Ultrafast Theory

The distinguishing aspect of femtosecond laser optics design is the need to control the phase characteristic of the optical system over the requisite wide pulse bandwidth. CVI Melles Griot has made an intensive theoretical study of these effects. Certain coating designs have been modified with control of the phase characteristics in mind. New proprietary designs have been created with desirable characteristics for femtosecond researchers. All optics in this section have been tested by researchers in the field and we are constantly fielding new requests.

Assume that the power, reflectivity, and polarization characteristics of a laser mirror are acceptable over the bandwidth of a femtosecond pulse. This means that, over the entire pulse bandwidth, a cavity mirror may have a reflectivity greater than 99.8%; a 50% beamsplitter may have a fairly constant reflection; a polarizer may maintain its rejection of one polarization with an acceptable transmission of the other. It is not enough, however, to simply preserve the power spectrum $S(\omega) = |E(\omega)|^2$ when dealing with femtosecond pulses. The phase relationship among the Fourier components of the pulse must also be preserved in order that the pulse not be broadened or distorted. What constraint on the performance of a mirror or transmissive optic does this imply?

Consider a general initial pulse shape $E_0(t)$. As a function of its Fourier components, it may be expressed as:

$$E_0(t) = \int E(\omega)^{-i\omega t}\, d\omega \qquad (1.124)$$

Suppose this pulse reflects off of a mirror. For this example, we assume the mirror is "ideal", and use the Fourier transform of its complex amplitude reflectance:

$$r(\omega) = re^{+i\Phi(\omega)} = re^{+i\omega t_d} \qquad (1.125)$$

For this "ideal" mirror, r is a real constant equal to the amplitude reflectivity that is assumed constant over the pulse bandwidth. All phase effects have been assumed to be describable by a single phase shift $\phi(\omega)$ that is linearly proportional to frequency with proportionality constant t_d. The reflected pulse is then:

$$\begin{aligned} E_r(t) &= r\int E(\omega)^{-i\omega(t-t_d)}\, d\omega \\ &= rE(t-t_d) \end{aligned} \qquad (1.126)$$

Thus, provided the phase shift is linear in frequency over the pulse bandwidth, the reflected pulse is scaled by the amplitude reflectance r, and delayed in time by the constant group delay t_d. It is, otherwise, an undistorted replica of the original pulse.

Examined over a large enough bandwidth, no optical system will exhibit the constant group delay over frequency needed for perfect fidelity. In general, the phase shift near some center frequency ω_0 may be expanded in a Taylor series for frequencies near ω_0:

$$\begin{aligned} \Phi(\omega) = \Phi(\omega_0) &+ \Phi'(\omega_0)(\omega-\omega_0) + \\ &\Phi''(\omega_0)(\omega-\omega_0)^2/2! + \\ &\Phi'''(\omega_0)(\omega-\omega_0)^3/3!\ \ldots \end{aligned} \qquad (1.127)$$

These derivatives are, respectively, the group delay $\Phi'(\omega_0)$, the group velocity dispersion $\Phi''(\omega_0)$, and the cubic term $\Phi'''(\omega_0)$, evaluated at a center frequency ω_0. This expansion is heuristically useful, in an exactly soluble model, for the propagation of a transform-limited Gaussian pulse. Note, however, that for extremely short pulses the expansion above may be insufficient. A full numerical calculation may have to be performed using the actual phase shift function $\Phi(\omega)$. CVI Melles Griot will be happy to assist those interested in the modeling of real optical elements.

To illustrate pulse distortion due to the dependence of the group delay on frequency, consider what happens when an unchirped, transform-limited Gaussian pulse passes through a medium, or is incident on a mirror whose dominating contribution to phase distortion is non-zero group velocity dispersion. The field envelope of the pulse is assumed to be of the form:

$$E(t) = \exp\left[-\left(2\ \ln 2t^2/\tau_0^2\right)\right] \qquad (1.128)$$

where τ_0 is the initial pulse duration (FWHM of the pulse intensity). Let the pulse enter a medium or reflect off of a mirror with non-zero $\Phi''(\omega)$, measured in fsec^2 radians. (For a continuous medium-like glass, $\Phi''(\omega)=\beta''(\omega) \times z$ where $\beta''(\omega)$ is the group velocity dispersion (GVD) per centimeter of material, and z is the physical path length, in centimeters, traveled through the material.) The Gaussian pulse will be both chirped and temporally broadened by its encounter with group velocity dispersion. The power envelope will remain Gaussian; the result for the broadened FWHM is:

$$\tau_1 = \tau_0\left[1+\left(4\ln 2\Phi''(\omega)/\tau_0^2\right)^2\right]^{1/2} \qquad (1.129)$$

This result, valid only for initially unchirped, transform-limited Gaussian pulses, is nevertheless an excellent model to study the effects of dispersion on pulse propagation. The graphs shown in Figure 1.61 represent the theoretical broadening from dispersion for initial pulse widths ranging from 10 to 100 femtoseconds.

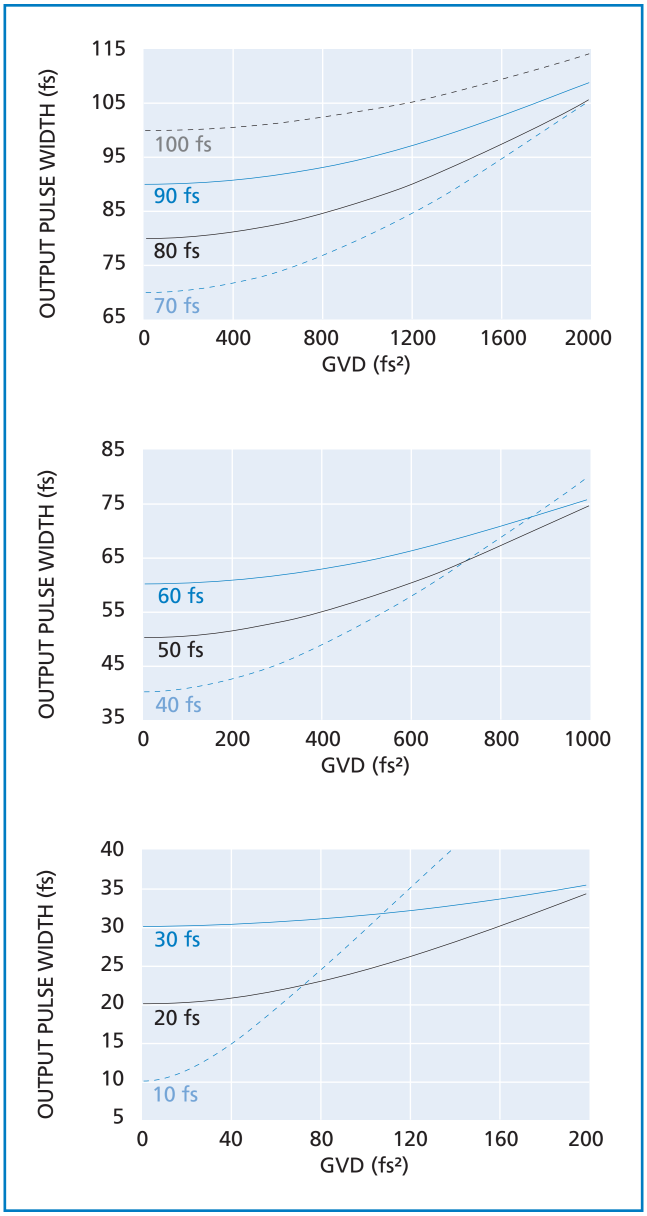

Figure 1.61 **Output pulse width vs. GVD**

GROUP-VELOCITY & CUBIC DISPERSION FOR VARIOUS OPTICAL MATERIALS

Figures 1.62 and 1.63 show the GVD and cubic dispersion respectively for some common used glasses. Some of the glasses can be used in the UV region. They should be useful in estimating material dispersion and pulse distortion effects. Please check these calculations independently before using them in a final design.

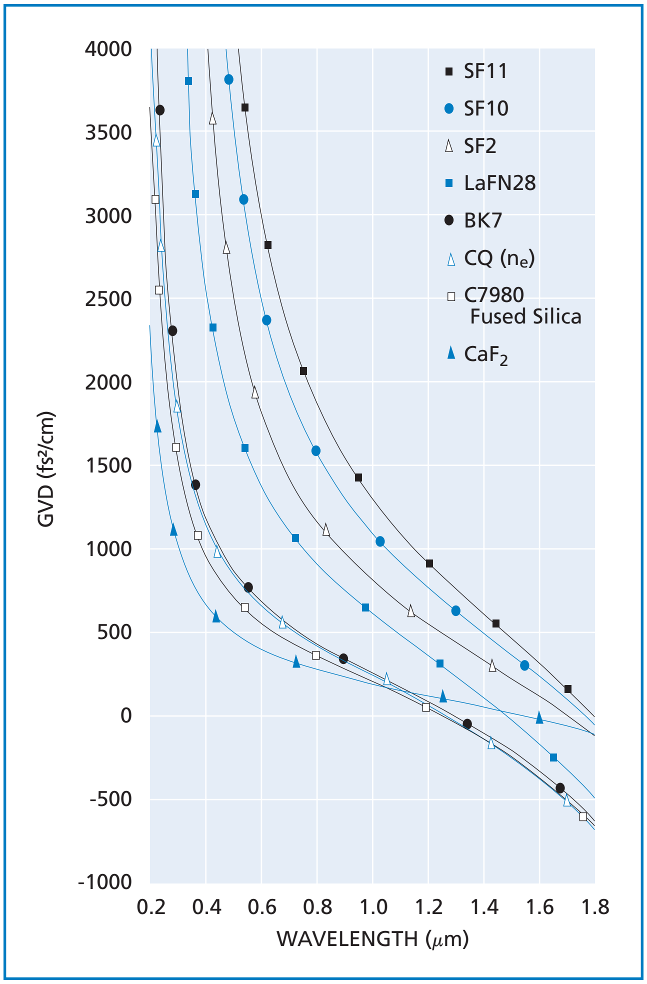

Figure 1.62 **GVD for common glasses**

Fundamental Optics
Gaussian Beam Optics
Optical Specifications
Material Properties
Optical Coatings

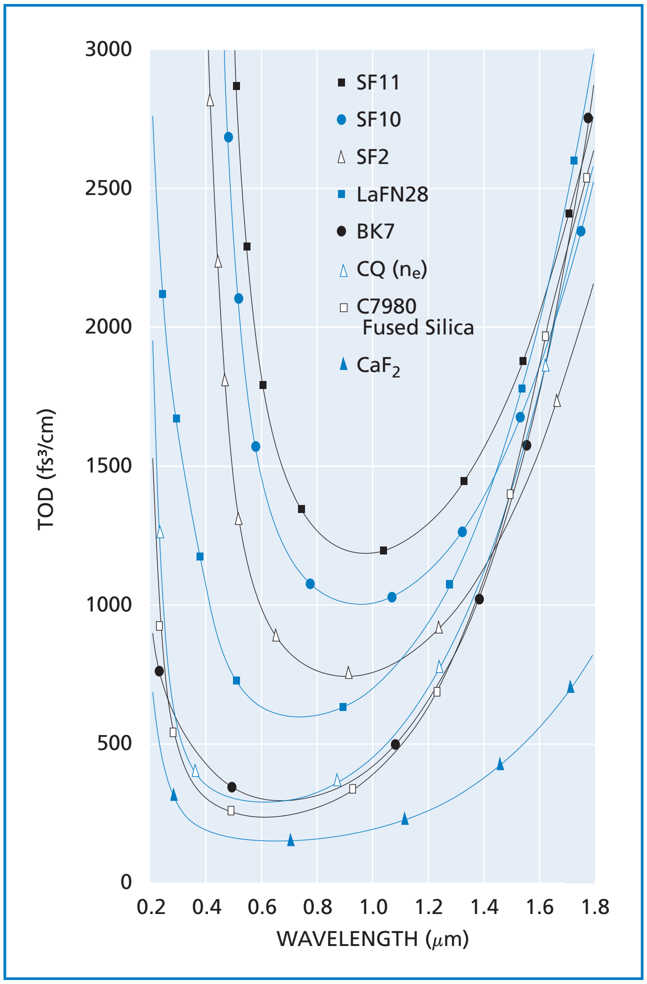

Figure 1.63 **Cubic dispersion for common glasses**

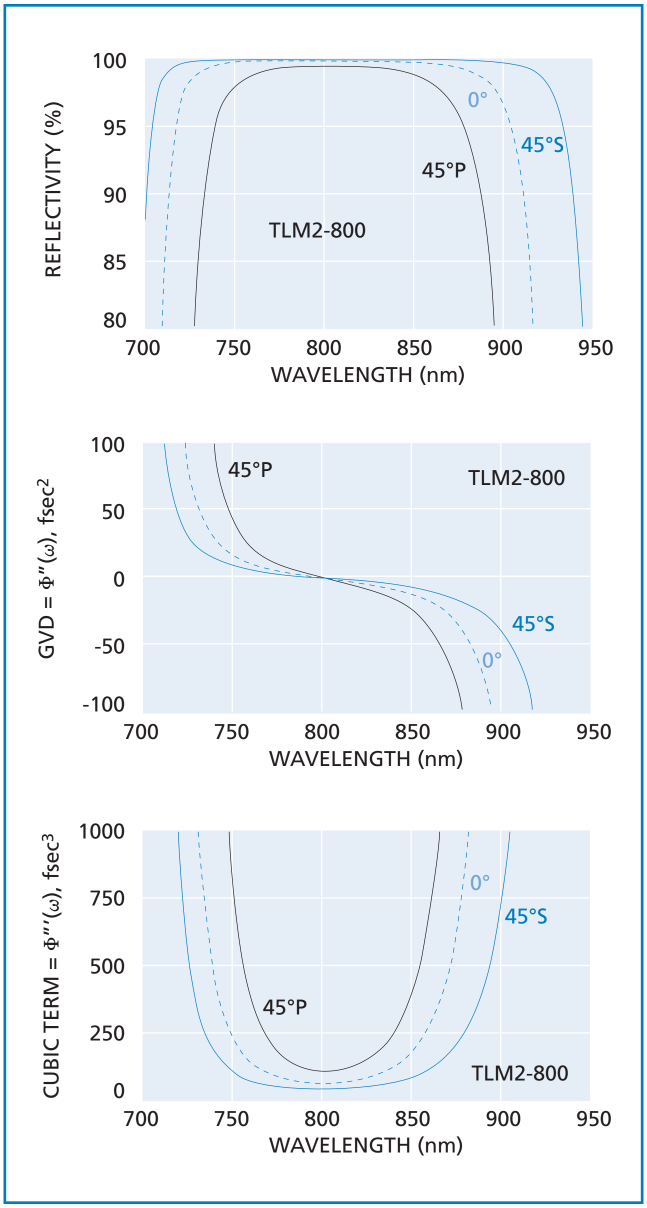

Figure 1.64 **Dispersion and reflectivity for mirrors TLM2-800-0 and TLM2-800-45**

DISPERSIVE PROPERTIES OF MIRRORS

CVI Melles Griot uses three basic designs; TLM1 mirrors for energy fluence greater than 100 mJ/cm^2, TLM2 mirrors for cw oscillators and low-fluence pulses, and TLMB mirrors which are a hybrid of the two. The reflectivity, GVD parameter, and cubic dispersion parameter for TLM2 high reflectors are shown in Figure 1.64. In these examples, the mirrors are centered at 800 nm and are designed for use at normal incidence and at 45 degrees. Note that, at the design wavelength, (a) GVD is zero, (b) the cubic term is minimized, and (c) at 45° incidence, the GVD of the p-polarization component is very sensitive to wavelength, while the GVD for s-polarization component is nearly zero over a broad wavelength range. Thus one should avoid using mirrors at 45° incidence with the p-polarization. On the other hand, at 45° incidence, s-polarization provides very broad bandwidth and minimizes pulse distortion problems and should be used whenever possible.

Ti:Sapphire and other femtosecond laser systems need prismless compensation of the built-in positive chirp encountered in the laser optical circuit. This becomes mandatory in industrial and biomedical applications where the laser must provide a compact, stable, and reliable solution.

Negative Group Velocity Dispersion Mirrors (TNM2) meet these needs with off-the-shelf availability, and can be employed both intracavity and extracavity to satisfy chirp control requirements.

In experiments using CVI Melles Griot TNM2 negative group velocity dispersion mirrors, 200-mW, 80-fsec pulses centered at 785 nm were achieved in a simple, prismless, Ti:Sapphire oscillator. The configuration is shown in Figure 1.65.

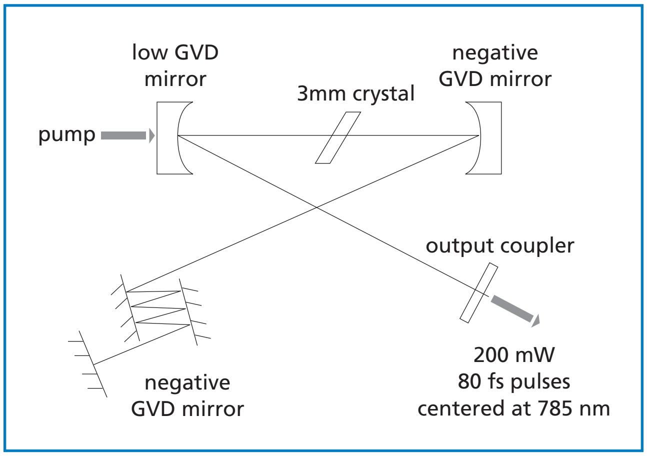

Figure 1.65 **Typical optical setup incorporating low GVD and Negative GVD mirrors in an ultrafast application**

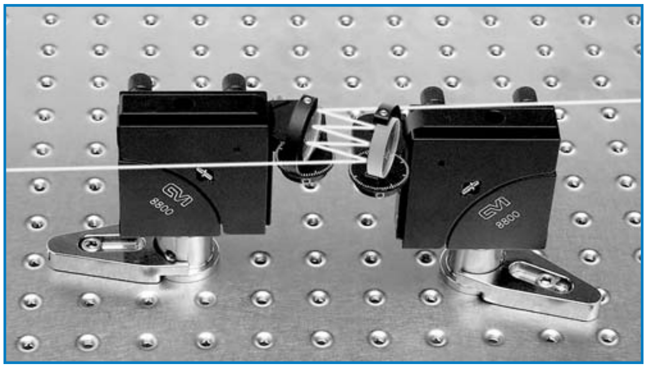

Figure 1.66 **Typical optical set-up of negative GVD mirrors**

OUTPUT COUPLERS AND BEAMSPLITTERS

Output-coupler partial reflectors and beamsplitters behave similarly; however, here is an additional consideration in their analysis. The behavior of the transmitted phase of the coating and the effect of material dispersion within the substrate on the transmitted beam have to be taken into account in a detailed analysis. In general, the coating transmitted phase has similar properties and magnitudes of GVD and cubic to the reflected phase. As usual, centering is important. As a beamsplitter, we recommend the 1.5 mm thick fused silica substrate PW-1006-UV. As an output coupler substrate, we recommend the 3.0 mm thick, 30 minute wedge fused silica substrate IF-1012-UV.

CVI Melles Griot has developed the TFPK Series Broadband Low Dispersion Polarizing Beamsplitters to satisfy requirements for very-high-power, short-pulse lasers. These optics are ideal for intracavity use in femtosecond regenerative amplifiers. The main emphasis is on linear phase characteristics. See Chapter 9 of Lasers, A. E. Siegman (University Science Books, Mill Valley, California, 1986), for a good discussion of linear pulse propagation.

In chirped pulse regenerative amplification, the pulse may have to pass through one or two polarizers twice per round trip. There can be 10 to 20 round trips before the gain is saturated and the pulse is ejected. At this stage the pulse is long (100–1000 psec); however the phase shift at each frequency must still be maintained to minimize the recompressed pulse width. The many round trips of the pulse in the regenerative amplifier put stringent requirements on the phase characteristics of the coatings.

Figure 1.67 shows the power transmission curves for both s- and p-polarization and the transmitted phase characteristics of the p component for a TFPK optimized at 800 nm. (Users may specify any wavelength

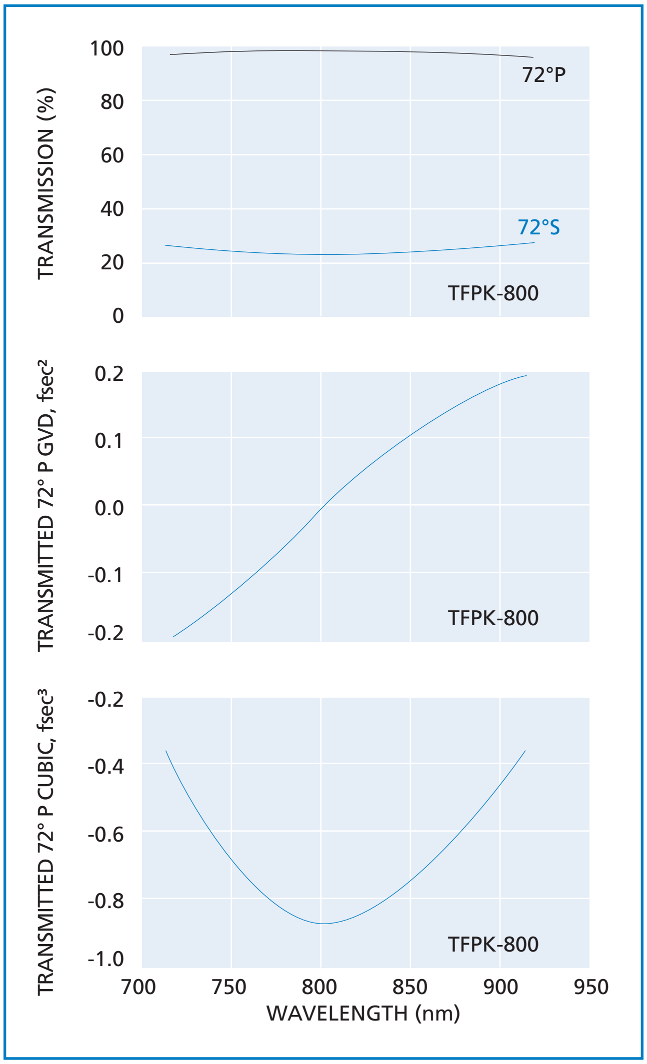

Figure 1.67 **Properties for one coated side of a TFPK polarizing beamsplitter optimized for 800 nm. Both sides are coated for these properties.**

from 250 nm to 1550 nm.) The phase characteristics shown are the GVD and the cubic phase term. Not shown are the reflected phase characteristics for *s*-polarization; they are similar to the *p*-polarization transmission curves, and have the same low nonlinearity and broad bandwidth. Note that both sides of the optic have the coating whose properties are described in Figure 1.67. Therefore, the *s*- and *p*-polarization transmissions per surface should be squared in determining the specifications. The phase characteristics show that in all modes of operation, the TFPK polarizer performance is dominated by the substrate.

There are some subtleties associated with the TFPK. The near 72° angle has to be set properly and optimized. Some thought has to be given to mechanical clearances of the laser beam at such a steep incidence angle. The reflectivity for *s*-polarization is limited to 75%. Variant designs can increase this at a slight loss in bandwidth, increase in incidence angle, and increase in insertion loss for the transmitted *p*-polarized component.

The FABS autocorrelator beamsplitters from CVI Melles Griot are broadband, 50% all-dielectric beamsplitters. They are useful in many types of pump-probe experiments and in the construction of antiresonant ring configurations. They are essentially lossless and extremely durable. Both have advantages over partially reflecting metal coatings.

Power transmission curves for the *s*- and *p*-polarized versions of the FABS, along with the corresponding reflected phase characteristics for beamsplitters optimized at 800 nm, are shown in Figures 1.68 and 1.69. The linear pulse propagation properties of these beamsplitters are dominated by the substrate material dispersion. As with virtually all dielectric coated optics, the *s*-polarized version is broader than *p*-polarized version. CVI Melles Griot can produce FABS in other than 50:50 with excellent phase characteristics.

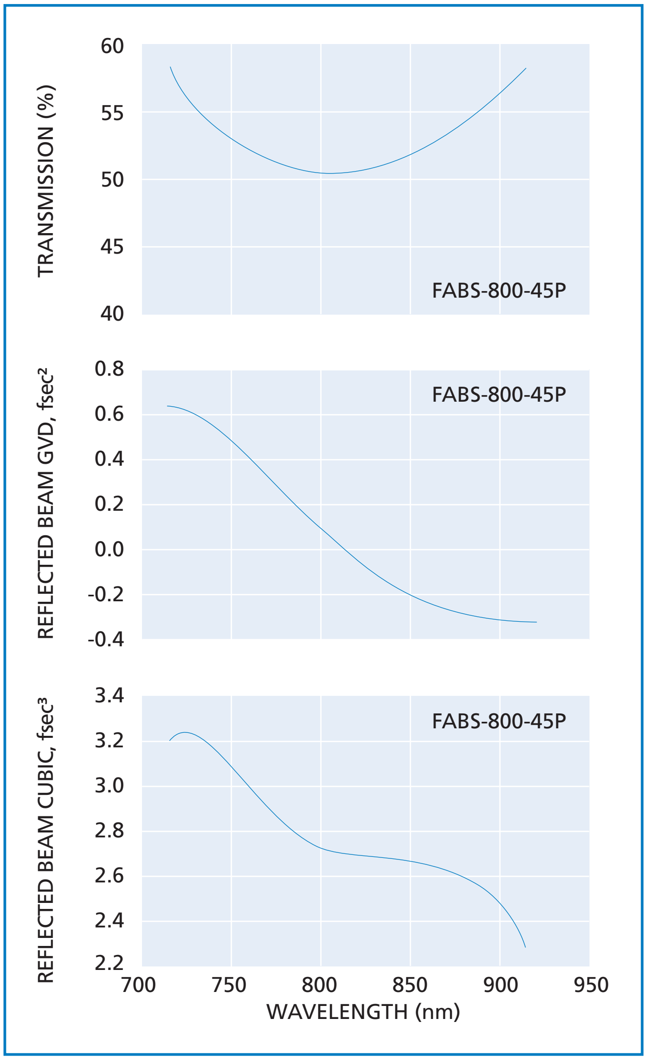

Figure 1.68 **Transmission characteristics for FABS series polarizers with *p*-polarized light**

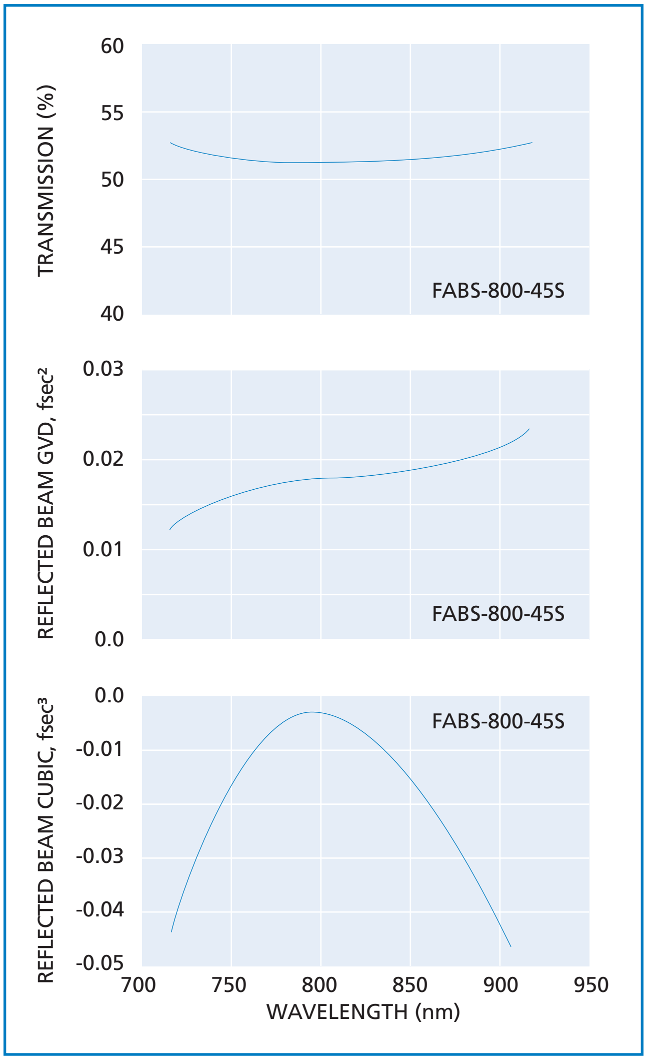

Figure 1.69 **Transmission characteristics for FABS series polarizers with *s*-polarized light**

ANTIREFLECTION COATINGS

All CVI Melles Griot antireflection coating designs work well in femtosecond operation as the forward-going phasor is the dominant contribution to the phase shift; the AR coating is very thin and simply "fixes" the small Fresnel reflection of the substrate.

PRISMS

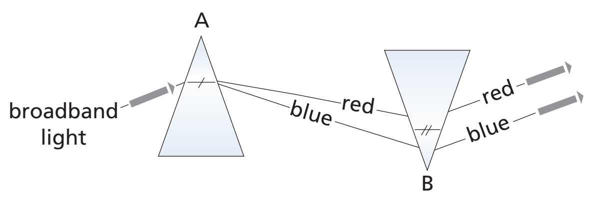

Figure 1.70 **Brewster prism**

Very-high-quality isosceles Brewster's angle prisms for intra and extra-cavity use are available from CVI Melles Griot. The design of these prisms satisfies the condition of minimum loss due to entrance and exit at Brewster's angle. To calculate GVD at Brewsters angle, refer to Figure 1.70 and use the following equation:

$$\mathrm{GVD} = \frac{d^2}{d\omega^2}\psi\bigg|_{\omega-\omega_l} \approx \frac{\lambda_l^3}{2\pi c^2}\left[L\,\frac{d^2\eta}{d\lambda^2}\bigg|_{\lambda_l} - 4l\left(\frac{d\eta}{d\lambda}\bigg|_{\lambda_l}\right)^2\right] \qquad (1.130)$$

where

η = refractive index of the prisms (assuming the same material)
l = tip to tip distance ($\overline{AB}$)
L = total avg. glass path
ψ = spectral phase of the electric field
$\omega_l \lambda_l = 2\pi_c$ (assumes Brewster prism at minimum deviation).

For more on the Ultrafast phenomena, see J.C. Diels and W. Rudolph, Ultrashort Laser Pulse Phenomena, Academic Press, 1996.