High-Accuracy Optical Group Delay Measurements and Modulator Chirp Characterization

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Abstract – **We present group delay measurements of a molecular absorption line for absolute calibration with 0.17 ps resolution. The distortion caused by modulator chirp is investigated, and a novel, high-resolution method for chirp characterization is introduced.**

I. INTRODUCTION

Microwave photonic systems designed to operate at tens of gigahertz require accurate true-time-delays for applications such as optically phased arrays and photonic signal processing. Achieving optimum performance can depend critically on the ability to measure and calibrate the variations in propagation time (group delay) of a signal through optical components to subpicosecond levels. In this work we describe a high-resolution measurement system for group delay that is calibrated to an artifact reference based on a molecular absorption line.

Microwave photonic applications that involve long transmission distances or phase-sensitive quantities, such as our group-delay measurement system, can be adversely affected by the chirp of optical modulators. Chirp describes the phase modulation that can arise when a carrier is intensity modulated. We conducted experimental and theoretical investigations of the dependence of our measurement technique on chirp. These same results also suggest a strong potential for a high-resolution, narrow-band technique of characterizing modulator chirp that can be used throughout the megahertz and gigahertz regimes.

II. HIGH ACCURACY DELAY MEASUREMENTS

Our technique for measuring group delay relies on refinements to the established modulation phase shift (MPS) method [1, 2], yielding enhanced phase stability over the interval of the measurement. The MPS technique offers both high wavelength and temporal resolutions [3, 4]. The method records, as a function of wavelength, the change in RF phase of a modulated optical carrier after traveling through a device under test (DUT). Observed changes in arrival phase represent variations in the propagation time through the device, where 360° of phase represents one period at the modulation frequency.

Shown in Fig. 1 is our measurement apparatus [5], including a tunable measurement laser, Mach-Zehnder modulator, AC-coupled photoreceiver, and lock-in amplifier for phase detection. To achieve measurements with the highest resolution and lowest uncertainty, the exact method of data collection is critically important. Real-time variations in phase at a fixed wavelength position represent the phase drift of the system. We minimized these drifts by normalizing each value of phase to a subsequent reference phase measured at a fixed wavelength. A mechanical optical switch allowed rapid alternation between a fixed reference laser and the tunable measurement laser.

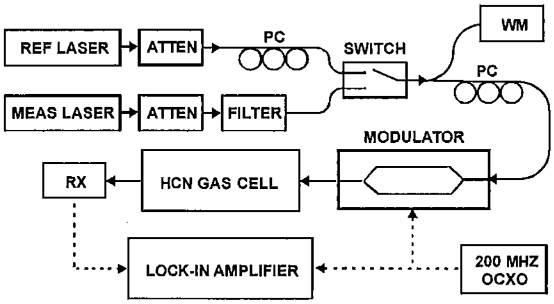

Fig. 1. The modulation phase-shift system for measuring group delay of optical components. WM, wavelength meter; PC, polarization controller; OCXO, oven-controlled crystal oscillator; RX, photoreceiver.

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A tracking filter was used to remove the measurement laser's amplified spontaneous emission noise, which can cause group delay errors in some circumstances [6]. Programmable optical attenuators were used to counteract the power dependence of phase caused by electrical devices such as the photoreceiver, lock-in amplifier, and RF amplifiers. This is especially important when the DUT has large spectral variations in transmittance, such as occur in optical filters and molecular absorption lines. The modulator was run stably at quadrature to avoid phase drifts while being driven by an oven-controlled crystal oscillator at 200 MHz. The measurement wavelength was monitored with a wavelength meter having subpicometer resolution and accuracy.

The many sources of uncertainty in this method make the existence of a calibration artifact with a theoretically predictable group delay very important. Neither Bragg gratings nor thin-film filters provide such an artifact, as their group delay shape and ripple vary greatly with device. In fact, it has been shown that the MPS method can give erroneous or misleading results when inappropriately used [7]. However, the group-delay profiles of molecular gas absorption lines can be predicted from their absorption spectra, giving them the potential to be stable and well-characterized absolute standards [5, 8]. Hydrogen cyanide $H^{13}C^{14}N$ has about 50 strong absorption lines in the 1530-1560 nm region and a number of weaker lines [9].

The main plot in Fig. 2 shows the measured group delay profile of $H^{13}C^{14}N$ line P(16) recorded with wavelength steps as small as 3 pm in a gas cell with a total optical path of 22.5 cm and a pressure of 13 kPa (100 Torr). Also shown is a theoretical prediction based on the measured, normalized transmittance given in the inset plot. Good agreement is achieved, particularly in the magnitude of the delay at the center of line P(16) and the resolution of the ~1 ps weaker side features. The standard deviation between the measurement and calculation across the ~1 nm measurement is only 0.17 ps for a single scan without averaging. The modulator chirp was negligible for this measurement.

III. MODULATOR CHIRP

Experimental results in our lab have shown that the accuracy of the MPS method can depend strongly on the chirp of the external modulation. In particular, we have observed distortions in our measurements of gas absorption lines, with magnitudes that depend on the size of the chirp (α), and signs that depend on both the sign of the chirp and the slope of the spectral transmittance. The result is both under- and over-estimates of group delay features, such that measured profiles show an asymmetry.

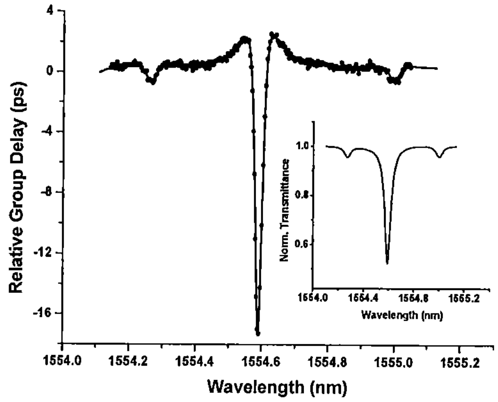

Fig. 2. Measured group delay for line P(16) of hydrogen cyanide (shown by dots) along with a theoretical prediction (solid line). The measured group delay resolution is ~0.17 ps.

To better understand this we considered a simple model of the Mach-Zehnder modulation process and the measurement of group delay. Following [10] we assumed that sinusoidal phase modulation amplitudes m_1 and m_2 (proportional to drive voltages V_1 and V_2) were applied to waveguide arms 1 and 2 of the modulator, respectively, at a modulation frequency ω_m. At quadrature bias the alpha parameter for the chirp is expressed as

$$\alpha = (m_1 + m_2)/(m_1 - m_2). \qquad (1)$$

In the small-signal regime the sinusoidal modulation produces first-order sidebands on the carrier frequency ω_0 located at $\omega_0 + \omega_m$ and $\omega_0 - \omega_m$ as shown in Fig. 3.

After transmission through the DUT the spectral components are modified according to the optical amplitude profile A(ω) and optical phase profile $\varphi(\omega)$ of the DUT, also shown in Fig. 3. For simplicity we denote the phase and amplitude values at the carrier

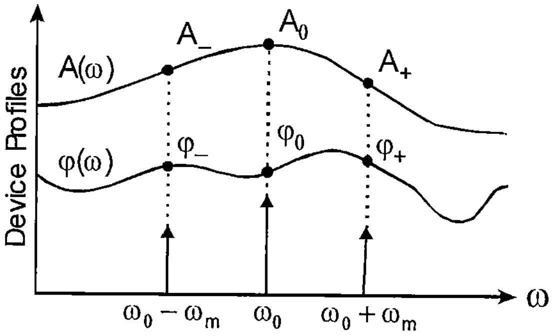

Fig. 3. The optical carrier ω_0 and its modulation sidebands sample the A(ω) optical amplitude and φ(ω) optical phase profiles of the device under test.

as A_0 and φ_0, and at the upper and lower sidebands A_+, φ_+ and A_-, φ_-, respectively. The detected optical intensity is the square of the amplitude spectrum after it has been modified by the DUT. The electrical phase $\Delta\theta_{RF}$ measured by a lock-in amplifier is the phase of the detected intensity component at ω_m. When the modulator is driven in a push-pull, zero-chirp arrangement ($m_1 = -m_2$) the measured RF phase is as derived in [7],

$$\Delta\theta_{RF} = (\varphi_+ - \varphi_-)/2 . \tag{2}$$

Therefore, when the chirp is zero the RF phase measurement is simply proportional to the difference in the optical phase at the upper and lower sidebands. The change in group delay of the DUT over the frequency interval ω_m is given by $\tau = \Delta\theta_{RF}/\omega_m$.

For the general case in which $m_1 \neq -m_2$, the result is much more complicated and is given by

$$\Delta\theta_{RF} = \tan^{-1}\left[\frac{A_+ \sin\Delta_+ + A_- \sin\Delta_-}{A_+ \cos\Delta_+ + A_- \cos\Delta_-}\right], \tag{3}$$

where we have defined

$$\begin{aligned} \Delta_+ &= \varphi_+ - \varphi_0 + \tan^{-1}(-N/M) \\ \Delta_- &= \varphi_0 - \varphi_- + \tan^{-1}(-N/-M) . \end{aligned} \tag{4}$$

In addition, the M and N terms are defined as

$$\begin{aligned} M &= J_0(m_1)J_1(m_1) + J_0(m_2)J_1(m_2) , \\ N &= J_0(m_2)J_1(m_1) - J_0(m_1)J_1(m_2) , \end{aligned} \tag{5}$$

where $J_k(m_i)$ is the kth-order Bessel function of the first kind. Care must be taken in evaluating the tan^{-1} functions of Eqn. 4; the minus signs are explicitly shown since the tan^{-1} function is sensitive to the sign of the argument. The measurement now depends on the modulation amplitudes m_1 and m_2 through the Bessel functions and on the amplitude profile of the DUT through A_+ and A_-. However, if *either* the chirp is zero ($m_1 = -m_2$) or the absorption spectrum is flat ($A(\omega)$ = constant), Eqn. 3 reduces to Eqn. 2. When the DUT is a gas cell, the amplitude and phase profiles of an absorption line together act as a phase discriminator for the modulation sidebands.

IV. CHIRP MEASUREMENTS

We used a dual-electrode modulator in our measurement system to allow the alpha parameter to be set according to Eqn. 1. We measured the group delay of line P(16) of HCN while the modulator was driven with an alpha parameter of about 0.17 in magnitude, as shown by the dots of Fig. 4. Predictions based on Eqn. 3 are shown for the true symmetric group delay (α = 0) and the measured asymmetric group delay ($|\alpha|$ = 0.17). Also shown is the residual between the measurement and the true group delay. We defined the group delay asymmetry as the peak-to-peak amplitude of the residual, where the asymmetry shown is defined as positive and has a magnitude of 4.5 ps. By operating at the opposite quadrature point or swapping the orientation of the modulation amplitudes, the sign of the alpha parameter was switched. This caused the residual curve to invert, as predicted by Eqn. 3.

The measurement shown in Fig. 4 was extended to other values of alpha (0, ±0.6, ±0.11, ±0.17, 0.48) by changing the modulation amplitudes. Also, a single drive modulator having fixed chirp was used to perform measurements with alpha values of ±0.7. The asymmetries we measured for both modulators

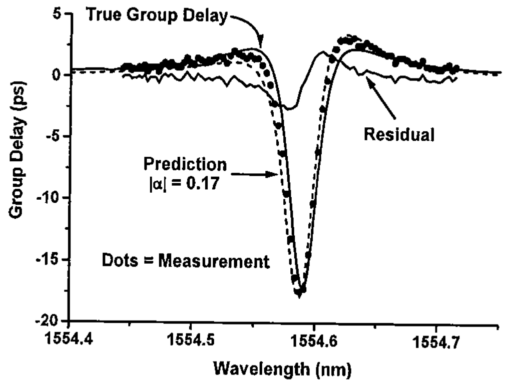

Fig. 4. The chirped measurement of group delay for line P(16) of HCN, shown with dots. The residual is the difference between the measurement and the true group-delay profile. Also shown as a dashed line is the prediction for $|\alpha| = 0.17$.

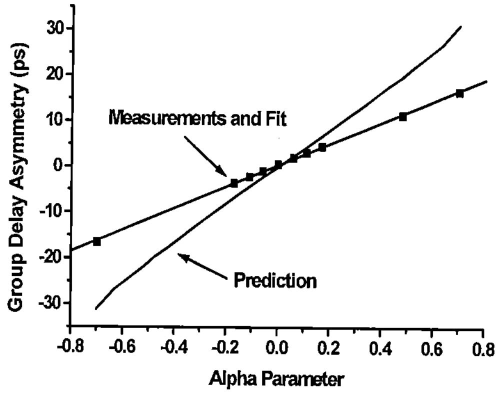

Fig. 5. The measured asymmetry depends linearly on the modulator alpha parameter. A single drive modulator was used for measurements with alpha = ±0.7; all other values used a dual drive modulator.

as a function of α are presented in Fig. 5 and show excellent agreement with a linear fit. The two modulators gave consistent results despite originating from different manufacturers and having different electrode structures. The measured asymmetry was close to zero when alpha was zero, with an offset of ~0.5 ps that we attribute to imbalanced electrodes, finite extinction, uncertainty in the applied drive powers, and finite wavelength resolution of the MPS method.

Also shown in Fig. 5 is a theoretical prediction based on Eqn. 3, which agrees in many aspects with the experimental results. Like the measurement, the prediction is nearly linear and crosses through the origin with only a slight offset (-0.1 ps), which is caused by the finite wavelength resolution of the MPS technique. However, the slope of the prediction is almost twice that of the measured behavior; this discrepancy is currently being investigated.

The experimental results of Fig. 5 show that our group-delay measurement system is very sensitive to modulator chirp. To achieve results with subpicosecond accuracy, the measured slope of 23.6 ps for the curve of asymmetry versus alpha suggests that the alpha parameter should be less than 0.04. This specification can be a challenge given that manufacturers of "zero-chirp" modulators typically specify the alpha parameter to no better than ±0.1. As a result, careful operation of a dual electrode modulator may be the best solution.

Fig. 5 also demonstrates the potential for a high-resolution method of measuring a modulator's alpha parameter. Asymmetries of less than 0.5 ps can easily be detected, resulting in a resolution of the alpha parameter of better than 0.02, which is equal to or better than that obtained with conventional techniques. Unlike the frequency-null method for measuring chirp [11], this technique is inherently narrow-band and does not require a long (>100 km) length of fiber with known chromatic dispersion. As compared to the spectrum analysis method [10, 12], this technique can be performed at low frequencies. To measure the alpha parameter at higher frequencies would require a higher modulation frequency and a broader gas absorption line to compensate for the increased sideband spacing. The absorption linewidth can be broadened by increasing the gas cell pressure.

V. CONCLUSION

We have shown that the MPS method can be implemented to measure optical group delay very accurately. The group delay of a gas absorption line provides a convenient and high-accuracy artifact for absolute calibration. This measurement capability is critical to the characterization of components whose group delay cannot be predicted by other means, and for which the MPS method can otherwise give erroneous or misleading results. For a single measurement spanning 1 nm, we achieved a group delay resolution of 0.17 ps in a 3.2 pm (2 ×200 MHz) optical bandwidth. This temporal and wavelength resolution should be sufficient for microwave photonic applications well beyond 10 GHz.

We have demonstrated that the MPS method is very sensitive to modulator chirp and that an alpha parameter of less than 0.04 is necessary for subpicosecond accuracy. Conversely, this sensitivity can be used advantageously to measure the chirp of narrow-band intensity modulation, independent of the type of modulator or electrode structure. The proposed method has resolution advantages over some conventional techniques, and does not require electronics with gigahertz-bandwidths.

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