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Interferometric measurements of femtosecond group delay in optical components

Wayne H. Knox, Nathaniel M. Pearson, Kathryn D. Li,* and Charles A. Hirlimann†

AT&T Bell Laboratories, Holmdel, New Jersey 07733

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We report direct measurements of the frequency dependence of the optical group delay for a number of optical components commonly used in femtosecond optics. We have investigated the group-delay errors that occur on reflection from metal and dielectric mirrors under various conditions and passage through devices that introduce angular dispersion. We obtain measurement accuracy of about ±1 fsec over the spectral range of 400–750 nm.

The production of optical pulses of less than 100-fsec duration is routinely accomplished in many laboratories, and lasers based on the colliding-pulse mode-locking (CPM) effect[1] are capable of producing pulses of less than 30-fsec duration.[2] Optical pulse compression has resulted in pulses of 8-fsec duration[3] by using a 7-mm optical fiber and a pair of diffraction gratings for group-delay compensation, and recently 6-fsec pulses have been obtained by the inclusion of Brewster prisms as a further dispersion-compensating devices.[4] Ultrashort optical pulses can be easily distorted and reshaped in undesirable ways in the use of a variety of common optical components such as mirrors and polarizers or by diffractive, refractive, or strongly absorbing elements. In this Letter, we discuss our technique for directly obtaining frequency-dependent group-delay information with 1-fsec accuracy and the applications to some important devices.[5]

When a quasi-monochromatic wave packet of center frequency ω_0 passes through an optical element with group delay $\tau_g(\omega_0)$, it experiences a phase retardation of $\exp[i\omega_0\tau_g(\omega_0)]$. To measure the frequency dependence of the optical group delay $\tau_g(\omega)$ in an optical element over a broad frequency range in the visible, we use a phase- and intensity-compensated Michelson interferometer with a white-light source (Fig. 1). This is essentially identical to that used by Michelson in 1904,[6] and we note that interferometry has been used by a number of researchers for measurements of atomic dispersion and, more recently, for direct measurements of dispersion in optical fibers in the infrared range.[7] The equivalence of the interferometric method and the more conventional time-of-flight technique was shown in this research.[7] A white-light point source (Oriel model 6342) is collimated to within less than 1° divergence by a 5× microscope objective and passed into the interferometer. A beam splitter splits the beam as usual, and a second identical beam splitter acts as a compensation plate to equalize the optical path for the reference arm.[8] We obtain white-light fringes with a FWHM of 5 fsec. After the beams are recombined, they are passed through a tunable interference filter of 10–15-nm bandwidth. The transmitted beam is recorded by a photomultiplier and lock-in amplifier, while the white-light beam is chopped at a 1-kHz frequency. The reference arm is scanned in time delay by a 360,000 step/revolution stepper motor that drives a precision linear translation stage. A step size of 45 nm (corresponding to 0.3-fsec time steps) is used for these measurements. Before measuring the frequency dependence of the group delay in an optical element, the compensation of the interferometer is tested by scanning the reference arm delay for successive transmission wavelengths of the interference filter and recording the intensity pattern obtained at each wavelength. Figure 1 shows the results of scanning the compensated interferometer and after insertion of a 1-mm microscope slide into one arm. The relative group delay for light at each frequency is obtained from the data by locating the time center of each fringe pattern and following the variation in this time as the wavelength is changed. For the compensated case, the center of the pattern is found to vary by ±1 fsec over the range of 400–750 nm. This sets the measurement accuracy for any single data run.[9] We thus obtain information on the frequency dependence of the optical group delay in arbitrary reflective, refractive, diffractive, or absorbing elements by placing them in one arm of the interferometer. Differential group-delay spectroscopy is accomplished by placing samples in the two arms. This method is valid as long as the group delay changes by less than the quasi-monochromatic coherence length (corresponding to a 10-nm bandwidth in this case) over the filter bandwidth. A mathematical analysis of this will be given in a future publication.[10]

Metal mirrors have extremely broadband reflectivity, which is needed for reflection of extremely short optical pulses (less than 10-fsec duration); however, the loss on a single reflection varies from 5 to 40%, depending on the wavelength and metal coating used.[11] To reduce the loss but maintain broad reflectivity, thin dielectric layers are applied to metal mirrors. We find that these layers contribute a measurable dispersion, as shown in curves (a)–(d) of Fig. 2. The measured delay[12] is shown for a Cu–Ag mirror with two quarter-wave dielectric stack [Newport Research Corporation (NRC) ER.2] mirrors, a Cu–Ag

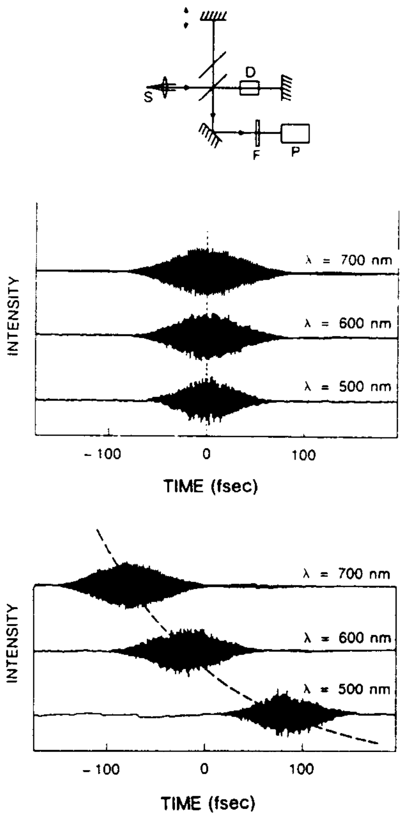

Fig. 1. Experimental arrangement and detected intensity as a function of delay time in the reference arm (a) for compensated interferometer and (b) after insertion of 1-mm glass slide into one arm. S, source; D, device under test; F, tunable filter; P, photomultiplier tube. The center of the fringe pattern moves by less than ±1 fsec for the compensated case as the wavelength is changed.

mirror with only one quarter-wave dielectric stack (NRC ER.1) mirror, an aluminum mirror with a thin MgF_2 protective overlayer (AL.2), and a pure gold mirror with no overlayer. While addition of overlayers on metal mirrors increases the reflectivity, we find that it also increases the dispersion. For a pure gold film [curve (d)] we deduce that the optical delay on reflection is constant to within ±0.2 fsec over the range of 500–750 nm, while errors of 2 fsec per bounce are obtained between 400 and 600 nm for an ER.2 mirror.

Curve (e) of Fig. 2 shows the result of a single normal incidence reflection from a common broadband dielectric mirror (NRC BD.1). This mirror has been found to distort 16-fsec pulses centered at 625 nm on reflection.[13] We find that red light experiences a 50-fsec delay relative to blue light for this mirror. This mirror is composed of three succesive reflection stacks centered at 550, 600, and 650 nm. This result is easily understood: we simply measure the time taken for light to penetrate these layers. This result explains why the 16-fsec pulses at 625 nm were broadened[13] and also shows that such a mirror could be used for a 16-fsec pulse if it were centered at 480 nm. These results are consistent with the discussion and results in Ref. 13. The time delay is relatively constant in the blue region since all the reflection occurs in a single stack on the top layer. Theoretical analyses[13,14] and empirical experimental results from laser work have shown that single-stack dielectric coatings result in less dispersion than multilayer coatings and are thus desirable for use inside femtosecond laser cavities. Curve (f) shows a 3% output coupler mirror, which is a single-stack coating centered at 610 nm at normal incidence. The group delay is constant to within a few femtoseconds over a frequency range that is quite broad. Curve (g) shows a single-stack-coating mirror at a 45° incidence angle centered at 615 nm in *p* polarization, and curve (h) shows the same mirror in *s* polarization. Reduced group-delay variation is obtained in the range of 625 nm for this mirror compared with the BD.1 mirror, as expected, and we obtain the additional result that the residual dispersion is lowered by using this mirror in *s* polarization, although it was designed for *p* polarization. In any case, it is clear that this mirror does not contribute significant group-delay error in either polarization even in generation of pulses as short as 27 fsec in a CPM laser.

Although grating and prism dispersive correctors have been in wide use for some time, no direct measurements of group delay have been reported for either case. Two types of dispersive correctors are used commonly: pairs of Brewster prisms, which provide dispersion compensation in femtosecond lasers,[2,15] and parallel diffraction gratings, which were discussed theoretically by Treacy in 1969.[16] Results for prisms only are discussed here. Pairs of Brewster prisms act as a tunable group-delay corrector. Figure 2 shows

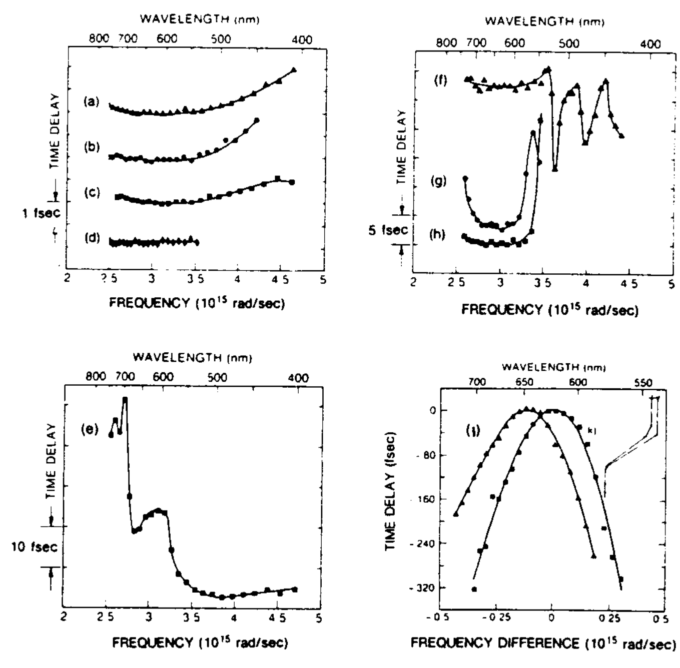

Fig. 2. Group delay as a function of frequency for curves (a) ER.2 mirror, (b) ER.1 mirror, (c) AL.2 mirror, (d) pure gold mirror, (e) BD.1 broadband dielectric mirror, (f) 3% output coupler at normal incidence, (g) CPM laser corner mirror at 45° incidence angle for *p* polarization, (h) CPM laser corner mirror at 45° incidence angle for *s* polarization. In curves (j) and (k) results for flint Brewster prisms are shown, with curve (j) corresponding to less glass and curve (k) to more glass.

two measurements of time delay as a function of frequency for a pair of flint-glass Brewster prisms at a 25-cm apex-to-apex separation, with curve (j) corresponding to less glass and curve (k) corresponding to more glass, obtained by translating one prism along the direction perpendicular to its base. This shows the transition from a positive slope of group delay with frequency to a negative slope when the prism position is varied around the exact compensation point, as predicted theoretically.[16] The residual curvature at the exact compensation point produces predominantly a cubic phase compensation that has been used[4] to cancel the cubic phase error[16] in femtosecond pulse-compression experiments.[17,18]

We have investigated strongly absorbing media such as laser dyes and semiconductor-doped glasses and find complicated group-delay errors. These results as well as discussion of the group-delay correction functions of grating pairs and resonant Gires–Tournois interferometers will be given in a future publication.[10]

We have shown that white-light interferometric techniques can be applied successfully to the study of frequency-dependent optical group-delay errors that are introduced by common optical elements in femtosecond spectroscopy. Accuracy of 1 fsec has been obtained. The results of these studies will be useful in designing new experiments in ultrashort pulse generation in laser cavities, further attempts at optical pulse compression to less than three cycles (6 fsec), and applications in measurements in which specific group-delay corrections are required.

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* Present address, Department of Applied Physics, Stanford University, Stanford, California.

† Present address, Université P. et M. Curie, Laboratoire de Physique des Solides, T 13-2, 4 Place Jussieu, 75232 Paris Cedex 05, France.

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9. We find the center of the fringe pattern in a noise-insensitive manner by subtracting the dc value, squaring the result, and integrating. The 50% rise point represents the center of the packet. To compensate for long-term drift in the translation stage over the approximately 30-min interval of a complete scan, we return the tunable filter to the same reference wavelength after each new wavelength scan and check that the time center of the fringe pattern is unchanged. Small systematic errors are effectively canceled in this way. In addition, a He–Be reference interferometer beam is simultaneously read for accurate on-line length calibrations.
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