# Phase response measurement technique for waveguide grating filters

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A simple interferometric technique is described which can be used to accurately measure the phase response of waveguide grating filters. A narrowband, tunable Ti:sapphire laser is used in a Michelson interferometer configuration, where light reflected from a waveguide grating filter is combined with a reference beam. The intensity of the combined beams is measured as the wavelength of the Ti:sapphire laser is tuned. The measured intensity exhibits a quasisinusoidal wavelength dependence, from which the phase response of the filter can be deduced. This method is successfully demonstrated using both an integrated optic waveguide grating filter and a bulk grating pair. 

The recent emergence of many integrated and fiber optical devices has led to an increased interest in waveguide grating filters. These filters most often consist of structures which are photoimprinted in photosensitive fibers, or of surface corrugations which are etched into planar waveguides. Presently, most devices are reflective, where the periodicity of the grating allows selective coupling between the forward and backward propagating modes in a waveguide. Such devices have been used as reflectors for distributed feedback (DFB) and distributed Bragg reflector (DBR) lasers,[1,2] narrow bandstop filters,[3] and sensors.[4] Recently, there has also been much interest in modeling and fabricating dispersion compensating filters to counteract the chromatic dispersion encountered by pulses propagating through fiber communication systems.[5,6] These filters employ chirped gratings, and exhibit a phase response which is a quadratic function of frequency.

It is essential to measure both the amplitude and phase response of these waveguide grating filters in order to obtain a complete characterization of the device. The amplitude response is easily measured using either a narrowband, tunable source or a white light source in conjunction with a high resolution monochromator. Phase measurements are considerably more difficult, however, and only a few of such measurements have been reported.[5–7] In Ref. 5, a tunable laser was modulated by a sinusoidal signal at a fixed microwave frequency. The signal reflected from the filter experiences a time delay $\tau_d$, which can be measured using a network analyzer. The time delay is approximately given by

$$\tau_d(\omega_c) = -\left.\frac{d\phi(\omega)}{d\omega}\right|_{\omega=\omega_c}, \tag{1}$$

where $\omega_c$ is the laser frequency and $\phi(\omega)$ is the phase response of the waveguide grating filter. This method was used to determine the dispersion characteristics of a fiber-optic chirped grating filter.

In the past, interferometric techniques have been used to measure the phase delay of optical fibers as a function of wavelength,[8,9] in an effort to determine the chromatic dispersion. In most of these techniques, a broadband optical source is used in conjunction with a Mach–Zehnder interferometer and a high resolution monochromator. The fiber is placed in one arm of the interferometer and the other arm serves as a reference path. The beams from the two paths are combined and filtered by the monochromator, after which a detector measures the power of the interfering beams. As the monochromator is tuned, power values are collected at wavelengths spanning the band of interest. The phase delay of the fiber is easily computed from these measured power values. Yao and Feinberg[10] modified this basic technique by using a pulsed source instead of broadband cw source. In addition, they used their method to measure the dispersion of bulk grating pairs. In this letter, we describe a modified interferometric technique, validate its accuracy, and use it to measure the phase response of a chirped waveguide grating filter.

The experimental setup for the phase measurement is shown in Fig. 1. A Michelson interferometer was built to interfere light reflected from a waveguide grating filter with light from a reference path. A tunable, narrow-linewidth (<1 GHz), ring Ti:sapphire laser operating in the 800 nm range was used as the light source. The reference and signal beams were aligned in order to image a small portion of a single fringe of the interfering pattern onto a detector using a mi-

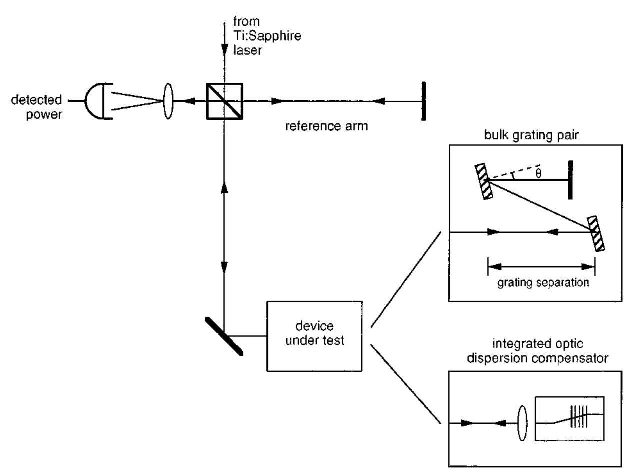


FIG. 1. Experimental setup of the phase response measurement technique.

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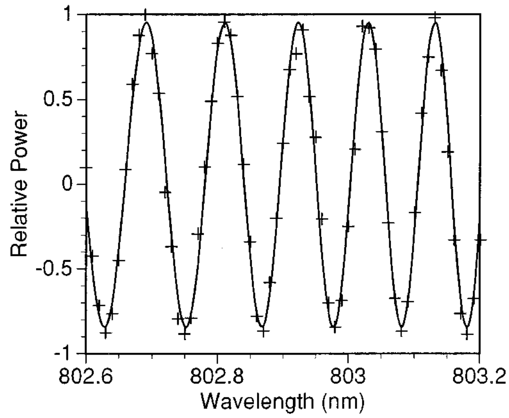


FIG. 2. Typical data for dispersion measurement of bulk grating pair.

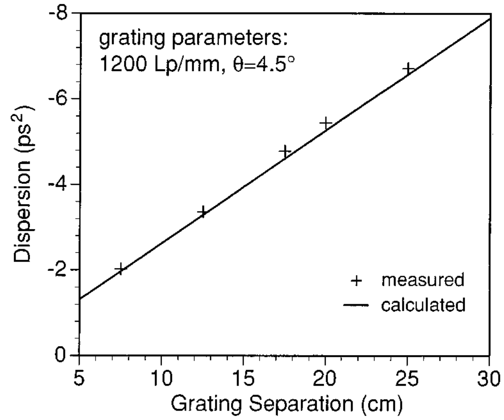


FIG. 3. Dispersion of bulk grating pairs as a function of grating separation.

croscope objective. The detected power, $P(\lambda)$, was measured using a lock-in amplifier as the wavelength $\lambda$ of the laser was tuned. A shutter placed in the reference arm also enabled the power reflected from the filter, $P_1(\lambda)$ (closed shutter), to be measured as the wavelength was tuned. The detected power can be described by

$$P(\lambda)=P_0+P_1(\lambda)+2\alpha\sqrt{P_0P_1(\lambda)}\cos[\phi(\lambda)]. \tag{2}$$

Here, $P_0$ is the reference beam power and $\phi(\lambda)$ is the phase difference between the beam reflected from the device and the reference beam. The constant, $\alpha<1$, appears in the expression because the detector collects power over some finite region of a single fringe. Larger collection regions will result in more averaging, and hence smaller $\alpha$ values.

In order to verify the accuracy of this phase measurement method, it was applied to a bulk grating pair, whose dispersion, $d^2\phi/d\omega^2$, can be easily calculated analytically.[11] The expression for the dispersion of a two-pass grating pair is

$$\frac{d^2\phi}{d\omega^2}=-\frac{\lambda^3 d}{\pi c^2\Lambda^2[1-(\sin\,\theta-\lambda/\Lambda)^2]^{3/2}}, \tag{3}$$

where $d$ is the perpendicular grating-to-grating separation, $\Lambda$ is the grating period, $\theta$ is the angle of incidence measured with respect to the grating normal, and $c$ is the vacuum speed of light.

A pair of identical gratings (1200 line pairs/mm) was placed parallel to each other at $\theta=4.5°$ in one arm of the interferometer as shown in Fig. 1. $P_0$, $P(\lambda)$, and $P_1(\lambda)$ were measured, and the quantity

$$Q(\lambda)=\frac{P(\lambda)-P_0-P_1(\lambda)}{2\sqrt{P_0P_1(\lambda)}} \tag{4}$$

was computed. A least squares fit of the form

$$A\,\cos(a_0+a_1\lambda+a_2\lambda^2) \tag{5}$$

was then made to the collected data, $Q(\lambda)$. Figure 2 shows some typical experimental data together with the corresponding fit. In order to facilitate the fitting process, the path length of the reference arm was adjusted so that $P(\lambda)$ passed through approximately a dozen maximum and minimum as the laser was tuned over a 0.5 nm range. The dispersion of the grating pair can be determined from the fit coefficient $a_2$,

$$\frac{d^2\phi}{d\omega^2}=\frac{\lambda^4 a_2}{2\pi^2c^2}. \tag{6}$$

The dispersion corresponding to the fit shown in Fig. 2 is 3.36 $ps^2$. Using the above procedure, dispersion values were measured for five different grating separations $d$ and the results are plotted in Fig. 3. Also shown are the calculated values given by Eq. (3). The measured and computed values agree to within 5%.

The above technique was used to measure the phase response of waveguide grating filters. Waveguide grating filters in optical fibers and planar waveguides can be either of the photoimprinted or surface relief type. In both cases, however, the grating gives rise to a periodic perturbation of the guide's effective index $N(z)$ of the following form

$$N(z)=N_0+\Delta N(z)\cos\left(\frac{2\pi}{\Lambda_0}z+\theta(z)\right). \tag{7}$$

Here, $N_0$ is the nominal effective index of the waveguide, $\Lambda_0$ is the nominal grating period, $\Delta N(z)$ is the magnitude of the effective index perturbation, and $\theta(z)$ is a phase dependence. The phase and magnitude response of the grating filter described by Eq. (7) can be determined by numerically integrating the standard coupled mode equations.[12] The phase response of this filter can be approximated by

$$b_0+b_1\lambda+b_2\lambda^2, \tag{8}$$

provided $\lambda\approx\lambda_0$, where $\lambda_0$ is the Bragg wavelength corresponding to a grating period of $\Lambda_0$, and $b_0$, $b_1$, and $b_2$ are constants.

Waveguide grating filters have been designed to compensate for the chromatic dispersion in fiber optical communication systems.[5,6] These filters require a phase response which is a quadratic function of frequency. Ouellette has shown, theoretically, that such devices can be realized by using gratings whose periods are linearly chirped along the length of the waveguide.[13] We implemented a chirped grating by etching a uniform grating (period $\Lambda_0$) onto a curved ion-exchanged glass waveguide.[6] The curve shape,

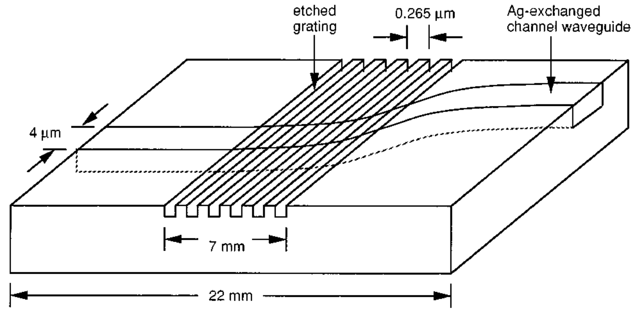


FIG. 4. Schematic diagram of integrated optic dispersion compensator.

$$y(z)=\frac{2}{3}z^{3/2}\sqrt{\frac{C\Lambda_0}{\pi}}, \tag{9}$$

was chosen to yield a linearly chirped grating with $\theta(z)=-Cz^2$. A schematic diagram of our fabricated device is shown in Fig. 4. A value of approximately 4.6 $mm^{-2}$ was chosen for $C$. The expected phase response of our filter was computed using coupled mode theory, and a least squares fit of the form given by Eq. (8) was performed. The phase response, together with the residual fit error, is shown in Fig. 5.

The waveguide grating filter was placed in one arm of the Michelson interferometer shown in Fig. 1. $P_0$, $P_1(\lambda)$, and $P(\lambda)$ were measured. A least squares fit of the quasisinusoidal expression given by Eq. (5) was then made to $Q(\lambda)$ as described earlier. A good fit is obtained as shown in Fig. 6. Furthermore, the quadratic coefficient, $a_2=88.6\ nm^{-2}$, in this fit is within 5% of the calculated value, $b_2=93.0\ nm^{-2}$. This $a_2$ value corresponds to a measured dispersion of 20.4 $ps^2$.

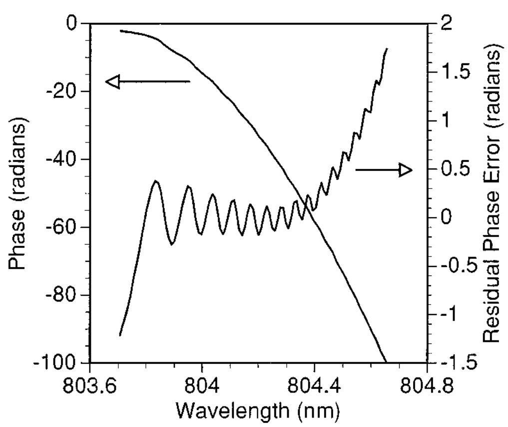


FIG. 5. Theoretical phase response and residual phase error of dispersion compensator.

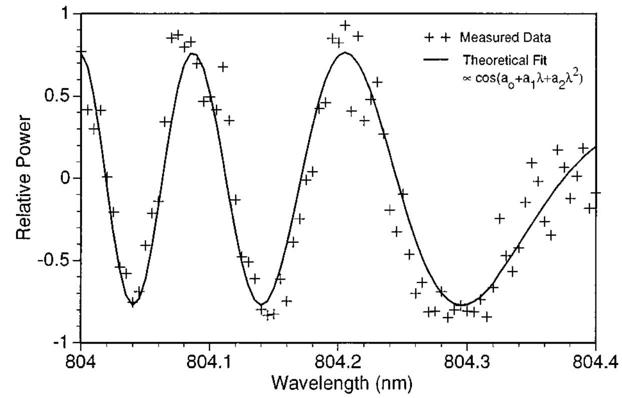


FIG. 6. Phase response measurement of integrated optic dispersion compensator.

In summary, an interferometric technique for measuring the phase response of waveguide grating filters has been devised. The method was successfully tested on bulk grating pairs, and then applied to an integrated optic dispersion compensator, whose dispersion was accurately measured. The measurement technique is simple and could be applied to completely characterize a variety of fiber and integrated optic waveguide grating filters.

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