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New method to improve the accuracy of group delay measurements using the phase-shift technique

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Abstract

We propose and demonstrate a novel method to improve the accuracy of measurements of group delays using the conventional phase-shift technique. In particular, the method allows for accurate reconstruction of the actual group delay when a high modulation frequency is employed to increase the timing resolution. The method is based on post-processing of the measured data in a deconvolution operation with the instrument function of the measurement setup. We present practical examples of it for both fiber Bragg gratings and narrow-band thin-film filters. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Group-delay measurements; Grating; Thin-film filter

1. Introduction

The dispersion of various optical components has become an important issue in assessing the performance of optical networks. It can be quantified by measuring the group delay of light propagating through the optical system as a function of the wavelength. Accurate measurements of the group delay and the amplitude response of optical components can be performed by using interferometric methods [1,2] or by applying various modulation-phase-shift techniques [3,4]. The phase-shift technique is the most common of these due to its simplicity and robustness. Indeed, it is also applied in several commercial dispersion measurement systems. For certain components such as chirped fiber Bragg gratings (FBGs), the group delay often exhibits significant fluctuation with the wavelength. This fluctuation which is referred to as group delay ripple is due to apodization of the refractive index profile of the grating and imperfections in the manufacturing process. Variation in the group delay can also be observed in narrow-band filters, which are used in for instance multiplexers and add/drop components. These filters typically have dispersion, which increases towards the edges of the band. In optical network systems, fluctuations in the group delay causes power penalty and intersymbolic interference [5–10], leading to degradation of the system performance. When the phase-shift technique is

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utilized to characterize the group delay ripple, the measured value of the amplitude of the ripple has been observed to depend on the modulation frequency [11–13]. Typically, a high modulation frequency is applied in order to achieve good timing resolution. Attempts have been made to modify the standard phase-shift technique to make it less sensitive to the value chosen for the modulation frequency in the measurement [14].

In this paper, we first derive the instrument function for a group delay measurement with the phase-shift technique. This function is then used to investigate the effects of the modulation frequency on the measured group delay ripple of FBGs and estimate the error induced by the technique. Furthermore, a new method to increase the accuracy of group delay measurements using the phase-shift technique is presented. The method allows the actual group delay of the component to be accurately reconstructed and it is applicable to any arbitrary group delay profile. Finally, we present two applications of this method: first, we apply it to reconstruct the amplitude of the dense group delay ripple of FBGs and secondly, to reconstruct the group delay of a narrow-band thin-film filter.

2. Phase-shift technique

Our experimental setup is based on a conventional phase-shift technique and it is outlined in Fig. 1. The light source is a narrow linewidth wavelength-tunable laser (Photonetics TUNICS-PRI) whose wavelength is monitored with a wavemeter (HP 86120B). The laser is externally modulated to produce a sinusoidally varying output intensity at frequency ω_m. Polarization of the light entering the modulator is tuned with a polarization controller. The optical signal is amplified with a fiber amplifier and divided into a reference path and a path containing the device under test (DUT). The two optical signals are detected and electrically amplified before they are displayed in two channels of a digital sampling oscilloscope (Tektronix TDS820). The stored time traces of the signals are transferred to a computer for analysis of their phases and amplitudes. The resolution of the setup depends primarily on the resolution of the electrical phase measurement. In general, the resolution of the group delay measurement improves when a higher modulation frequency is used. The devices conventionally utilized for phase determination are vector voltmeters or network analyzers, which typically have a phase resolution of $\sim 0.1°$. This allows a sub-picosecond resolution to be achieved in the group delay measurement. We have tested the stability and the resolution of our setup using a fiber-optic beam expander with a variable air gap as the DUT. The results indicate that a group delay resolution of ~ 1 ps can reliably be obtained with our experimental setup.

The relation between the optical phase $\phi(\omega)$ and the group delay is given by

$$\tau(\omega) = \mathrm{d}\phi(\omega)/\mathrm{d}\omega. \quad (1)$$

The optical phase shifts measured at the frequencies of the two induced modulation sidebands applying the setup of Fig. 1 can be used to give an approximate value for the group delay

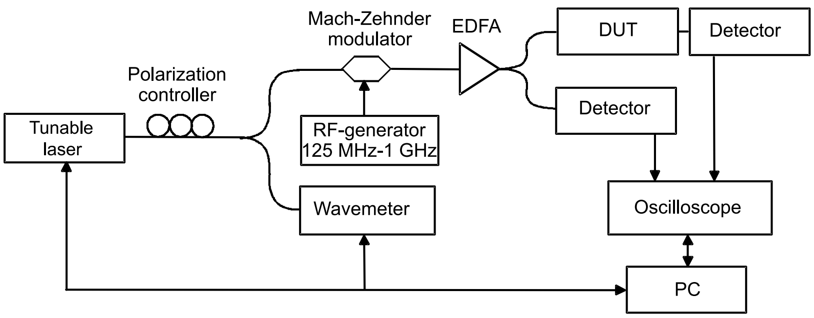

Fig. 1. Experimental setup for group delay measurements using the phase-shift technique.

$$\tau(\omega) \approx \frac{\phi^+ - \phi^-}{2\omega_m} = \tau_{meas}, \tag{2}$$

where ω_m is the applied modulation frequency applied and ϕ^+ and ϕ^- are the optical phase shifts at the frequencies $\omega + \omega_m$ and $\omega - \omega_m$, respectively.

The approximation gives accurate results when the variation of the group delay with wavelength is small, which is the case, e.g., for an optical fiber. However, optical components such as fiber Bragg gratings or thin-film filters can exhibit strong fluctuations in the group delay with wavelength within the bandwidth of the optical signal. Consequently, the previous approximation is no longer valid and a more accurate model is required.

3. Instrument function

Knowing the instrument function of the measurement setup, the data collected could be post-processed in a deconvolution operation to obtain better accuracy. In order to find an expression for the instrument function we integrate Eq. (1) over the modulation bandwidth and identify the result to be directly related to the measured group delay τ_{meas} as

$$\frac{1}{2\omega_m}\int_{\omega-\omega_m}^{\omega+\omega_m} \tau(x)\mathrm{d}x = \frac{\phi^+ - \phi^-}{2\omega_m} = \tau_{meas}. \tag{3}$$

By writing $\tau(\omega)$ with the help of its Fourier transform $\tilde{\tau}(u)$ as

$$\tau(\omega) = \int_{-\infty}^{\infty} \tilde{\tau}(u)\cdot \mathrm{e}^{\mathrm{j}\omega u}\,\mathrm{d}u, \tag{4}$$

we insert Eq. (4) into Eq. (3) and invert the order of the two integrations to obtain a connection between the actual and the measured values of the group delay

$$\tau_{meas} = \frac{1}{2\omega_m}\int_{-\infty}^{\infty}\left(\int_{\omega-\omega_m}^{\omega+\omega_m} \tilde{\tau}(u)\cdot \mathrm{e}^{\mathrm{j}ux}\,\mathrm{d}x\right)\mathrm{d}u. \tag{5}$$

The inner integral is easily evaluated and we can write Eq. (5) in the form

$$\begin{aligned}\tau_{meas} &= \int_{-\infty}^{\infty} \tilde{\tau}(u)\cdot\frac{\sin(\omega_m u)}{\omega_m u}\cdot \mathrm{e}^{\mathrm{j}\omega u}\,\mathrm{d}u \\ &= \tau(\omega)^* \,\mathrm{rect}(\omega/2\omega_m),\end{aligned} \tag{6}$$

where 'rect' and '$*$' denote the rectangular function and the convolution operation, respectively. This expression defines the measured group delay as the convolution of the group delay of the component and the instrument function of the phase-shift technique. The instrument function can be identified as a rectangular function of width $2\omega_m$.

4. Effect of modulation frequency on the measured group delay ripple of fiber Bragg gratings

The effect of the modulation frequency on the measurement result for arbitrarily shaped group delay profiles can be investigated simply by inserting their Fourier transform into Eq. (6). For components such as chirped FBGs, the variation of the group delay with wavelength is periodic. In the following we assume the functional form of the dependence of the delay on frequency to be locally sinusoidal of the form [15,16]:

$$\tau(\omega) = A\cdot\sin\left(\frac{\omega}{p}\right). \tag{7}$$

Here A represents the amplitude and p the period of the group delay. When such a group delay is analyzed using the phase-shift method the measured amplitude of the ripple as a function of the modulation frequency is then [13]

$$A_{meas} = A\cdot \mathrm{sinc}\left(\frac{\omega_m}{p}\right). \tag{8}$$

This expression can be directly derived from Eq. (6), by relating the variable u to the period of the ripple as $u = 1/p$.

Eq. (8) shows that the amplitude of the measured sinusoidally varying group delay decreases with the modulation frequency. A ratio between the modulation frequency ω_m and the ripple period p of more than 2 will induce an attenuation of the measured amplitude of at least 50%. Furthermore, the ripple cannot be distinguished if the modulation frequency corresponds to a multiple of half the ripple period. Moreover, as illustrated in Fig. 2, a phase shift of π in the measured ripple is observed when the ratio of the modulation frequency to the ripple period lies within $(2k-1)\pi$ and $2k\pi$,

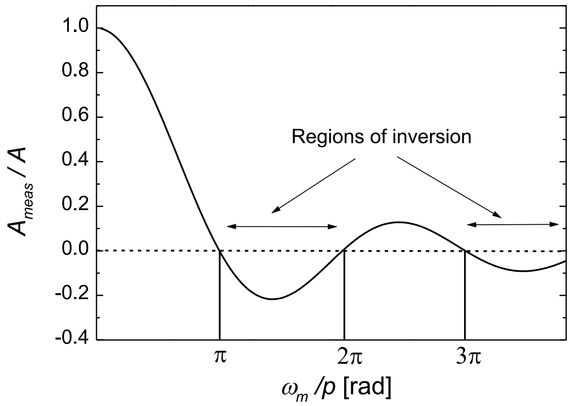

Fig. 2. Normalized amplitude of the measured ripple as a function of ω_m/p.

where k is an integer number. On the other hand, if the modulation frequency is small compared to the ripple period, then the amplitude of the ripple is close to the actual one.

To experimentally demonstrate the effect of the modulation frequency, we characterized the reflectivity of a linearly chirped FBG. The bandwidth of the grating is $\sim$2 nm and the measured group delay indicates a nominal dispersion of −660 ps/nm. A portion of the measured group delay for four different modulation frequencies by utilizing a wavelength step of 1 pm (125 MHz) is shown in Fig. 3. The wavelength step was chosen to be much smaller than the ripple period in order to resolve the small period variations of the group delay [16]. For clarity an arbitrary offset has been added to each curve. In addition, the wavelength axis has been converted into an optical frequency axis and shifted from the center frequency.

The measured group delay can be decomposed into a sum of sinusoidal ripples with different periods p. These periods can be obtained simply by calculating the Fourier transform of the measured profile. Indeed, peaks in the spectrum appear at particular Fourier frequencies $u = 1/p$. The Fourier frequencies are calculated using fast Fourier-transform algorithms. According to Fig. 2, a Fourier component corresponding to a particular period p is affected differently depending on the value of ω_m. Thus, knowing the values of p, the theoretical effects of using a higher modulation frequency in the measurements can be investigated. As an illustration, we first consider the Fourier transform of the group delay measured at $\omega_m = 2\pi \cdot 250$ MHz. Its normalized Fourier components versus $\omega_m u = \omega_m/p$ are plotted as solid line in the upper part of Fig. 4. For clarity an offset of 1.2 has been added. From this plot, we can easily extract the main period of the ripple shown in Fig. 3. This main period corresponds to the highest peak of the spectrum and can be calculated as

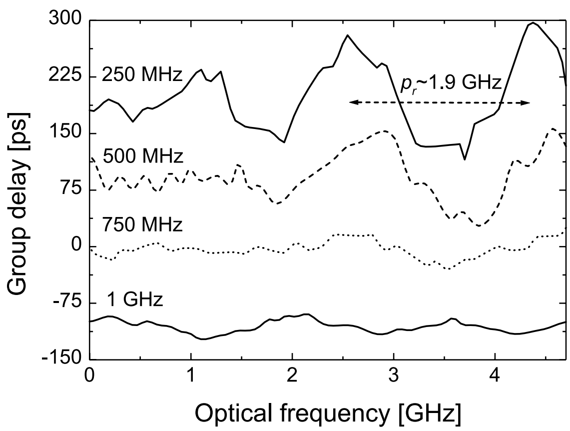

Fig. 3. Traces of the group delay ripple of a fiber Bragg grating for four different modulation frequencies.

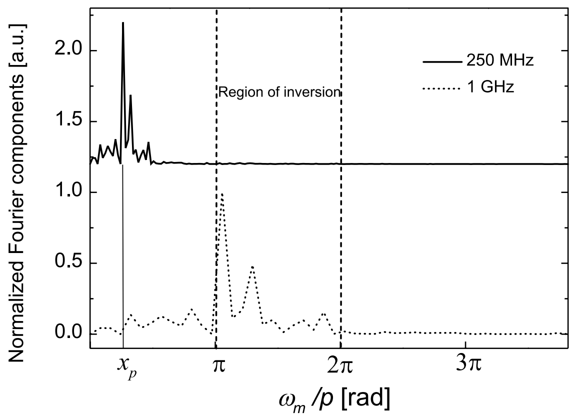

Fig. 4. Fourier spectrum of the measured group delay at 250 MHz versus ω_m/p for two different values of ω_m. The area delimited by the vertical dashed lines represents the region of inversion and attenuation.

$$p_r = \frac{\omega_m}{x_p}, \tag{9}$$

where p_r is the main period of the ripple and x_p the position of the highest peak on the x-axis. By using $\omega_m = 2\pi \cdot 250$ MHz and $x_p \sim 0.83$, we achieved a value of $p_r \sim 1.9$ GHz. A rough estimation of this main period can also be obtained directly from Fig. 3.

The value of the quantity ω_m/p is smaller than 1.5 rad for most of the Fourier components. Therefore, according to Fig. 2 the measured signal has not been significantly altered by the measurement except for the addition of noise. Consequently, we can assimilate this measured group delay to the actual group delay of the FBG. We now investigate the effects of using a modulation frequency of 1 GHz assuming that the Fourier components of the signal measured at 250 MHz can be considered as the actual group delay. For this purpose, the Fourier components of the signal measured at 250 MHz are replotted as dots in the lower part of Fig. 4 versus the quantity ω_m/p with ω_m equal to $2\pi \cdot 1$ GHz. The largest components fall in the region of inversion and attenuation delimited by dashed lines. According to Fig. 2, this means that the amplitude of the measured ripple using $\omega_m = 2\pi \cdot 1$ GHz is decreased and has an opposite sign compared to the actual ripple amplitude, in agreement with the measurements shown in Fig. 3. When using $\omega_m = 2\pi \cdot 500$ MHz and $\omega_m = 2\pi \cdot 750$ MHz for the measurements, the Fourier components of the signal are located before the first zero of the sinc-function and are attenuated as can be observed in Fig. 3.

5. Reconstruction of the group delay

A straightforward way of reconstructing the actual profile of the group delay is to perform deconvolution of Eq. (6). This operation can be conveniently done in the Fourier domain

$$\tau(\omega) = \mathfrak{I}^{-1}\left[\frac{\tau_{\text{meas}}(u)}{\text{sinc}(\omega_m u)}\right]_{\omega}, \tag{10}$$

where $\mathfrak{I}^{-1}$ designates the inverse Fourier transform. However, this operation has unpleasant features: (a) division by zero for some particular values of u; (b) amplification of the Fourier components corresponding to the highest values of u, which leads to an increase of noise in the reconstructed profile.

Due to the convolution operation some of the original information is definitively lost during the measurements and, consequently, this information cannot be retrieved. In particular, the distribution of the Fourier components of the measured signal relatively to the sinc-function will determine which part of the information can be retrieved. If most of the Fourier components are located before the first zero of the sinc-function, the reconstructed profile of the group delay will resemble the actual one. This occurs when low modulation frequencies are used or the group delay varies slowly with wavelength. On the contrary, if the Fourier components of the signal are located after the first zero of the sinc-function the reconstruction is more difficult.

Nevertheless, if careful processing of the measured signal is done, a good estimation of the actual group delay can be obtained. In particular, a numerical low-pass filter can be applied to the measured signal to suppress the high frequency components, which mainly correspond to noise. The cut-off frequency of this filter depends on the distribution of the Fourier component of the measured group delay. A tradeoff should be made to preserve most of the actual Fourier components of the signal and to avoid amplification of noise when dividing by the sinc term. The zero points of the sinc-function must also be removed before carrying out the division.

5.1. Fiber Bragg grating

We have applied the method described above to reconstruct the actual profile of the group delay of the FBG presented earlier. The measurement data obtained for 1 GHz, which represent the worst case since the Fourier components of the signal are then located in the inversion and attenuation region of the sinc-function, were used. To avoid the amplification of the noise when performing the division by the sinc-function, a numerical low-pass filter was applied. The normalized Fourier spectrum of the 1-GHz measurement and the cut-off frequency, ω_c, of the numerical low-pass filter are shown in Fig. 5. The spectrum shown in Fig. 5 is directly obtained from the measurement at 1 GHz and, consequently, is distorted by the sinc-function compared to the spectrum shown in the lower part of Fig. 4.

The reconstructed profile from the data measured at 1 GHz is plotted as dots in Fig. 6 and it is in good agreement with the actual group delay marked with a solid line. The reconstruction method allows to overcome the decrease and inversion of sign induced on the ripple amplitude by the use of high modulation frequencies. The smoothness of the profile is caused by the low-pass filtering operation.

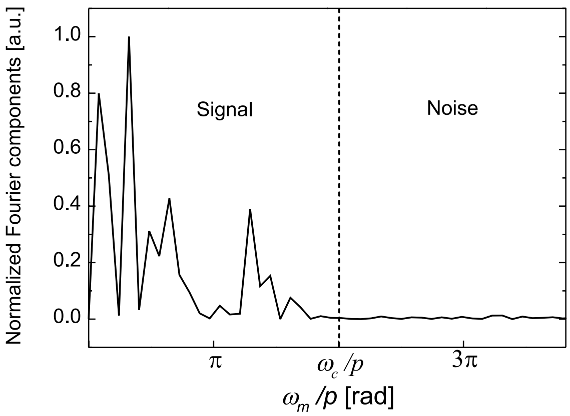

Fig. 5. Fourier spectrum of the measured group delay at 1 GHz versus ω_m/p. The vertical dashed line represents the cut-off frequency of the filter applied. The cut-off frequency of the numerical filter was chosen so that $\omega_c/p = 2\pi$.

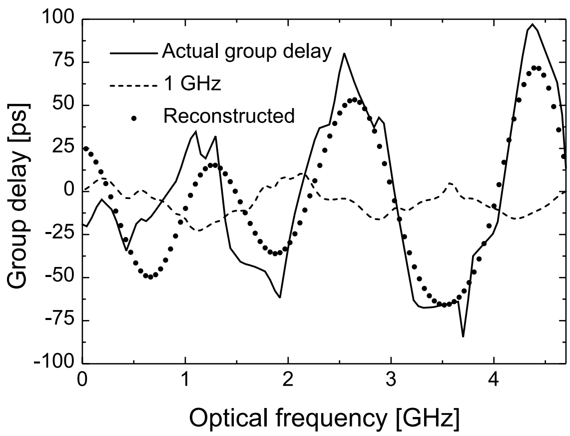

Fig. 6. Reconstruction of the actual group delay of a fiber Bragg grating using the data measured at 1 GHz. The measured data and the actual profile are also plotted.

5.2. Narrow-band filter

We have also investigated the effects of the modulation frequency on the group delay of a filter based on thin films through numerical simulations. A stack of $\lambda/4$-thick layers forms the mirrors and three $\lambda/2$-layers form the cavities of the filter. One example of the structure of the thin-film stack can be presented as: [Glass $(HL)^9$ H 2L $(HL)^{19}$ H 2L $(HL)^{19}$ H 2L $(HL)^9$ H Glass]. Here H presents the film having a high refractive index $(\eta_H = 2.1)$ and L presents the film having a low refractive index $(\eta_L) = 1.43)$. The transmission and group delay of the filter were calculated using a matrix method [16]. The method gives a complex reflectivity and transmissivity of the optical field through the thin-film stack. The group delay and the dispersion of the filter can then be calculated from the phase of these complex coefficients. The −3-dB bandwidth of the modeled bandpass filter is ~25 GHz. One half of the calculated symmetrical group delay is depicted in Fig. 7 with a solid line. The corresponding transmission spectrum is also plotted in the same figure as a dashed line.

A simulation model of the phase-shift setup was applied to obtain measurement results. The model was built with the commercial simulation tool

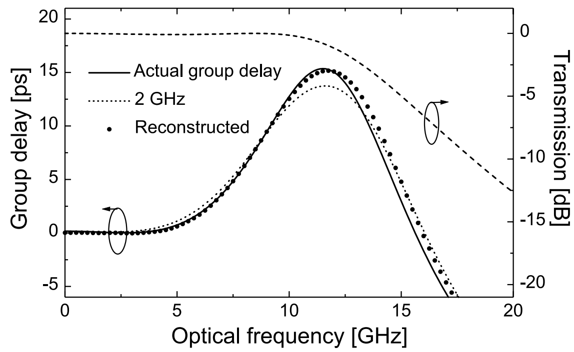

Fig. 7. Reconstruction of the group delay of a narrow-band thin-film filter. The transmission spectrum of the filter is plotted as a dashed line.

GOLD [17]. The simulated setup was similar to the one used for experimental measurements (see Fig. 1). The simulation program allows for a fast and simple way of testing the effect of different parameters, such as modulation frequency, on the measured value of the group delay. The simulation was executed for a modulation frequency of 2 GHz and a wavelength step of 125 MHz. The modulation frequency was selected to match the modulation frequency of commercially available measurement systems. The measured group delay obtained from the simulation program is shown in Fig. 7 as a dotted line. A decrease in the measured delay near the sharp peak is observed.

To reconstruct the group delay of the component, the method described previously was used. After the reconstruction the height of the peaks in the original group delay was restored. However, the reconstruction is not perfect near the edges of the filter where the transmission of the component starts to fall off. This is due to the fact that the phase-shift technique does not measure exactly the group delay if the transmission exhibits large variations within the bandwidth of the sinusoidally modulated signal. The reconstruction of the group delay for this type of a filter is more straightforward since most of the Fourier components of the group delay are located before the first zero and the inversion region of the sinc-function for the selected modulation frequency. Since the group delay values were obtained through numerical simulations, it was not necessary to low-pass filter the results.

6. Conclusions

In this paper, we have presented a novel method capable of improving the accuracy of measurements of group delays performed utilizing the conventional phase-shift technique. Access to the actual value of the group delay is obtained by performing a deconvolution of the measured data with the instrument function of the phase-shift technique. Considerable improvement of the accuracy may be achieved, especially, when high modulation frequencies are employed in order to attain good timing resolution. Furthermore, the method is applicable to any arbitrary group delay profile. Low-pass filtering of the measured data may be necessary to improve the efficiency of the method.

We have also demonstrated that the instrument function can be used to explain the observed modulation-frequency dependent effects on the group delay. These effects include degradation of the magnitude of the delay with high modulation frequencies and inversion of the sign of the amplitude.

As an example, we have applied the method to estimate the error emerging in group delay measurements performed on a chirped FBG using the phase-shift technique. The error can be evaluated by calculating the ratio between the period of the fluctuation of the ripple and the modulation frequency. As a rule of thumb if the modulation frequency is higher than one-third of the period of the ripple, then the decrease in the measured amplitude of the ripple will be more than 50%. We have also employed the method to reconstruct the group delay of a chirped FBG exhibiting large ripple. The amplitude of the ripple in the actual delay was accurately reproduced.

Furthermore, we have investigated the effect of the modulation frequency on the group delay of a narrow-band filter through numerical simulations. It was observed that the measured group delay at the edges of the filter transmission spectrum was reduced when a high modulation frequency was used. By applying our method, the amplitude of the original delay variation could also in this case be accurately reproduced.

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