsed laser wavelengths is possible with solid-state etalons. At repetition rates below 400 Hz, every pulse can be measured and analyzed individually. The only requirement on the laser is sufficient coherence of the pulses--with typical etalon geometries the maximum tolerable laser linewidth is 40 GHz, corresponding to a Fourier-limited pulse length of greater than 25 ps. By generating suitable time gates (separation interval greater than or equal to 200 ns), one can even simultaneously detect two pulsed laser sources with different wavelengths. A practical application thereof is the investigation of multi-level atoms, where the wavelengths of a pump and probe laser beam can be measured by a single WLM.

The absolute calibration at a standard resolution of 10^{-6} can be performed with an off-the-shelf gas discharge lamp coupled to a multimode fiber. The most precise WLMs with a resolution of 4×10^{-8} and better, however, require calibration with a frequency-stabilized reference laser and a single mode fiber (see Fig. 2).

The accessible wavelength range of solid-state WLMs is limited by the spectral sensitivity of the CCD detectors used. If the standard low-cost silicon chips are substituted with materials with a higher efficiency for UV or IR light (which, unfortunately are still expensive but nonetheless available), the range can thus be extended to shorter and longer wavelengths too.

Since the interference pattern of all solid-state etalons are read in parallel, no moving parts are needed within the instruments, promising very low maintenance. The robustness of the design has been proven even under extreme conditions, like in the free-fall dropping experiments at the Center of Applied Space Technology and Microgravity (Bremen, Germany).[2] In another study that requires extreme mechanical stability the WLM is used in airborne lidar experiments as integral part of an international research project.

Latest developments

The ultimate step in laser frequency characterization is a direct frequency measurement.* Here the interferometric schemes discussed before are replaced by actual counting of the oscillations of the optical field of the coherent laser beam in a fixed time period, conventionally within a second. While modern electronics is capable of counting up to a few tens of gigahertz (radio frequency or RF), the few hundred terahertz regime of optical frequencies is not directly accessible unless one resorts to a “trick.” Here the optical frequencies are down-converted to the RF regime by frequency mixing, or vice versa--RF is up-converted by non-linear processes to the optical domain.

National standards laboratories such as PTB, NPL, and NIST have very accurately derived radio frequencies from atomic standards like the cesium atomic clock by coupling them in a phase-locked manner to optical frequencies, preserving the accuracy from the atomic standard for optical measurements. Using frequency multiplying and frequency division in so-called frequency chains, the most precise measurements of optical emission frequencies or optical transitions within atoms have been realized. For some selected frequencies a precision of the order of 10^{14} has been achieved and the precision of the cesium time standard could be reached.

Recently, an even better scheme has demonstrated the potential to revolutionize the approach completely. “Frequency combs,” derived from spectrally broadband pulses from mode- and phase-locked femtosecond lasers are changing the field. In frequency space, their emission spectrum consists of an equidistant, phase-rigid multitude of spectral lines, with a frequency spacing equal to the repetition frequency.[3] Frequency and phase of this laser light can once again be stabilized to RF sources. With this approach a precision of 10^{17} and higher comes into reach for all optical frequencies. In the beginning this new technique is for experts only, but within the next few decades we will certainly see it at an affordable price level in practical use around the world. Strangely enough, the WLMs based on solid-state technology serve in this scheme for determining the fundamental order of the comb structure.

REFERENCES

1. *J. L. Hall* und *S. A. Lee*, Patent US 4,165,183 (1979)
2. www.zarm.uni-bremen.de
3. *Th. Udem, R. Holzwarth* und *T. W. Hänsch*, Nature 416, 233 (2002)

**Although wavelength and oscillation frequency of a laser are linked in principal only by the speed of light, the frequency is a more favorable quantity to measure, because in contrast to the wavelength, its value is conserved during the transition from one medium to another.*

FIGURE 1. Frequency measurement of a tunable diode laser that is locked to hyperfine transitions and crossover lines of the Rubidium D_2 transition. The laser is frequency switched and relocked to another resonance after 300 and 2100 s. The absolute error in this example is smaller than 15 MHz and the relative error is less than 5 MHz. Measurements were made with the HighFinesse-Ångstrom WS-Ultimate measurement system (available from TOPTICA Photonics).

FIGURE 2. A single-mode fiber coupled the output of a stabilized HeNe laser into the HighFinesse-Ångstrom WS-Ultimate measurement system, which measured the laser frequency stability over a five-hour period.

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