Measurement of the group delay of laser mirrors by a Fabry–Perot interferometer

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The group delay of multilayer laser mirrors was measured by determining the spectral position of transmission maxima of a Fabry–Perot interferometer formed by the mirrors to be characterized. By optimizing the spacer thickness, we obtained an accuracy of the group-delay measurement of better than 0.23 fs. To our knowledge, this is the most precise direct measuring method reported. © 1995 Optical Society of America

As became known in the early days of femtosecond lasers[1,2] and was analyzed recently,[3] the group-delay dispersion (GDD) of multilayer mirrors has an effect on the duration and the phase structure of ultrashort pulses. On one hand, this means that proper care should be taken when one selects multilayer laser mirrors for intracavity applications and for beam-steering purposes. On the other hand, specially designed high-reflectivity laser mirrors have proved to be good candidates for controlling both intracavity and extracavity GDD in femtosecond lasers.[4–7] The recently generated transform-limited pulse in a mirror-dispersion-controlled Ti:sapphire laser is as short as 8 fs.[8] To construct such a high-performance laser, it is essential to have precise knowledge of the expected phase shift versus frequency.[9–12] In this Letter we present a very accurate, simple, and fairly inexpensive experimental technique for measuring the group delay of multilayer laser mirrors over a wide spectral range.

Let us take a dielectric mirror that shifts the phase of the reflected light by $\phi(\omega)$. If such mirrors form part of a Fabry–Perot interferometer (FPI) with a vacuum spacer of thickness h, then the condition of maximum transmission at a certain frequency depends on $\phi(\omega)$ and is written in general form as

$$\delta(\omega) = 2\left[\frac{h\cos\alpha}{c}\,\omega + \phi(\omega)\right] = 2\pi i\,, \tag{1}$$

where i is the order of interference, α is the angle of incidence, and c is the velocity of light in vacuum. Thus from the spectral positions of neighboring transmission maxima the phase shift and the group delay τ of the mirror can uniquely be derived as

$$\tau(\omega_{i,i-1}) = \frac{\mathrm{d}\phi}{\mathrm{d}\omega}\bigg|_{\omega_{i,i-1}} \approx \frac{\phi(\omega_i) - \phi(\omega_{i-1})}{\omega_i - \omega_{i-1}} = -\frac{h\cos\alpha}{c} + \frac{\lambda_i\lambda_{i-1}}{2c(\lambda_i - \lambda_{i-1})}\,, \tag{2}$$

where $\omega_{i,i-1} = (\omega_i + \omega_{i-1})/2$. In practice usually the wavelength is measured, so the quantities derived in frequency are expressed in wavelength.

Because this method is based on multiple-beam interference rather than on two-beam interference,[12] it is expected to be more accurate the sharper the resonance is. In practice the resonance sharpness of a FPI, however, is affected by the possible fluctuation of the spacer thickness that is due to slight thermal and mechanical instability. An experimental resolution of this problem is that the whole spectrum of interest is recorded at the same time within a few seconds.

The precision achievable with a FPI is therefore determined by the error $\Delta\lambda$ in the wavelength measurement. This $\Delta\lambda$ can be thought of as the exact position of a transmission maximum not measurable above a certain intensity level T_L (Fig. 1). From the well-known formula

$$T(\omega) = \frac{(1-R)^2}{(1-R)^2 + 4R\,\sin^2[\delta(\omega)/2]} \tag{3}$$

of the transmission of a FPI consisting of two identical mirrors with reflectivity R, besides the frequency, we find that $\Delta\lambda$ is affected by R and the spacer thickness h in $\delta(\omega)$ [Eq. (1)]. The effect of R on $\Delta\lambda$ is quite clear: the method works better if mirrors with higher reflectivity are to be characterized. Throughout this Letter we assume that the reflectivities of two neighboring maxima are just slightly different from each other.

The effect of h, however, is more complicated. On one hand, the increase of the spacer thickness results in a smaller free spectral range. Consequently the numerical error of group delay $\Delta\tau_n$, which originates from approximating the tangent of $\phi(\omega)$ at $(\omega_i + \omega_{i-1})/2$ by the difference between $\phi(\omega_i)$ and $\phi(\omega_{i-1})$ in relation (2), defined as

$$\Delta\tau_n = \frac{\mathrm{d}\phi(\omega)}{\mathrm{d}\omega}\bigg|_{\omega_{i,i-1}} - \frac{\phi(\omega_i) - \phi(\omega_{i-1})}{\omega_i - \omega_{i-1}}\,, \tag{4}$$

is smaller. Taking the Taylor series of $\phi(\omega)$ up to third order, we can write this error in the form

$$\Delta\tau_n = \frac{(\pi - \Delta\phi)^2}{24}\,\frac{\mathrm{d}^3\phi(\omega)}{\mathrm{d}\omega^3}\bigg|_{\omega_{i,i-1}}\left(\frac{c}{h'}\right)^2, \tag{5}$$

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