NIST Optoelectronic Measurements for Fiber Optic Applications

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Abstract: We describe current measurement capabilities as well as research focused on two areas: improving temporal and frequency response characterization of detectors and instrumentation using electro-optic sampling, and improving wavelength metrology using frequency combs.

OCIS codes: (120.3940) Metrology; (120.4800) Optical standards and testing; (040.0040) Detectors

1. Introduction

The National Institute of Standards and Technology (NIST) has the responsibility "to develop, maintain and retain custody of the national standards of measurement, and to provide the means and methods for making measurements consistent with those standards; and to assure the compatibility of United States national measurement standards with those of other nations." This responsibility is twofold: to ensure that U.S. national standards are accurate realizations of the SI units, and to transfer the values of those standards to the U.S. measurement system through calibrations and other types of measurement services. This invokes the concept of traceability, which is the property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons, all having stated uncertainties.

NIST researchers have contributed to the improvement of measurements for optical fiber applications since 1976, when the organization was known as the National Bureau of Standards. Early work concentrated on optical fiber properties such as attenuation and fiber diameter, basic properties that affect the loss budget of optical fiber links. With the advent of optical amplifiers, optical losses can be overcome, and parameters that limit transmission capacity and fidelity in optical fiber communications become limiting factors. In this paper we discuss our current measurements that provide traceable optical fiber measurements, and describe two research efforts intended to meet emerging and future needs.

2. Optical fiber measurements

NIST currently has optical fiber measurement efforts in polarization mode dispersion, fiber diameter, and mode-field diameter, and traceability for these measurements is enabled through Reference Materials (RMs), including Standard Reference Materials and Nist-Traceable Reference Materials. RMs have NIST-certified measurand values and uncertainties, and can be used in one's laboratory to calibrate instrumentation. Our efforts in chromatic dispersion, relative group delay, and fiber Bragg grating reflectance/transmittance spectra measurements provide traceability through use of a NIST Special Test, in which a user sends a stable device or component to NIST for measurement. NIST also has significant efforts in laser power and energy calibrations, including the calibration of optical fiber power meters. Current measurements and uncertainties are described at http://www.boulder.nist.gov/div815. In addition, we periodically compare our measurements with those of other National Measurement Institutes to verify international measurement uniformity and capabilities. Recent comparisons include fiber optic power, relative group delay, excimer laser energy, and others.

3. Fast waveform metrology

Ultimately, transmitted optical signals must be detected and converted to an electrical data stream. Transmission distance is typically limited by the degradations of the digital waveform due to added noise (optical signal-to-noise ratio reductions), distortions arising from rise/fall time limitations in the transmitter or receiver, or from other sources of intersymbol interference (ISI) in the channel. To ensure fidelity, waveforms are often required to meet certain specifications for rise-time, overshoot, pulse shape, etc.

A common example of a waveform specification is the mask specification used in SONET standards. For this test, the signal waveform is detected with an optical detector with a specified response (e.g., fourth-order Bessel-Thomson filter response) and displayed on an oscilloscope atop a mask template overlay. Manufacturing tolerances on the filter, however, cause significant differences in the detected waveform and can even lead to false-pass results. Thus, it becomes important to calibrate the response of the detector and oscilloscope. This need is especially critical for higher-data-rate systems that push components to current technology limits and require tighter measurement margins.

To meet this need, NIST currently offers Special Tests for high-speed optoelectronic frequency response. Heterodyne (scalar) frequency response measurement of a modulation depth transfer artifact, consisting of a photodiode and a microwave power meter, has the lowest uncertainty [1] and can be used to measure the modulation depth of a modulated source. The frequency range of this measurement is limited essentially by the power sensor, but can be 110 GHz or more. A characterized photodiode (alone) can be used to characterize the response of a network analyzer or lightwave component. Measurement of heterodyne frequency response of photodiodes are currently available up to 50 GHz as a Special Test, and are traceable to fundamental microwave power standards [2]. Vector frequency response measurements are essential when phase response or time-domain properties are needed, and this special test is available up to 110 GHz by use of our electro-optic sampling (EOS) [3,4] system (Figure 1).

EOS is not a new concept. However, to use it as a metrology tool, we correct for the complex characteristic impedance of the coplanar waveguide, mismatches, and multiple reflections in the measurement system, by using impedance measurements made by a vector network analyzer. This allows us to completely characterize the photoreceiver [3] at the coaxial connector from measurements made at the coplanar waveguide (CPW) reference plane by using a general circuit model (Figure 2). Our uncertainty analysis for photodiodes with a 1.00 mm male connector shows that measurement uncertainty (95 % confidence interval) is typically less than 0.5 dB (for magnitude) and less than 3 degrees (for phase) up to 110 GHz. Once characterized, the photodiode can then be used to calibrate high-speed instrumentation, including lightwave component analyzers [5] and oscilloscopes.

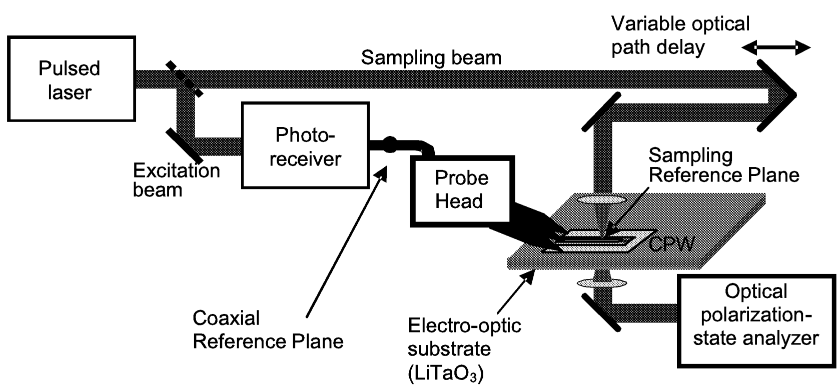

Fig. 1. Schematic of the electro-optic sampling system. By changing the optical path delay, the system maps the photoreceiver's temporal response by measuring the polarization change that arises from the optical and electrical interaction in the electro-optic substrate and the coplanar waveguide (CPW).

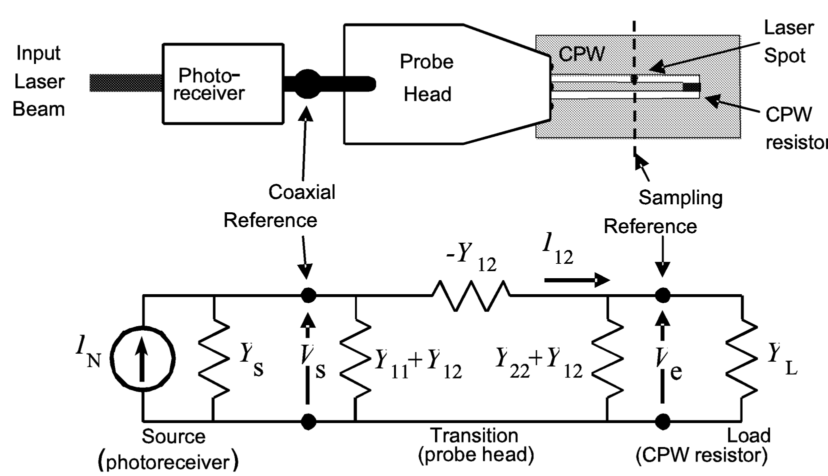

Fig. 2. A schematic of the optical-to-electronic interface, and the equivalent circuit used for impedance corrections.

4. Wavelength measurements and standards

For several years, NIST has enabled wavelength traceability using standards based on fiber-coupled molecular gas absorption cells. These cells cover the C- and L-bands, and, with wavelength uncertainties as low as 0.1 pm, appear to meet current WDM wavelength metrology needs [6].

To achieve even lower uncertainties, we are developing wavelength metrology based on an infrared optical frequency comb that spans the near IR spectrum from 1 to 2 μm [7]. Optical frequency combs can provide a set of evenly spaced lines in optical frequency whose frequency values are known with respect to an absolute microwave standard [8,9]. The frequency comb (Figure 3) is generated with a mode-locked erbium-doped fiber laser whose output is amplified and spectrally broadened in novel dispersion-flattened, highly nonlinear optical fiber to span from 1 to 2 μm. This supercontinuum output comprises a frequency comb with a spacing set by the laser repetition rate of 50 MHz and an overall offset frequency set by the carrier-envelope offset (ceo) frequency. This offset frequency is measured in the microwave domain using a standard f-to-2f heterodyne technique [10]. The comb spacing, f_{rep}, is phase-locked to a stable rf signal with a fiber stretcher in the laser cavity, and offset frequency, f_{ceo}, is likewise locked by controlling the pump laser power. Once these microwave frequencies are phase-locked, the optical frequency of the n*th* comb line is defined simply as $nf_{rep}+ f_{ceo}$. This infrared comb permits frequency metrology experiments in the near infrared in a compact, fiber-laser-based system. Moreover, it can be used to stabilize the absolute frequency of a laser anywhere across the telecommunications grid.

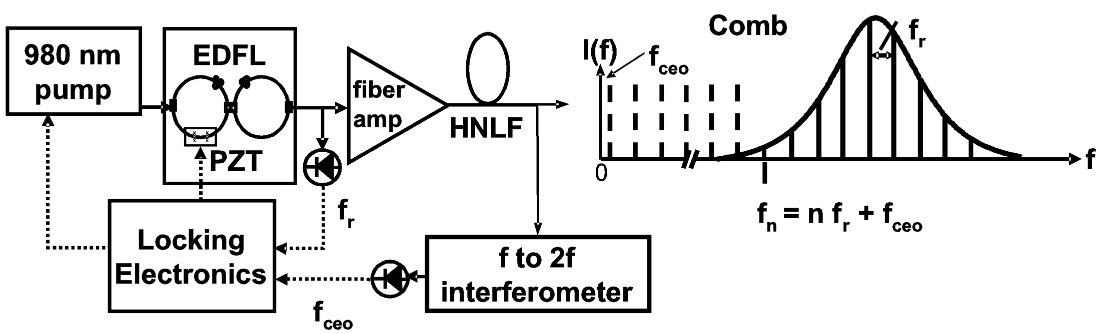

Fig. 3. Schematic of the fiber-laser based frequency comb. The repetition rate is detected and phase-locked to a microwave source by feeding back to a fiber stretcher in the cavity. The ceo frequency (or comb offset frequency) is detected in the f-to-2f interferometer and phase-locked to a microwave source.

5. References

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