Limitations of Phase-Shift Method in Measuring Dense Group Delay Ripple of Fiber Bragg Gratings

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Abstract—The phase-shift method is an established technique for measuring the group delay of fiber-optic components. In devices, such as chirped fiber Bragg gratings, the group delay exhibits ripple as a function of wavelength. We have analyzed the dependence of the measured ripple amplitude on the modulation frequency and present a physical model, which gives an analytical formula for estimating the measurement error.

Index Terms—Gratings, optical fiber filters, optical fiber measurement applications, optical filters, optical variables measurement.

I. INTRODUCTION

ACCURATE knowledge of the group delay and amplitude response of various fiber-optic components is essential in optimization of the properties of these devices in the production stage and in designing advanced optical networks. The performance of the optical communication system may degrade if the properties of the optical filters are inadequate. The group delay of an optical device can be measured using interferometric methods [1], [2] or various modulation phase-shift techniques [3], [4]. The phase-shift method is an established technique for performing high-accuracy measurements. It has traditionally been used to determine the dispersion of an optical fiber, which can be derived from the measured group delay by differentiation with wavelength. Nowadays, the method is also employed for characterization of optical filters such as fiber Bragg gratings (FBGs). The group delay of chirped FBG often shows significant fluctuations with optical wavelength known as group delay ripple. It typically originates from interference effects caused by imperfections in the production of the grating. The group delay ripple seriously limits the utilization of these components as dispersion compensating elements [5].

When the phase-shift method is used to characterize the group delay of chirped FBGs, the measured value has been found to depend on the modulation frequency at high frequencies [6], [7]. Attempts have been made to overcome this problem by modifying the standard phase-shift method [8].

In this letter, we investigate the effect of the modulation frequency on the measured group delay ripple of a chirped FBG.

A simple physical model of the phase-shift measurement setup was applied to develop an analytical formula for predicting the accuracy of the measured group delay values. Experimental measurements and simulations show that careful selection of the modulation frequency is essential for obtaining accurate results.

II. GROUP DELAY MEASUREMENTS

Our experimental setup for characterization of FBGs is based on the standard phase-shift technique. The light source is a narrow linewidth wavelength-tunable laser (Photonetics TU-NICS-PRI), whose wavelength is monitored with a wavemeter (HP 86 120B). The laser is modulated externally to produce a sinusoidal signal. The optical signal is divided into a reference path and the path including the component under test. They are detected, electrically amplified, and 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 relative group delay $\tau_{GD}(\nu_0)$ of the component at the optical carrier frequency ν_0 and the measured electrical phase shift $\theta(\nu_0)$ of the intensity modulated signal are related by the well-known equation

$$\tau_{GD}(\nu_0) = \frac{\theta(\nu_0)}{2\pi f_m} \tag{1}$$

where f_m is the modulation frequency. 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 with a higher modulation frequency. The devices conventionally used for phase determination are vector voltmeters or network analyzers, which typically have a phase resolution of $\sim 0.1°$. This allows for subpicosecond resolution in the group delay measurement. We have tested the stability and the resolution using a fiber-optic beam expander with a variable air gap. The results indicate that a group delay resolution of $\sim > 1$ ps can reliably be obtained with our experimental setup.

We have applied the setup to characterize the reflectivity of a 20-cm long linearly chirped FBG. The bandwidth of the grating is ~ 2 nm and the measured group delay indicates a nominal dispersion of -660 ps/nm. A portion of the measured group delay for three modulation frequencies is shown in Fig. 1. We used a wavelength step of 1 pm (125 MHz), which is the smallest that can be achieved with our tunable laser. Each curve is an average of five measurements.
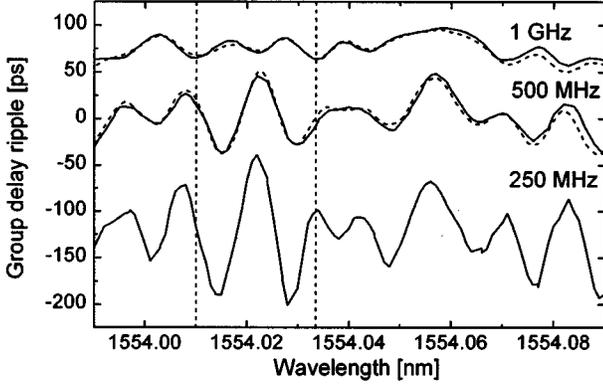
Fig. 1. Traces of the group delay ripple measured with three different modulation frequencies (solid lines). Simulations confirm the measured data (dashed lines).

Fig. 2. Variation of the group delay and the modulated signal in the model of the measurement system.

In the wavelength range between 1554.01–1554.033 nm, the group delay has approximately one and a half period of almost sinusoidal ripple. Our investigation is concentrated to this portion of the group delay. The period of this ripple is ~1.9 GHz and its peak-to-peak amplitude is ~150 ps for a modulation frequency of 250 MHz. The ripple amplitude decreases significantly as the modulation frequency is increased to 500 MHz and 1 GHz. Note that the ripple measured for the modulation frequency of 1 GHz is both decreased and inverted compared to the measurements performed using lower modulation frequencies. The effects of polarization were investigated by placing a polarization controller before the grating and performing several measurements with different settings of the controller. The variation between the measurement results was found to be negligible.

To confirm the group delay values measured at higher frequencies, we used the data measured with a modulation frequency of 250 MHz to build a numerical simulation model of the measurement setup. The model was built with the commercial simulation tool GOLD [8]. The simulated traces for the modulation frequencies of 500 MHz and 1 GHz are included in Fig. 1 as dashed lines. The agreement between the simulated and measured traces is good.

III. ANALYSIS

To explain the observed inversion of the sign of amplitude and to estimate the error for the measured amplitude of the ripple, we developed a simple model of the measurement. The relation between the optical phase response of the component $\phi(\omega)$ and its group delay τ_{GD} is given by $\tau_{GD} = d\phi(\omega)/d\omega$. The group delay is usually approximated to have a constant value in a narrowband near the optical carrier [4]. In this case, the optical phase shift for the two intensity modulation induced sidebands is given by

$$\phi(\nu_0 \pm f_m) = \pm 2\pi \tau_{GD}(\nu_0) f_m \qquad (2)$$

where $\tau_{GD}(\nu_0)$ is the approximated value of the group delay at the optical carrier frequency. The measured electrical phase shift between the detected signals can be related to the optical phase
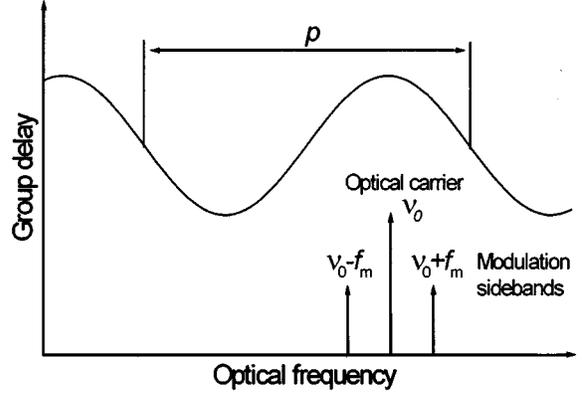
shift as $\theta(\nu_0) = (\phi^+ - \phi^-)/2$, which leads to (1). This approximation gives accurate results when the variation of the group delay is small with wavelength as in an optical fiber. However, for components in which the group delay fluctuation is large within the bandwidth of the optical signal, this is not necessarily true. In our model, we assume that the group delay of the component varies sinusoidally. The model of the group delay and the optical carrier with modulation induced sidebands are displayed in Fig. 2.

The sinusoidal group delay variation can be written as

$$\tau(\nu_0) = A_p \sin\left(2\pi \frac{\nu_0}{p}\right) \qquad (3)$$

where A_p is the peak amplitude of the ripple and p indicates the period of the ripple. We also assume that the optical carrier is located at the peak of the ripple. The amplitude of the measured sinusoidal ripple as a function of the modulation frequency is then

$$A(f_m) = A_p \text{sinc}\left(2\pi \frac{f_m}{p}\right). \qquad (4)$$

This equation can be applied for ripple with an arbitrary amplitude and period by analyzing the Fourier components of the measured group delay [10]. The model shows that the amplitude of the sinusoidal ripple is zero if the modulation frequency is a multiple of a half of the ripple period. An inversion of the measured ripple amplitude can be observed when the modulation frequency is between half and full period of the ripple. A comparison between the modeled and the measured ripple amplitudes is given in Fig. 3. The solid line plots (4) with $p = 1.9$ GHz and the solid squares are the measured ripple amplitudes. The error bars indicate the maximum variation of the amplitude between the five successive measurements. The amplitudes obtained with the numerical simulations are presented as open circles. The overall agreement between both the measured and simulated ripple amplitudes and the analytical model is good.

The model predicts that the amplitude of the ripple is inverted for modulation frequency values ranging from 0.95 to 1.9 GHz. This behavior was verified both with measurements using a modulation frequency of 1 GHz and with simulations for frequencies up to 2 GHz. When modulation frequencies higher than 1 GHz were used in the simulations the structure of the
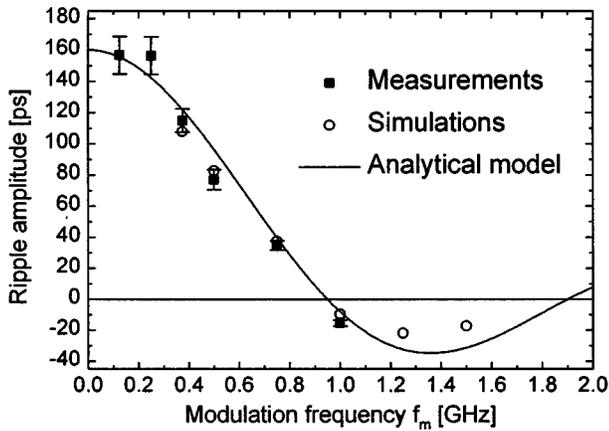
Fig. 3. Comparison between the model and the measured group delay amplitude.

ripple was not any more sinusoidal with a well-defined amplitude. The analytical model allows a convenient means to estimate the accuracy of the measurement results.

IV. DISCUSSION

We have analyzed the effect of the modulation frequency on the amplitude of the group delay ripple of a linearly chirped FBG. Assuming the variations of the ripple amplitude to be sinusoidal, an analytical model was developed to estimate the measurement error. The model predicts that the amplitude of the ripple falls off as a sinc function with the modulation frequency. We found that if the modulation frequency is more than 0.3 times the ripple period, the decrease in the measured amplitude of the ripple will be more than 50%. Group delay ripple in gratings is not necessarily sinusoidal and it may vary with the grating parameters [11]–[13]. However, the model developed in our work is not restricted to purely sinusoidal ripple, but can be extended to cover group delays with an arbitrary amplitude and period by dividing them into Fourier components and analyzing them separately. In general, if the step size or the mod-

ulation frequency is larger by more than half of the period of the ripple, the amplitude of the ripple will in practice vanish. Accurate verification of the ripple is important since it degrades the performance of dispersion compensated systems applying chirped Bragg gratings. We believe that the results of this work can be applied in development of accurate standardized measurement procedures for chirped gratings.

REFERENCES

[1] M. Volanthen, H. Geiger, M. J. Cole, R. I. Laming, and J. P. Dakin, "Low coherence technique to characterize reflectivity and time delay as a function of wavelength within a long fiber grating," *Electron. Lett.*, vol. 32, pp. 757–758, 1996.

[2] S. D. Dyer and K. B. Rochford, "Low-coherence interferometric measurements of fiber Bragg grating dispersion," *Electron. Lett.*, vol. 35, pp. 1485–1486, 1999.

[3] M. L. Rocha and R. Kashyap, "Characterization of fiber Bragg gratings: A study on accuracy and repeatability," in *Dig. 4th Optical Fiber Measurement Conf.*, Teddington, U.K., 1997, pp. 14–17.

[4] S. Ryu, Y. Horiuchi, and K. Mochizuki, "Novel chromatic dispersion measurement method over continuous gigahertz tuning range," *J. Lightwave Technol.*, vol. 7, pp. 1177–1180, Aug. 1989.

[5] C. Clark, M. Farries, K. Visvanatha, and A. Tager, "Measuring chromatic dispersion of fiber gratings," *Lightwave*, vol. 17, pp. 70–77, Feb. 1999.

[6] Y. Li, D. Way, N. Robinson, and S. Liu, "Impact of dispersion compensation gratings on OC-192 systems," in *Conf. Optical Amplifiers and Their Applications*, Monterey, CA, 1998, paper TuB5.

[7] K. Enneser, M. Ibsen, M. Durkin, M. N. Zervas, and R. I. Laming, "Influence of nonideal chirped fiber grating characteristics on dispersion cancellation," *IEEE Photon. Technol. Lett.*, vol. 10, pp. 1476–1478, Oct. 1998.

[8] *Gigabit Optical Link Designer (GOLD), Users Manual*, Virtual Photonics Pty. LTD, 1999.

[9] R. Fortenberry, "Enhanced wavelength resolution chromatic dispersion measurements using fixed sideband technique," presented at the *Optical Fiber Communications Conf.*, Baltimore, MD, 2000, TuG8, pp. 107–109.

[10] T. Niemi, G. Genty, and H. Ludvigsen, "Group delay measurements using the phase-shift method: Improvement of the accuracy," in *Eur. Conf. Optical Communications 2001*, Paper Th. M. 1. 5.

[11] R. Kashyap and M. L. Rocha, "On the group delay characteristics of chirped fiber Bragg gratings," *Opt. Communications*, vol. 153, pp. 19–22, 1998.

[12] R. Kashyap, *Fiber Bragg Gratings*. San Diego, CA: Academic, 1999.

[13] L. Poladian, "Understanding profile-induced group-delay ripple in Bragg gratings," *Appl. Opt.*, vol. 39, pp. 1920–1923, 2000.