

WK2 Fig. 1. Experimental apparatus for single-scan characterization of optical devices.

lightwaves with respect to the other by an amount, τ , and recombines them with orthogonal polarizations, using a polarizing beam combiner. This recombined lightwave stimulates the DUT. The reflected light from the DUT interferes with light from the LO path at the reflection receiver, while the transmitted light interferes with the light from the LO at the transmission receiver.

From the frequency, phase, and amplitude of the interference signals measured at the receiver, the polarization-resolved transfer function of the DUT is extracted. With this information, the transmissivity, reflectivity, PDL, PMD, group delay, and CD can be determined; the PMD and group delay are obtained using methods similar to those described in Sano et al.⁵ All of these parameters are thus determined from measurements obtained during a single scan of the TLS over the wavelength range of interest. The results shown in this paper were obtained by scanning the wavelength of the tunable laser at 40 nm/s.

The ability to perform these measurements in a single scan is a significant advantage. As mentioned earlier, many polarization-related measurements require a sequence of measurements to be performed. Any disturbance of the DUT or its pigtailed during this process can also disturb the results. With a single-scan, this risk is minimized.

3. Results

The UV-writing process used to fabricate typical fiber Bragg gratings (FBGs) is known to generate

a photoinduced birefringence in the grating region.⁶ This birefringence, in turn, results in a polarization-dependence of the properties of FBGs, such as the reflectivity and group delay. The polarization dependent reflectivity of a typical FBG was measured using the apparatus shown in Fig. 1, and the results are shown in Fig. 2(a). At every wavelength, the measurement finds two nearly orthogonal states of polarization that correspond to maximum and minimum reflectivities. The reflectivities associated with these two polarization states are plotted in black and gray, respectively. While the maximum and minimum reflectivities are nearly identical in the passband, they fluctuate significantly in the sidebands.

The two reflectivities plotted in Fig. 2(a) appear to be offset in wavelength with respect to each other. This effect can be understood by referring to the phase-matching (Bragg) condition, $\lambda = 2n_e\Lambda$, where λ is the design peak reflection wavelength, n_e is the effective index of the medium, and Λ is the grating period. Using this condition, the birefringence of the grating (polarization-dependent variations in n_e) can be related to variations in the nominal wavelength of the grating, λ . Close examination of Fig. 2(a) reveals a wavelength offset, $\Delta\lambda$, of approximately 20 pm. This value corresponds to a value for the birefringence of roughly 2×10^{-5} , which is of the same order as the FBG birefringence measured in.⁷

The birefringence that creates the polarization-dependent reflectivity shown in Fig. 2(b) also leads to PMD in the grating. The group delay of a device with PMD is polarization-dependent, and the polarization states corresponding to the largest and the smallest group delays of a device are referred to as the principle states of polarization.³ Figure 2(b) plots the group delays associated with each of these principle states of polarization of the grating. The two group delays in the sidebands of the grating fluctuate over roughly 1000 ps. The pairs of extrema in the sidebands are associated with the minima of Fig. 2(a). In the passband of the grating, the two group delays increase smoothly with wavelength. Their slopes, indicative of dispersion, vary in a range between roughly 100 and 250 ps/nm. The difference between these two group delays is called the differential group delay (DGD). DGD is a common parameter for specifying the level of PMD in a device or network. The DGD in the passband of the grating is found to be about 3 ps, though it also varies somewhat in the passband. The results shown in Figs. 2(a) and 2(b) were obtained during the same measurement scan.

4. Conclusions

The novel technique presented here is able to accomplish in one scan what ordinarily requires the use of several measurement setups. With one scan, reflectivity, transmissivity, group delay, CD, PMD, and PDL can all be determined. The interferometric nature of the measurement enables the excellent dynamic range and wavelength resolution indicated by Fig. 2. The greater than 50 dB dynamic range evident in Fig. 2 exceeds the dynamic range available in many other measurement techniques, such as the modulation phase-shift method.

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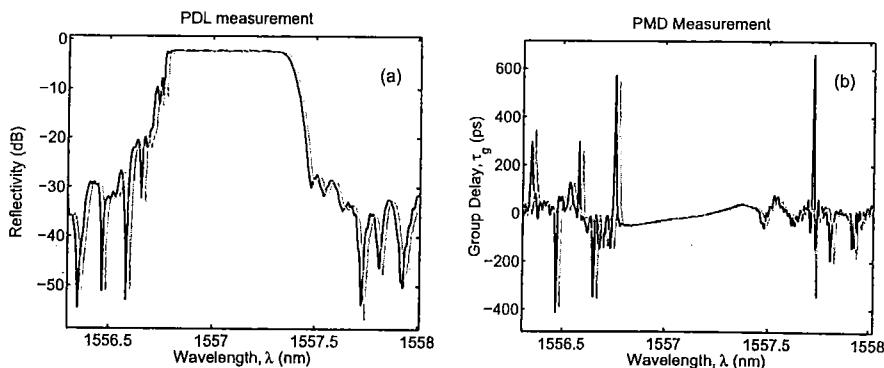
2:15 pm

Relative Group Delay Measurements with 0.3 ps Resolution: Toward 40 Gbit/s Component Metrology

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Introduction

Future dense wavelength division multiplexing systems operating at 40 Gbit/s pose a number of formidable metrology challenges. Among the phenomena requiring high-resolution characterization is chromatic dispersion, which broadens optical data pulses through the wavelength-dependent refractive index variation of system elements. At higher data rates, characterization of relative group delay (RGD) due to chromatic dispersion in components becomes critical to system throughput. In optical fibers, broadband descriptions of the chromatic dispersion are sufficient. However, it is more challenging to characterize optical components such as narrowband filters for 40 Gbit/s data rates, since these systems may need sub-picosecond RGD resolution in bandwidths on the order of tens of picometers. To help meet this industry challenge, the National Institute of Standards and Technology (NIST) has developed an RGD measurement



WK2 Fig. 2. Polarization dependence of (a) reflectivity, and (b) the group delay of a fiber Bragg grating.

technique targeted for 40 Gbit/s component metrology. Our technique relies on refinements to the established modulation phase shift method for measuring RGD,¹ yielding enhanced phase stability over the time interval of the measurement. Given the many sources of absolute uncertainty in this measurement, the development of a calibration artifact with a theoretically predictable group delay is critical to the success of optical component measurements.² We present experimental and theoretical results for the measurement of RGD of molecular gas absorption lines, which have the potential to be stable and well-characterized standards.

Experimental Apparatus

Figure 1 shows the experimental apparatus we constructed for measuring group delay. We used an extended-cavity diode laser having an 80 nm tuning range centered at 1560 nm, with a single-mode linewidth of ~5 MHz in a one-second time interval. The laser light was passed through a variable optical attenuator and a narrow-band tracking filter. A small portion of the light from the filter was directed to a wavelength meter having sub-picometer resolution and accuracy. The remaining light was amplitude-modulated by a Mach-Zehnder modulator driven electrically by an oven-controlled crystal oscillator (OCXO) at 200 MHz. The amplitude-modulated signal was passed three times through a gas cell containing hydrogen cyanide (H¹³C¹⁴N) gas at a pressure of 1 kPa (100 Torr). The total optical path through the gas was 22.5 cm. An AC-coupled photoreceiver was used to detect the modulated optical signal after the gas cell. The electrical amplitude and phase of the receiver signal were measured with a lock-in amplifier referenced to the OCXO. During a group delay measurement, the laser's wavelength was swept while the phase of the modulated signal from the receiver was recorded. Observed changes in arrival phase represent variations in the propagation time (group delay) through the device (360° of phase represents one period at the modulation frequency).

To achieve measurements with the highest resolution and lowest uncertainty, the exact method of data collection is critically important. The variable attenuator was necessary to counteract the power dependence of phase caused by electrical devices such as the photoreceiver, amplifiers, and lock-in amplifier. This was especially important when conducting measurements at the edge of a filter pass-band or at the center of a molecular absorption line. The tracking filter was used to remove amplified spontaneous emission noise from the laser, which we have observed to cause

phase errors in some circumstances. Temporal drift of the phase during a measurement can be particularly debilitating because it is indistinguishable from the RGD structure of an optical component. The effects of system drift were removed by normalizing each value of phase to a subsequent reference phase measured at a fixed wavelength. Variations in phase at this fixed position represent the phase drift of the system, and recording its value in real time helps to remove phase drift from the RGD measurement. However, the reference phase must be measured at a wavelength position having both sufficient transmitted power and small chromatic dispersion. If the chromatic dispersion at the reference wavelength is too large, variability in tuning to the reference wavelength will translate into errors in the reference phase. We also minimized system phase drift by using a modulator that was designed to operate at quadrature without a DC electrical bias, which tends to drift with time. The residual (background) dispersion in the fiber leads of the system was removed from the absorption cell measurements by subtracting the RGD curve measured without the cell in place.

Theoretical Development

The theoretical motivation for using a molecular absorption line as a calibration reference is provided by the Kramers-Kronig relation,³ which enables the relative group delay $\tau(\lambda)$ to be predicted from a normalized transmittance profile $P(\lambda)$. We begin by defining the imaginary dielectric constant $K_i(\lambda)$ for a weak gas:

$$K_i(\lambda) = -\frac{\lambda}{\pi} \ln P(\lambda). \quad (1)$$

The Kramers-Kronig relations can then be used to calculate the corresponding real dielectric constant $K_r(\lambda)$:

$$K_r(\lambda) = \frac{2}{\pi} \int_0^\infty \frac{K_i(\lambda') d\lambda'}{\lambda'^3 [(1/\lambda'^2) - (1/\lambda^2)]} + 1. \quad (2)$$

Using the expressions for $K_i(\lambda)$ and $K_r(\lambda)$ the refractive index profile can be expressed as:

$$n(\lambda) = \sqrt{(1/2)[K_r(\lambda) + \sqrt{K_r^2(\lambda) + K_i^2(\lambda)}]}. \quad (3)$$

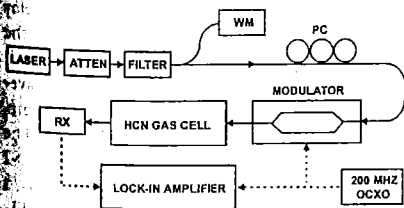
Finally, by differentiation of $n(\lambda)$ the relative group delay $\tau(\lambda)$ can be calculated from:

$$\tau(\lambda) = \frac{-\lambda}{c} \frac{dn(\lambda)}{d\lambda} \quad (4)$$

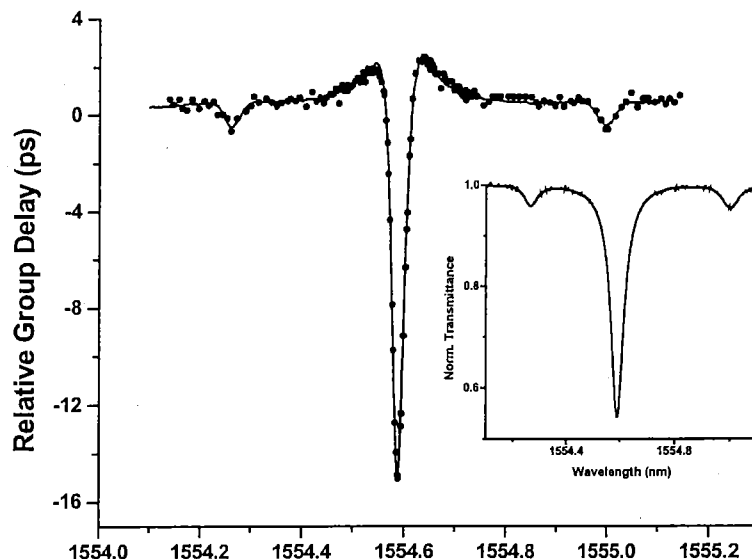
where c is the speed of light in vacuum. If these expressions are evaluated numerically, arbitrary profiles of measured spectra can be treated without assuming a functional form for the normalized transmittance. Some signal processing may be necessary to remove high-frequency noise originating from the spectral measurement.

Measurement Results

H¹³C¹⁴N has about 50 strong absorption lines in the 1530–1560 nm region and a number of weaker lines.⁴ Figure 2 shows our measurement of the RGD across line P(16), recorded with wavelength steps as small as 3 pm. The inset to the plot shows the normalized transmittance profile we measured for line P(16), which is centered at 1554.589 nm with an absorption depth of about 45%. Both the RGD and the transmittance plots show two weak absorption lines on either side of line P(16). The main plot of Figure 2 also shows a predicted RGD curve that was calculated by applying equations (1) through (4) to the measured transmittance. Aside from the removal of a measured background from the RGD measurement and the filtering of high-frequency noise from the calculation, no adjustments between the curves were made. The calculated curve and the measurement show good agreement, particularly in the magnitude of the RGD at the center of the P(16) line, and good measured resolution of the ~1 picosecond weaker features. The standard deviation between the curve and measured RGD is less than 0.3 ps, showing the potential for metrology of 40 Gbits/s components. The spectral position for measuring the reference phase was set to the beginning of the wavelength scale at 1554.1 nm. Without phase referencing, measurements of



WK3 Fig. 1. Experimental apparatus for measuring group delay on absorption lines in hydrogen cyanide gas. Solid paths represent optical fiber; dashed paths represent electrical connections. WM, wavelength meter; RX, photoreceiver; PC, polarization controller; OCXO, oven-controlled crystal oscillator.



WK3 Fig. 2. Measured relative group delay for line P(16) of hydrogen cyanide (shown by dots) along with a theoretical prediction (solid line). The reference phase was measured at 1554.1 nm. The prediction was calculated from the measured normalized transmittance of the line, shown in the inset.

the absorption line had drifts of almost 2 picoseconds over intervals of 0.1 nm or more. The results presented in Figure 2 show a significant reduction in long-term drift, in turn decreasing the standard deviation in RGD by a factor of two. However, because extra time was required to perform the phase referencing, more short-term drift between adjacent measurement points was observed. We are investigating schemes to increase the short-term stability, and have been making comparisons with RGD measurements acquired by a low-coherence interferometric technique.⁵

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under-test (DUT) and detected through a photodetector and lock-in RF phase-discriminator. The optical group-delays at each wavelength can then be calculated from the measured RF phase differences. The measurement is usually performed with an RF network analyzer and a tunable ECL which steps each measuring wavelength point-by-point, at a rate which take seconds per point, due to ECL wavelength settling time. Additionally, a wavelength meter may also be essential due to the poor wavelength accuracy of an ECL, which further increases the measurement time.

Recently a fast dispersion measurement technique was proposed with 10-Hz scan rate.¹ However, the wavelength sweep range was limited to ~ 6 nm, giving a sweep rate of 60 nm/s. Furthermore, it requires 30-times averaging for noise reduction, giving an effect sweep rate of only 2 nm/s. One way to achieve a high speed and wide-band swept-wavelength source is to employ a fiber ring laser with a fast wavelength tunable filter such as a fiber Fabry-Perot tunable filter (FFP-TF).² However, such swept laser will passively modelock at the cavity fundamental frequency of around several ten's of MHz due to the frequency shifted feedback.^{2,3} Since the output of such laser is pulsing, the MPS technique cannot be applied.

In this paper, we propose and demonstrate a fast dispersion measurement system based on an intra-cavity-modulated swept-laser (ICM-SL), by placing the modulator within the fiber ring cavity. The intra-cavity modulation suppresses the natural mode-locking of the swept-laser and directly produces synchronous wavelength-swept pulses for dispersion measurement. It is capable of a continuous scan over 50 nm wavelength range at 22 Hz, giving a "real-time" display of both the amplitude and phase response simultaneously. We have achieved a sweep rate of >1000 nm/s.

2. Experimental setup

The schematic of the ICM-SL is shown in Fig. 1. The laser is in a fiber ring configuration with a length of Erbium-doped fiber as the gain medium, pumped by a 980 nm diode laser. A FFP-TF is used as the swept-wavelength filter. The FFP-TF has a free-spectral range (FSR) of over 70 nm. It is driven by a piezo-electric transducer (PZT), which enables a very fast wavelength sweeping speed. The isolators in the cavity ensure unidirectional operation and prevent back reflections from the FFP-TF. A Lithium Niobate (LN) amplitude modulator is placed within the cavity of the swept-laser, as opposes to the standard MPS technique, which places the modulator at

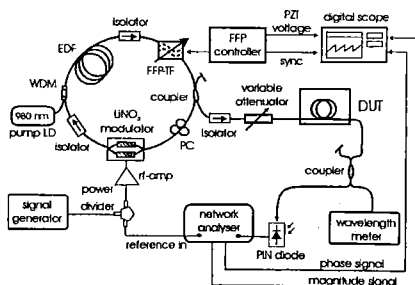
the output of a tunable laser. A polarization controller (PC) used to align the polarization of light before the LN modulator. Although it was found that the swept-laser itself is not very sensitive to the polarization alignment, and has a high tolerance to polarization changes. The laser output is coupled out of the cavity through a fiber coupler and a variable attenuator is used to limit the output power before launching to the device-under-test (DUT). The output power is typically >0 dBm when pumped at 50 mW. The LN modulator is driven, through an amplifier, by a reference radio-frequency (RF) signal from a signal generator. For the purpose of first concept demonstration, we use an RF reference frequency of 2 GHz. The swept-laser is then intra-cavity modulated with the reference RF signal, producing pulses in synchrony with the reference frequency. The ICM-SL has a repetition rates of 2 GHz and a pulse width of ~ 60 ps.

A PIN photodiode is used to detect the pulses from the DUT. The phase difference between the reference RF signal and the received RF signal from the PIN diode is measured using an analog network analyzer. The measured phase and amplitude signals are retrieved using a digital sampling oscilloscope, which is triggered by the FFP controller. The network analyzer can be replaced by a simple phase-detection circuitry, for example, an I/Q mixer and appropriate signal processing circuits.

3. Results and discussion

In order to confirm the applicability and accuracy of the ICM-SL for dispersion measurement, we compare its performance with the standard MPS method using a tunable external cavity laser (ECL). We use 20 km of standard single-mode fiber (SMF) as our DUT. First, we operate the ICM-SL in a point-by-point measurement mode, by discretely stepping the wavelength of the ICM-SL. The wavelength is measured using a wavelength meter. Fig. 2a shows the group delay of the SMF measured using the ICM-SL and that measured using an ECL, over a 50 nm bandwidth. The dispersion (D) and dispersion-slope (DS) are measured to be 16.49 ps/km/nm, and 0.058 ps/km/nm² respectively in the case using the ICM-SL. These results correspond very well to those measured using the standard technique with an ECL of $D = 16.60$ ps/km/nm, and $DS = 0.061$ ps/km/nm². It should be noted that the wavelength measurement of the ECL is solely based on the ECL setting, which was not calibrated against the wavelength meter. This probably gives rise to the slight discrepancies in the results of $<0.7\%$ in D and $<5\%$ in DS.

Fig. 2b shows the group delay measurement on 5 km of SMF when the ICM-SL is operated in a sweep mode at 22 Hz rate. The group delay measurements are relative, and we have offset the two traces by 1000 ps for ease of viewing. It should be noted that, the entire 50 nm wavelength range is swept across in 22.5 ms up-ramp, giving an effective sweep rate of 2200 nm/s. The full-scan measurement time using the ECL is >2 minutes (48 points at 2.5 sec/point) whereas it only takes an effective 22.5 ms with the ICM-SL, and the data point are solely determined by the sampling scope (in our case, 450 points at 50 ns/point). Since the wavelength cannot be measured with a wavelength meter at this sweep rate, it is estimated purely from the PZT control voltage. Therefore, the wavelength accuracy is af-



WK4 Fig. 1. Experimental setup of the intra-cavity-modulated swept-laser (ICM-SL).

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2:30 pm

Intra-Cavity-Modulated Swept-Lasers for "Real-Time" Dispersion Measurement

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1. Introduction

In today's networked world and the ever-increasing global demands in data bandwidth, optical communication systems are evolving towards employing higher channel data-rates at 10 Gb/s, 40 Gb/s and beyond. At such bit-rates, the dispersion or group-delay properties of not only the transmission fibers, but also of each optical components used, are important parameters for system designers and component vendors. Various methods have been proposed for group-delay or dispersion measurement. The most commonly adopted "industrial" standard for group-delay measurement is mainly based on the modulation phase-shift (MPS) technique. Typically, a tunable external-cavity laser (ECL) is used as an optical source and the output being intensity-modulated at a known radio-frequency (RF) signal. The modulated signal is launched through the device-