Group-delay measurement on laser mirrors by spectrally resolved white-light interferometry

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The frequency-dependent group delay of dielectric mirrors was measured by spectrally resolved white-light interferometry. Chirped mirrors and thin-film Gires–Tournois interferometers designed for dispersion control in a femtosecond Ti:sapphire laser oscillator–amplifier system were tested with a group-delay resolution of ±0.2 fs and a spectral resolution of ~1 nm over the spectral range of 670–870 nm.

The pulse duration of femtosecond laser oscillator–amplifier systems strongly depends on the frequency-dependent group delay of the optical components utilized.[1] Because all these systems contain dielectric mirrors, precise knowledge of their dispersion is essential. Furthermore, it has been demonstrated that dielectric mirrors with nearly constant second-order[2] and third-order[3,4] dispersion can be designed and manufactured. Recently, a number of studies have been devoted to the problem of group-delay measurement in optical components, e.g., optical glasses, prism pairs, dielectric mirrors, Gires–Tournois interferometers, Ti:sapphire crystals, and birefringent filters.[5–8]

In this Letter we report on a fully automated inexpensive alternative method for fast, accurate determination of the frequency-dependent group delay over a broad spectral range, which is introduced by reflection of light from laser mirrors. The method—previously used for refractive-index measurements of dye solutions[9]—is based on spectrally resolved white-light interferometry.

Figure 1 shows the experimental setup, which is basically a Michelson interferometer illuminated by a white-light source (tungsten halogen lamp). The spatial coherence of the light source in the vertical direction is increased by the horizontal slit S_1. The incoming collimated beam is divided by a beam splitter cube (Spindler & Hoyer No. 33520). We placed a low-dispersion plane gold mirror (M_R) in the reference arm and the plane dielectric mirror (M_S) to be measured in the sample arm (the substrates of the mirrors had a flatness of $\lambda/10$). When one of the mirrors is tilted around a horizontal axis and the other mirror is vertical, horizontal interference fringes (fringes of equal thickness) are generated by each spectral component of the white-light source at the plane of slit S_2. A transmission grating (200 grooves/mm) and an achromatic lens ($f = 50$ mm) are used to create the spectrally dispersed image of a vertical cut (slit S_2) of the superimposed (white-light) interference fringes on the CCD camera (Electrim Corporation EDC-1000, 165 × 196 pixels). The interference patterns corresponding to different wavelengths are linearly dispersed in the horizontal direction depending on the angular dispersion of the transmission grating. To provide a one-to-one correspondence between the horizontal pixel positions and wavelength values, we determined the pixel positions of some spectral lines (697, 852, and 894 nm) of a cesium spectral lamp. Note that pixel position y' is proportional to y, depending on the magnification of the imaging system. The inset of Fig. 1 illustrates a typical spectrally resolved interference pattern when the phase shift on reflection of the sample mirror is a second-order function of the frequency.

In the following, we show how the frequency-dependent group delay of the sample mirror $[\tau_S(\lambda)]$ can be obtained by computer processing of the spectrally resolved interference pattern detected on the CCD camera. Let us consider monochromatic, plane-wave, homogeneous illumination of the interferometer and suppose that the sample mirror is

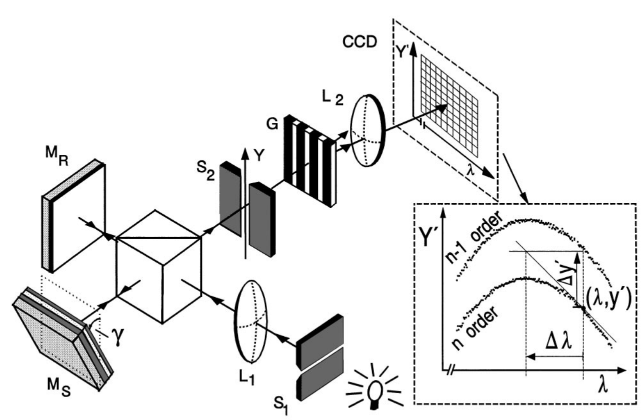

Fig. 1. Spectrally resolved white-light interferometer for group-delay measurement of dielectric mirrors. L_1, L_2, achromatic lenses; S_1, S_2, slits; M_S, sample mirror; M_R, reference mirror; G, transmission grating.

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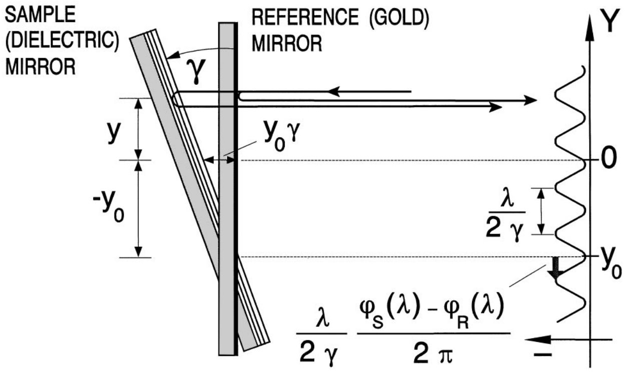

Fig. 2. Formation of interference fringes at the plane of slit S_2.

tilted around a horizontal axis with a small angle γ. The intensity distribution along the Y axis (parallel to slit S_2) is given by

$$I(y,\lambda) = I_S(\lambda) + I_R(\lambda) + 2\sqrt{I_S(\lambda)I_R(\lambda)}\cos[\varphi_{SR}(y,\lambda)], \qquad (1)$$

where I_S and I_R are the intensities reflected from the sample and the reference mirrors, respectively, λ is the wavelength of the monochromatic illumination in air, and $\varphi_{SR}(y,\lambda)$ can be expressed as (see Fig. 2)

$$\varphi_{SR}(y,\lambda) = \varphi_S(\lambda) - \varphi_R(\lambda) + \frac{2\pi}{\lambda}2(y-y_0)\gamma. \qquad (2)$$

In Eq. (2), φ_S, and φ_R are the phase shifts on reflection from the sample and the reference mirrors, respectively, and the third term describes the phase difference originating from tilting (γ) of the sample mirror and displacement ($y_0\gamma$) of the two mirrors. If we substitute Eq. (2) into Eq. (1), the intensity variation along the Y axis is described by a cosine function with periodicity of $\lambda/2\gamma$. The initial phase [$\varphi_{SR}(0,\lambda)$] of the cosine function at a reference position $y = 0$ is determined by two factors: the phase difference between the sample and the reference mirrors ($\varphi_S - \varphi_R$) as well as the phase term originating from the vertical coordinate (y_0) of the virtual intersection line of the mirror surfaces. If one had precise information on the phase shift of the reference mirror and the value of y_0, the phase shift of the sample mirror (φ_S) could be obtained by determining the $\varphi_{SR}(0,\lambda)$ function from any vertical cut of the interference pattern.

Our aim is to derive the frequency-dependent group delay ($\tau_S = \partial\varphi_S/\partial\omega$) of the sample mirror over a broad spectral range. For that purpose, we have to measure $\varphi_{SR}(0,\lambda)$ with high spectral resolution. There are two possible ways to do this when using a white-light source: dispersing the superimposed interference pattern in the plane of S_2 in time or in space. The first approach is rather theoretical since the relative positions of the two mirrors should be kept constant during the tuning of the frequency of the light source. The second way is that shown (and explained above) in Fig. 1, in which the cosinusoidal intensity distributions of all the spectral components are dispersed in space and detected practically at the same time in a CCD camera (in our experiment, an exposure time of 200 ms was used). Note that the spectral resolution depends on the width of slit S_2, the angular dispersion of the grating, the focal length of achromatic lens L_2, and, ultimately, on the spatial resolution of the CCD camera.

To determine the $\varphi_{SR}(0,\lambda)$ function from the recorded spectrally resolved interference pattern, we fitted a cosinusoidal function to the intensity distributions along the Y' axis at each wavelength, whose initial phase is just the $\varphi_{SR}(0,\lambda)$ function to be measured. Variation of the illumination along the Y axis, spectral distribution of the white-light source, and spectral sensitivity of the CCD camera were compensated by normalization of the detected interference pattern. In our experiment a gold mirror having almost constant group delay on reflection (see Ref. 8, Fig. 3d) was used as a reference mirror. Furthermore, $\varphi_{SR}(0,\lambda)$ contains a term that is proportional to ω and cannot be determined since the value of y_0 cannot be measured in practice [see Eq. (2)]. This phase term results in an additive constant group delay. Note, however, that this constant value in the measured group delay of the dielectric mirrors under test has no practical importance in the operation of femtosecond laser systems because it does not affect the pulse shape and it changes the cavity round-trip time only by a small amount. With these uncertainties, the frequency-dependent group delay [$\tau_S(\omega)$] was numerically calculated by polynomial fitting of 10 data points $\varphi_{SR}(0,\omega)$ around ω.

The inset in Fig. 1 presents another simple graphical method for determining the $\tau_S(\omega)$ function,

$$\tau_S(\lambda) = \frac{\lambda}{c\Delta y'}\left[\lambda\frac{\Delta y'}{\Delta\lambda} - (y' - y_0')\right], \qquad (3)$$

when the reference mirror has no phase dispersion. The black dots indicate the pixel positions of the CCD camera corresponding to a phase difference of $(2n+1)\pi$ at different wavelengths. Equation (3) has a simple physical explanation: the first term stands for the measured total group-delay difference between the sample and the reference arms at vertical position y, while the second term originates purely from the relative positions of the two mirror surfaces. This graphical method is very illustrative but not suitable for a precise and automatic determination of the group-delay function.

The experimental setup shown in Fig. 1 can be easily applied for fast visual quality control of dielectric mirrors designed for femtosecond laser systems. When the sample and the reference mirrors are of the same type, one can see a spectrally resolved interference pattern similar to that shown in Fig. 3(a). To record this image, we placed two gold mirrors in the two arms of the interferometer. In an ideal case, the period of the interference fringes in the vertical direction should be proportional to the wavelength. Furthermore, the vertical pixel positions corresponding to the same phase difference, e.g., minima and maxima, should be a linear function of the wavelength [see Eq. (2)]. It can be seen that the fringes in Fig. 3(a) exhibit some degree of

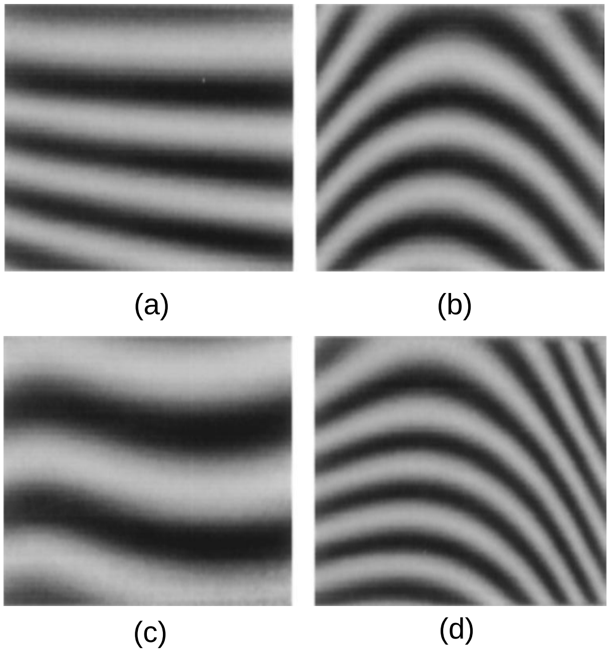

Fig. 3. Interference patterns recorded on a CCD camera with (a) two gold mirrors, (b) a chirped mirror designed for a Ti:sapphire oscillator, (c) a thin-film Gires–Tournois interferometer, (d) a chirped mirror designed for a Ti:sapphire laser amplifier. For recording images (b)–(d), four reflections from the mirrors were used.

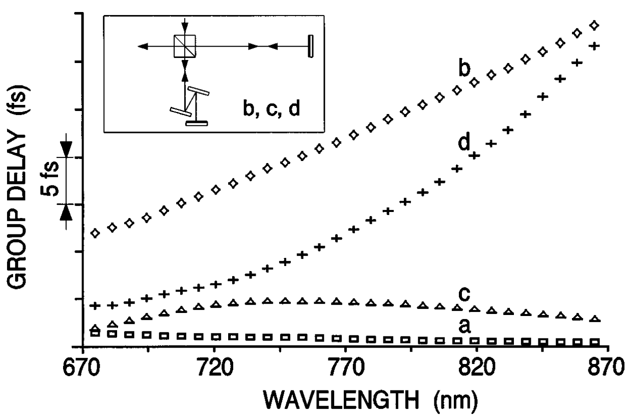

Fig. 4. Measured group-delay functions obtained by computer processing of the images shown in Fig. 3 (every fifth point is plotted). The curves correspond to a single reflection. Inset: four-reflection arrangement used for measuring curves b–d.

curvature. We found that this deviation originates from the beam splitter cube and had to be considered during the group-delay measurements. The accuracy of the measurement on laser mirrors was increased by the use of multiple reflections. We placed an additional pair of dielectric mirrors to be measured on one arm of the interferometer and used four reflections at a small angle of incidence. The interference pattern recorded for a chirped mirror having a nearly constant negative group-delay dispersion[2] is shown in Fig. 3(b). The mirror was designed for full dispersion control in a femtosecond-pulse Ti:sapphire laser.[10] The interference pattern when a pair of resonant thin-film Gires–Tournois interferometers is placed in one arm of the Michelson interferometer is displayed in Fig. 3(c). To show the negative third-order dispersion of the structure, we increased the period of the interference fringes by reducing the tilt angle of the two mirrors. The mirror is designed for a mirror-dispersion-controlled mode-locked Ti:sapphire laser.[10] Figure 3(d) shows the interference pattern recorded for a chirped mirror, which has a negative second-order and superimposed positive third-order dispersion over the spectral range of interest. Combination of these mirrors with prism pairs would permit the independent adjustment of second- and third-order dispersion[11] in a Ti:sapphire laser amplifier system.

In Fig. 4 group-delay functions obtained by computer processing of the images shown in Fig. 3 and numerical differentiation are plotted. There are two sources of error in our measurement: a systematic error originating from the optical path difference in the beam splitter cube, which can be eliminated by measuring the group-delay function of the bare interferometer, and a random-type error that is due to the inaccuracy in the cosine function fitting. We defined the group-delay resolution of our measurement as the random error that we obtained as the run-to-run difference of measured group-delay functions in the case of the bare interferometer.

In conclusion, a fast and inexpensive method for group-delay measurement on femtosecond laser mirrors is reported with a group-delay resolution of ±0.2 fs over a broad spectral range (670–870 nm) with a spectral resolution of 1 nm. This method is well suited for rapid visual quality control of laser mirrors as well.

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