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LAYERTEC[®]
OPTICAL COATINGS · OPTICS

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FEMTOSECOND LASER OPTICS

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INTRODUCTION TO FEMTOSECOND LASER OPTICS

Short pulse lasers are used in numerous applications such as time resolved spectroscopy, precision material processing and non-linear optics. Driven by these applications, recent developments in this field are directed to lasers generating higher output power and shorter pulses. Currently, most short pulse physics is done with Ti:Sapphire lasers. Solid-state lasers based on other transition metal or rare earth metal doped crystals (Yb:KGW) are also used for the generation of femtosecond pulses. The reproducible generation of sub-100 fs-pulses is closely connected to the development of broadband low loss dispersive delay lines consisting of prism or grating pairs or of dispersive multilayer reflectors.

The spectral bandwidth of a pulse is related to the pulse duration by a well-known theorem of Fourier analysis. For instance, the bandwidth (FWHM) of a 100 fs Gaussian pulse at 800 nm is 11 nm. For shorter pulses, the wavelength spectrum becomes significantly broader. A 10 fs pulse has a bandwidth of 107 nm.

If such a broad pulse passes through an optical medium, the spectral components of this pulse propagate with different speeds. Dispersive media, like glass, impose a so-called "positive chirp" on the pulse, meaning that the short wavelength ("blue")

components are delayed with respect to the long wavelength ("red") components (see schematic drawing in fig. 1).

A similar broadening can be observed if a pulse is reflected by a dielectric mirror and the bandwidth of the pulse is larger or equal to the width of the reflection band of the mirror. Consequently, broadband mirrors consisting of a double stack system cause pulse broadening because the path lengths of the spectral components of the pulse are extremely different in these coatings.

In the sub-100 fs-regime it is essential to control the phase properties of each optical element over the extremely wide bandwidth of the fs-laser. This holds not only for the stretcher and compressor units, but also for the cavity mirrors, output couplers and the beam propagation system. In addition to the power spectrum, i.e. reflectance or transmittance, the phase relationship among the Fourier components of the pulse must be preserved in order to avoid broadening or distortion of the pulse.

Mathematical analysis of the phase shift, which is applied to a pulse passing through a medium or being reflected by a mirror (see insert on page 73), shows that the main physical properties which

describe this phenomenon are the group delay dispersion (GDD) and the third order dispersion (TOD). These properties are defined as the second and third derivative of the phase with respect to the frequency.

Especially designed dielectric mirrors offer the possibility to impose a "negative chirp" on a pulse. Thus, the positive chirp which results from crystals, windows, etc. can be compensated. The schematic drawing in fig. 2 explains this effect in terms of different optical path lengths of blue, green and red light in a negative dispersion mirror.

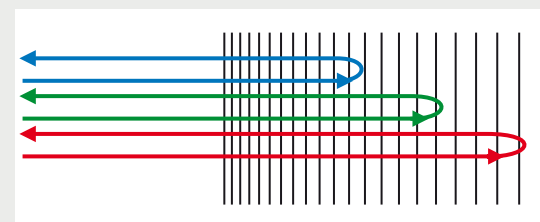


Figure 2: Optical path lengths of blue, green and red light in a negative dispersion mirror (schematic drawing)

LAYERTEC offers femtosecond laser optics with different bandwidths. This catalog shows optics for the wavelengths range of the Ti:Sapphire laser in three chapters, each representing a characteristic bandwidth of the optics: standard components with a bandwidth of about 120 nm, broadband components (bandwidth about 300 nm) and octave spanning components.

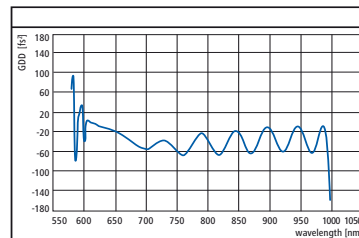
Each of these chapters shows low dispersion laser and turning mirrors, negative dispersion mirrors or mirror pairs, output couplers and beam splitters of corresponding bandwidth. Moreover, silver mirrors for fs applications are presented which offer the broadest low-GDD bandwidth available.



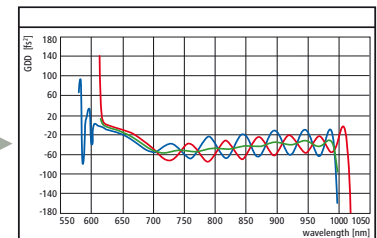
Figure 1: Broadening of a pulse by propagation through an optical medium (schematic drawing)

Please note that the GDD spectrum of a dielectric negative dispersion mirror is not a flat graph. All types of negative dispersion mirrors exhibit oscillations in the GDD spectrum. These oscillations are small for standard bandwidths. However, broadband and ultra-broadband negative dispersion mirrors exhibit strong GDD oscillations. Considerable reduction of these oscillations can be achieved by using mirror pairs consisting of mirrors with carefully shifted GDD oscillations. Fig. 3 shows a schematic drawing of said mirror pair and the corresponding GDD spectra.

GDD-spectrum of mirror 2



average GDD-spectrum



GDD-spectrum of mirror 1

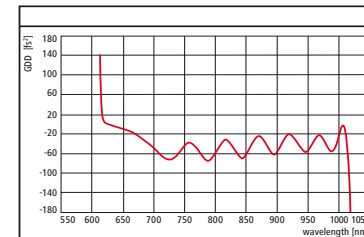


Figure 3: Schematic drawing of a negative dispersion mirror pair

GDD and TOD

If a pulse is reflected by a dielectric mirror, i. e. a stack of alternating high and low refractive index layers, there will be a phase shift between the original and the reflected pulse resulting from the time which it takes the different Fourier components of the pulse to pass through the layer system of the mirror. In general, the phase shift $\Phi(\omega)$ near the center frequency ω_0 may be expanded in a Taylor series for frequencies near ω_0 :

$$\Phi(\omega) = \Phi(\omega_0) + \Phi'(\omega_0)(\omega - \omega_0) + \frac{\Phi''(\omega_0)}{2}(\omega - \omega_0)^2 + \frac{\Phi'''(\omega_0)}{6}(\omega - \omega_0)^3 + \dots$$

The derivatives are, respectively, the **Group Delay (GD)** $\Phi'(\omega_0)$, the **Group Delay Dispersion (GDD)** $\Phi''(\omega_0)$ and the **Third Order Dispersion (TOD)** $\Phi'''(\omega_0)$. More strictly speaking, this expansion is only useful in an exactly soluble model, for the propagation of a transform limited Gaussian pulse and for pure phase dispersion. For extremely short pulses and combinations of amplitude and phase dispersion numerical calculations may be necessary. Nevertheless, this expansion clearly shows the physical meaning of the single terms:

Assuming the phase shift is linear in frequency (i.e. $\text{GD} \neq 0$, $\text{GDD} = 0$ and $\text{TOD} = 0$ over the pulse bandwidth), the reflected pulse is delayed in time by the constant group delay and, of course, scaled by the amplitude of reflectance R . The pulse spectrum will remain undistorted.

If $\text{GDD} \neq 0$, two important effects are observed:

- The reflected pulse is temporally broadened. This broadening effect depends only on the absolute value of the GDD. LAYERTEC offers "low GDD mirrors", i. e. mirrors with $|\text{GDD}| < 20 \text{ fs}^2$ over a given wavelength range, which guarantee the preservation of the pulse shape when the pulse is reflected by these mirrors.
- Moreover, the pulse becomes "chirped", i. e. it changes its momentary frequency during pulse time. This effect depends on the sign of the GDD, so that the momentary frequency may become higher (up-chirp, $\text{GDD} > 0$) or lower (down-chirp, $\text{GDD} < 0$). This allows to compensate positive GDD effects of nonlinear optical elements by using negative GDD mirrors.

The TOD determines also pulse length and pulse shape (distortion of the pulse) and becomes a very important factor at pulse lengths of 20 fs and below.

It is also possible to use negative dispersion mirrors with high values of negative GDD for pulse compression. These so-called Gires-Tournois-Interferometer (GTI) mirrors (see pages 96 – 97) are successfully used in Ti:Sapphire lasers, Yb:YAG and Yb:KGW oscillators and Er:Fiber lasers. Pulse compression in Yb:YAG and Yb:KGW oscillators provides pulses of some hundred femtoseconds pulse length. For each wavelength, components with different amounts of negative GDD are presented on the following pages.

Besides these optics for the spectral range of the

Ti:Sapphire fundamental and for the very promising Yb:YAG and Yb:KGW lasers, LAYERTEC also offers optics for the harmonics of this radiation down to the VUV wavelength range, optics for femtosecond lasers in the 1500 nm-range and especially designed optics for high power ultra-short pulse lasers. LAYERTEC has its own capabilities for design calculation and also for GDD-measurements in the wavelength range from 250 – 1700 nm.

References:

- H. Holzwarth, M. Zimmermann, Th. Udem, T.W. Hänsch, P. Russell, K. Gäbel, R. Poprawe, J.C. Knight, W.J. Wadsworth and P. St.J. Russell; Optics Letters, Vol. 26, No.17 (2001), p.1376 – 1378
- Y.-S. Lim, H.-S. Jeon, Y.-C. Noh, K.-J. Yee, D.S. Kim, J.-H. Lee, J.-S. Chang, J.-D. Park; Journal of the Korean Physical Society Vol.40, No.5 (2002), p. 837 – 843
- G. Tempea, V. Yakovlev and F. Krausz; "Interference coatings for Ultrafast Optics" in N. Kaiser, H.K. Pulker (eds.) "Optical Interference Coatings", Springer-Verlag Berlin Heidelberg 2003, p. 393 – 422 and the references therein

STANDARD FEMTOSECOND LASER OPTICS

- The coatings shown here are calculated for a bandwidth of 120 – 150 nm in the wavelength range between 600 nm and 1000 nm.
- Very high reflectance of the mirrors ($R > 99.99\%$).
- Spectral tolerance 1 % of center wavelength.
- In-house design calculation and GDD measurement capabilities.
- Center wavelength, GDD and TOD according to customer specifications.
- Measured GDD spectra available on request.

LIDT - INFO

0.4 J / cm², 800 nm, 42 fs, 1 kHz, Ø 80 µm *
 2 J / cm², 800 nm, 70 fs, 10 Hz, Ø 700 µm **
 For high power mirrors see page 88.

* Measurements were performed at Wigner Research Centre for Physics, Budapest
 ** Measurements were performed at Helmholtz-Zentrum Dresden-Rossendorf

STANDARD MIRRORS AOI = 0°

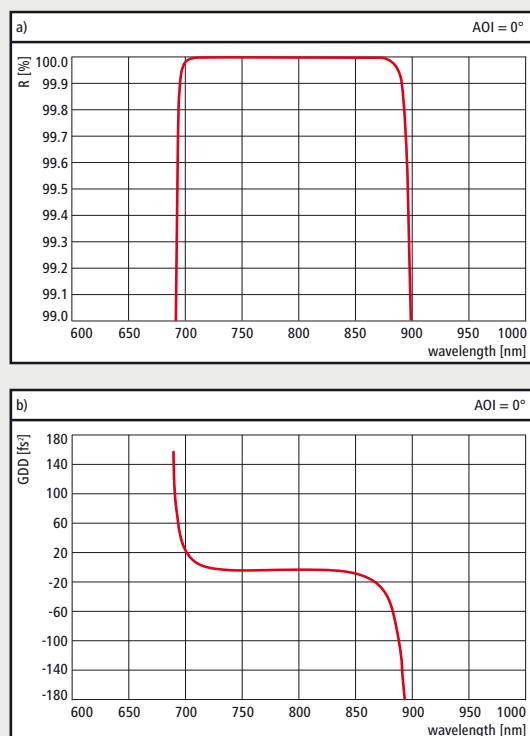


Figure 1: Reflectance and GDD spectra of a standard low dispersion femtosecond laser mirror

- a) Reflectance vs. wavelength
 b) GDD vs. wavelength

All types of mirrors are also available with negative GDD (e.g. - 40 fs²).

For high dispersion mirrors see page 76.

PUMP MIRRORS AOI = 0°

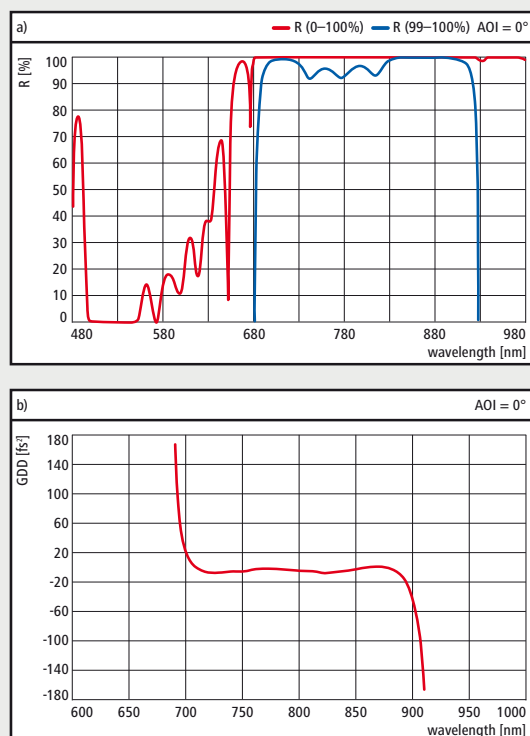


Figure 2: Reflectance and GDD spectra of a standard low dispersion pump laser mirror

- a) Reflectance vs. wavelength
 b) GDD vs. wavelength

TURNING MIRRORS AOI = 45°

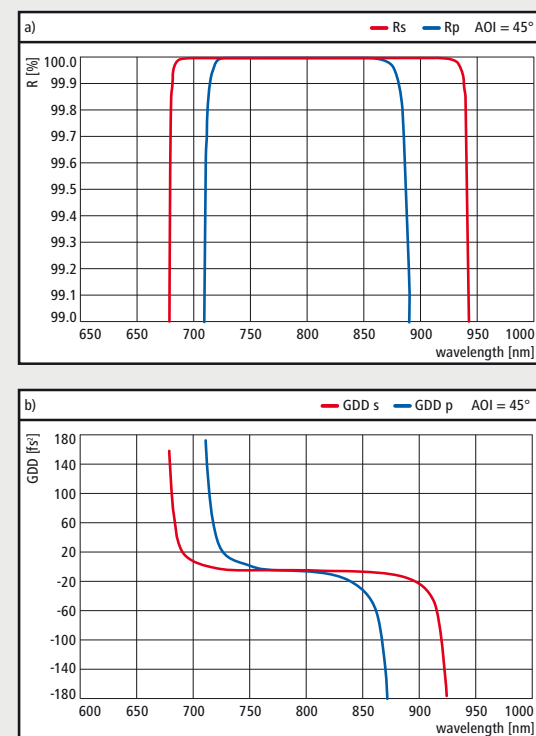


Figure 3: Reflectance and GDD spectra for a standard low dispersion turning mirror (bandwidth $R_u(45^\circ) > 99.9\% \sim 160$ nm)

- a) Reflectance vs. wavelength
 b) GDD vs. wavelength

120 – 150 nm BANDWIDTH

- Reflectance and transmittance of output couplers and beam splitters can be adjusted according to customer specifications.

- Tolerances for output couplers:
 - $R = 10 \% \dots 70 \% \pm 2.5 \%$
 - $R = 70 \% \dots 90 \% \pm 1.5 \%$
 - $R = 90 \% \dots 95 \% \pm 0.75 \%$
 - $R = 95 \% \dots 98 \% \pm 0.5 \%$
 - $R > 98 \% \pm 0.25 \%$

- Standard AR coatings:
 - $\text{AOI} = 0^\circ$: $R < 0.2 \%$
 - $\text{AOI} = 45^\circ$: R_s or $R_p < 0.2 \%$
 - In case of p-polarization, uncoated back side possible, R_p (fused silica, 45°) $\approx 0.6 \%$.

OUTPUT COUPLERS $\text{AOI} = 0^\circ$

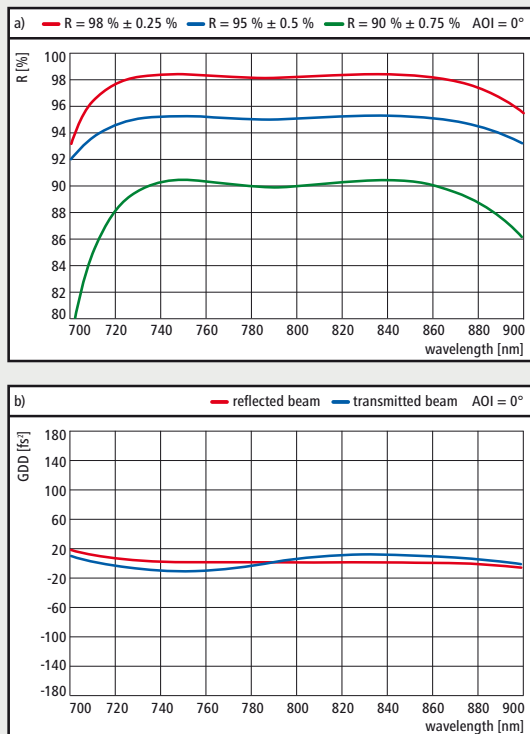


Figure 4: a) Reflectance spectra of several standard output couplers
b) GDD spectra of the output coupler with $R = 98 \%$; the GDD spectra are similar for all levels of reflectance

BEAM SPLITTERS FOR P-POLARIZED LIGHT AT $\text{AOI} = 45^\circ$

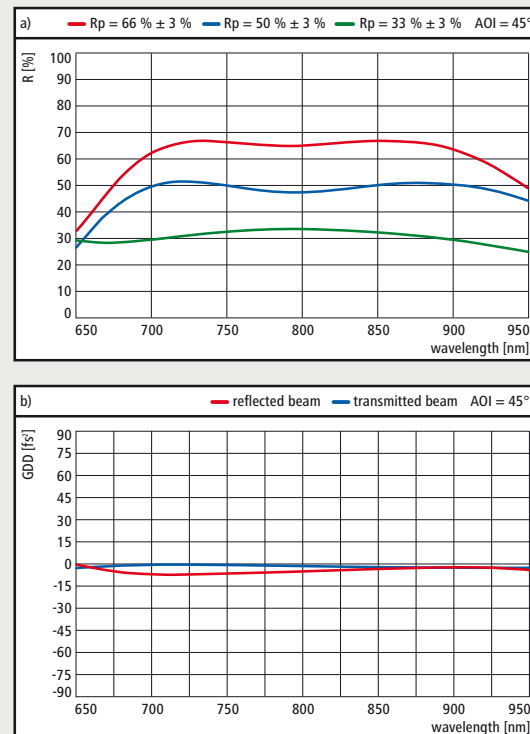


Figure 5: a) Reflectance spectra of several standard beam splitters for $\text{AOI} = 45^\circ$ and p-polarized light
b) GDD spectra of the beam splitter with $R = 50 \%$; the GDD spectra are similar for all levels of reflectance

BEAM SPLITTERS FOR S-POLARIZED LIGHT AT $\text{AOI} = 45^\circ$

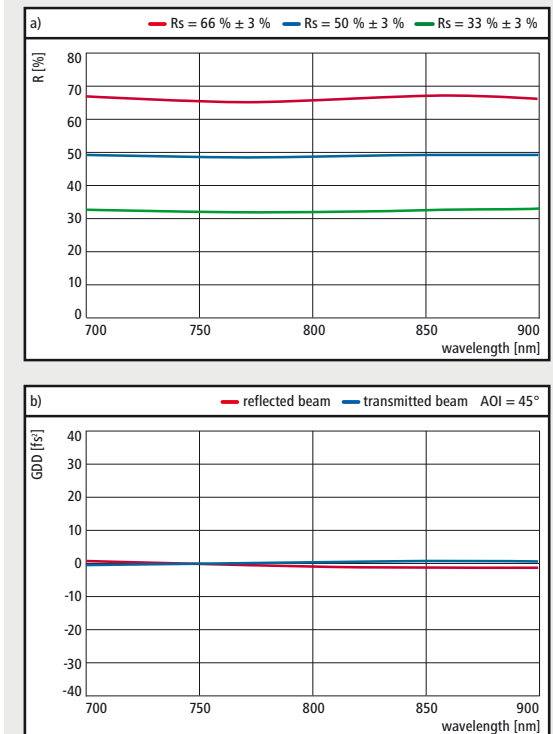


Figure 6: a) Reflectance spectra of several standard beam splitters for $\text{AOI} = 45^\circ$ and s-polarized light
b) GDD spectra of the beam splitter with $R = 50 \%$; the GDD spectra are similar for all levels of reflectance

STANDARD FEMTOSECOND LASER OPTICS

Recent advances in design calculation and process control enable LAYERTEC to offer high dispersion mirrors for pulse compression in advanced Ti:Sapphire

lasers. These mirrors and mirror pairs show spectral bandwidths of 100 nm – 300 nm and negative GDD values of some hundred fs². These mirrors can be used

for pulse compression. Compared to prism compressors, high dispersion mirrors reduce the intracavity losses resulting in higher output power of the laser.

NEGATIVE DISPERSION MIRRORS AOI = 0°

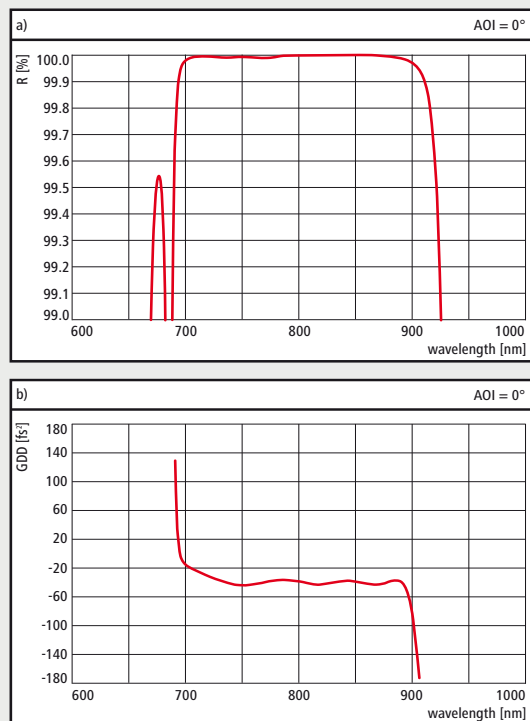
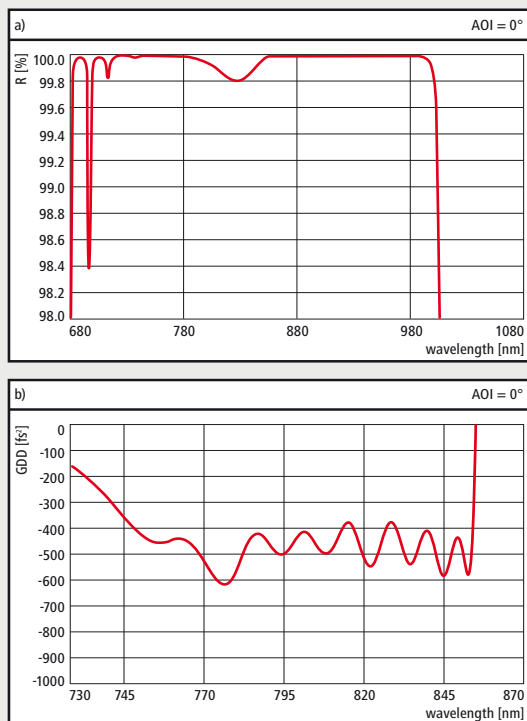


Figure 1: Reflectance and GDD spectra of a standard negative dispersion mirror with GDD = -40 ± 10 fs²

- a) Reflectance vs. wavelength
- b) GDD vs. wavelength

HIGH DISPERSION MIRRORS AOI = 0°



Measurement

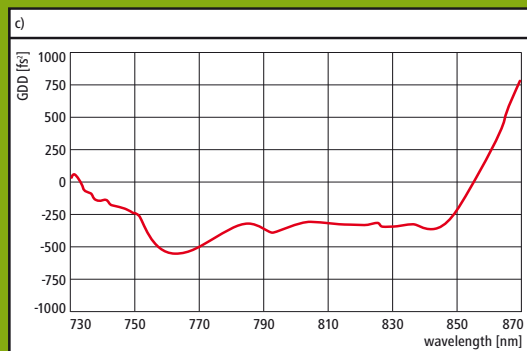
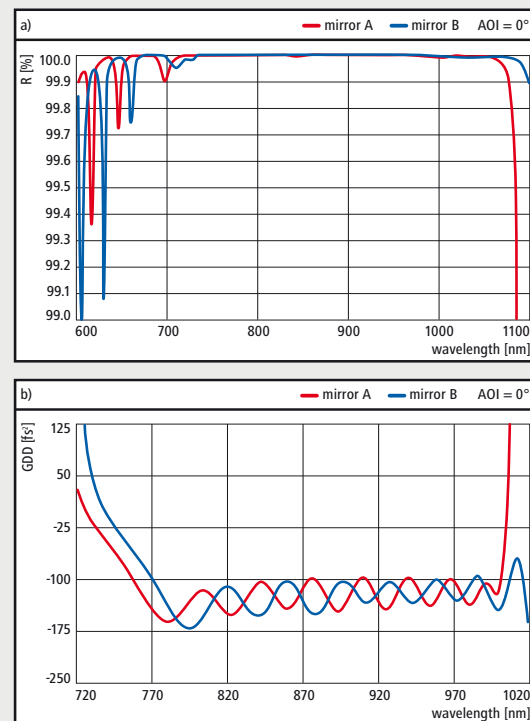


Figure 2: Reflectance and GDD spectra of a high dispersion mirror with a bandwidth of 120 nm and a GDD of -450 ± 100 fs² in the 800 nm range

- a) Reflectance vs. wavelength
- b) Calculated GDD vs. wavelength
- c) Measured GDD vs. wavelength

HIGH DISPERSION MIRROR PAIRS AOI = 0°



Measurement

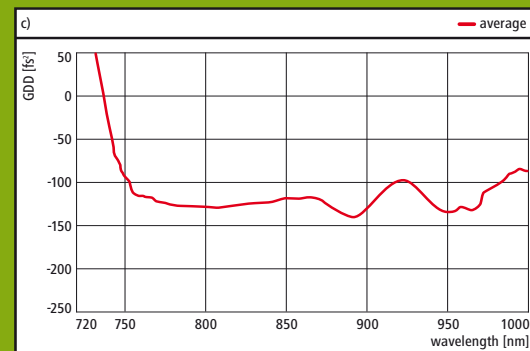


Figure 3: Reflectance and GDD spectra of a high dispersion mirror pair with a bandwidth of 200 nm and an average GDD of -120 ± 40 fs² per bounce in the 800 nm range

- a) Reflectance vs. wavelength
- b) Calculated GDD vs. wavelength
- c) Measured GDD vs. wavelength

Matching measured and calculated GDD-spectra prove the reliability of the coating process.

120 – 150 nm BANDWIDTH

This very special type of optical coatings can be used to compensate the third order dispersion which results from laser crystals, substrates or dispersive elements

like prisms or gratings. Positive as well as negative TOD can be achieved with this type of coatings. All coatings are optimized for nearly constant TOD which

means TOD oscillations in the order of some hundreds of fs^3 . Please note that without TOD optimization these oscillations are on the order of some thousands of fs^3 .

MIRRORS WITH NEGATIVE THIRD ORDER DISPERSION

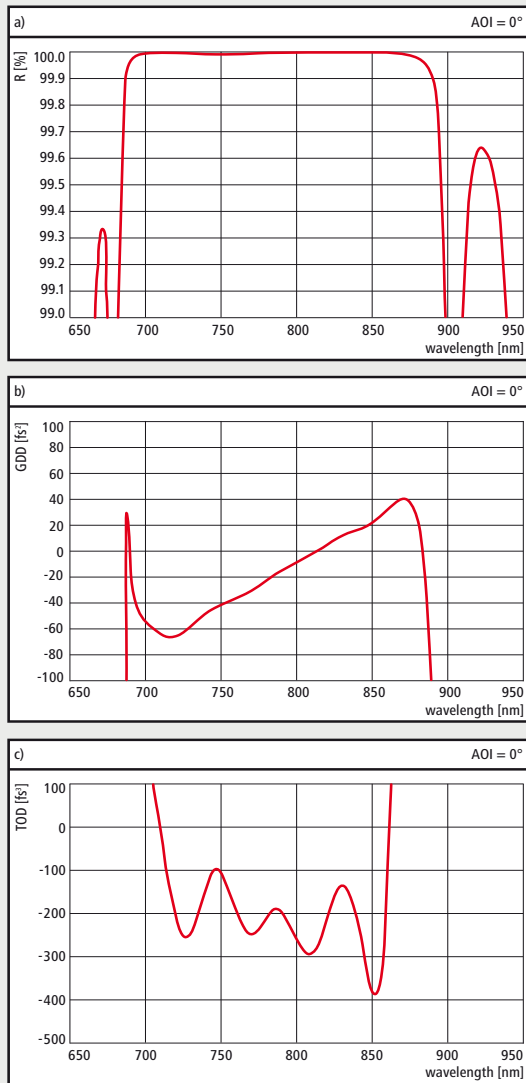


Figure 4: Reflectance, GDD and TOD spectra of a mirror optimized for nearly constant negative third order dispersion

- a) Reflectance vs. wavelength
- b) GDD vs. wavelength
- c) TOD vs. wavelength

MIRRORS WITH POSITIVE THIRD ORDER DISPERSION

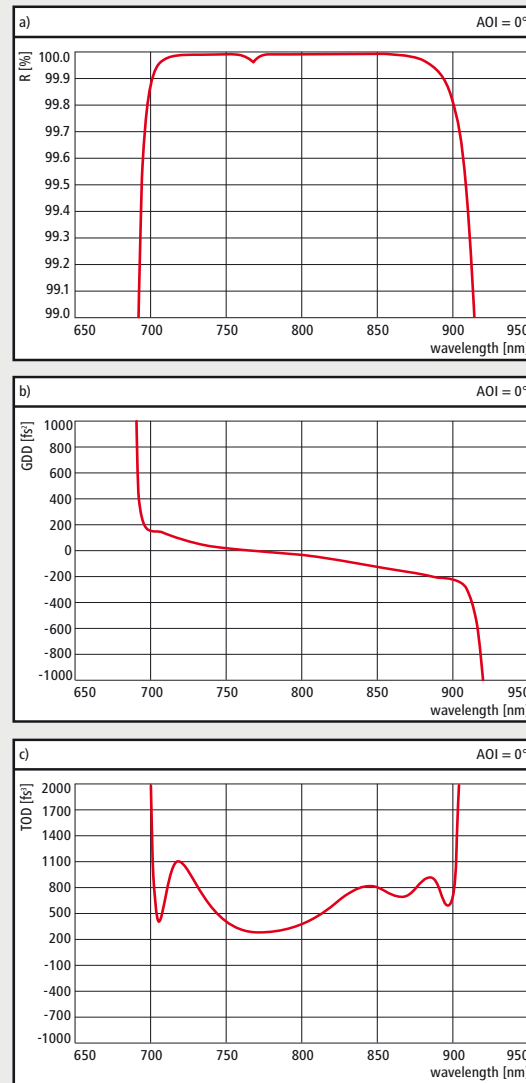


Figure 5: Reflectance, GDD and TOD spectra of a mirror optimized for nearly constant positive third order dispersion

- a) Reflectance vs. wavelength
- b) GDD vs. wavelength
- c) TOD vs. wavelength

MIRROR PAIRS WITH OPTIMIZED THIRD ORDER DISPERSION

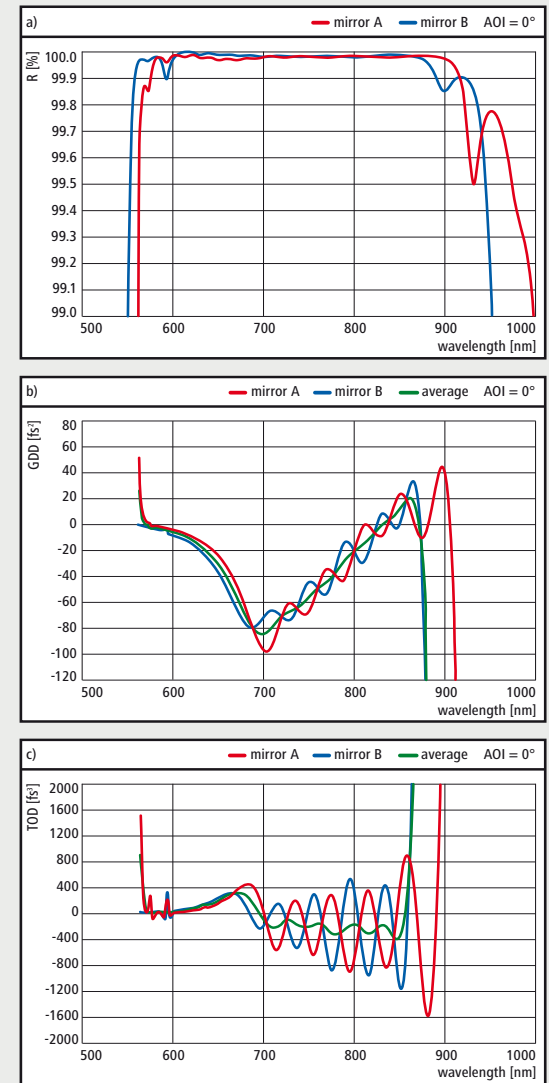


Figure 6: Reflectance, GDD and TOD spectra of a mirror pair optimized for nearly constant negative third order dispersion

- a) Reflectance vs. wavelength
- b) GDD vs. wavelength
- c) TOD vs. wavelength

STANDARD FEMTOSECOND LASER OPTICS

MIRRORS WITH DIFFERENT TOD VALUES

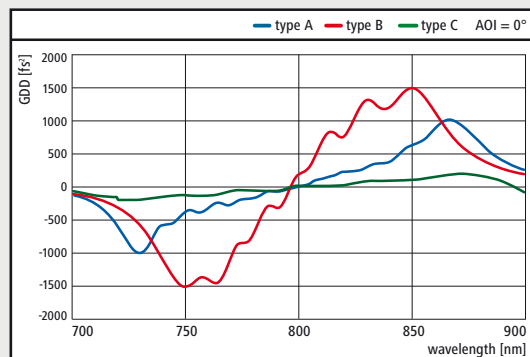


Figure 1: GDD spectra of three negative dispersive mirrors with different TOD values, i.e. different slope of the GDD curves

Increasing the GDD slope, i.e. increasing the absolute TOD results in a lower bandwidth and stronger GDD and TOD oscillations.

- Center wavelength and amount of TOD according to customer specifications.
- In the wavelength range of the Ti:Sapphire laser the bandwidth of single mirrors with optimized TOD is limited to about 150 nm.

THIN FILM POLARIZERS FOR AOI = 55°

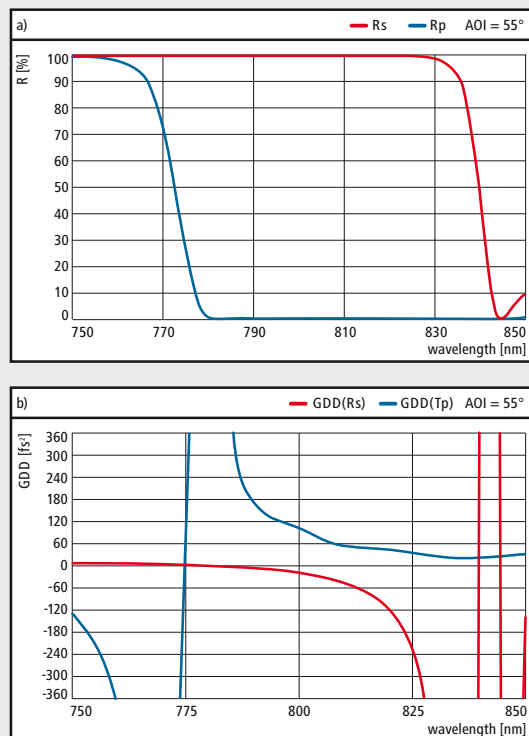


Figure 2: Reflectance and GDD spectra of a standard TFP (AOI = 55° to use the Brewster angle for the transmitted p-polarized light)
a) Reflectance vs. wavelength
b) GDD vs. wavelength

The bandwidth of thin film polarizers can be extended if large angles of incidence are used. As shown in fig. 4 a polarizer bandwidth as large as 100 nm can be achieved. However, this is combined with a reduced reflectance for the s-polarized light.

THIN FILM POLARIZERS FOR AOI = 65°

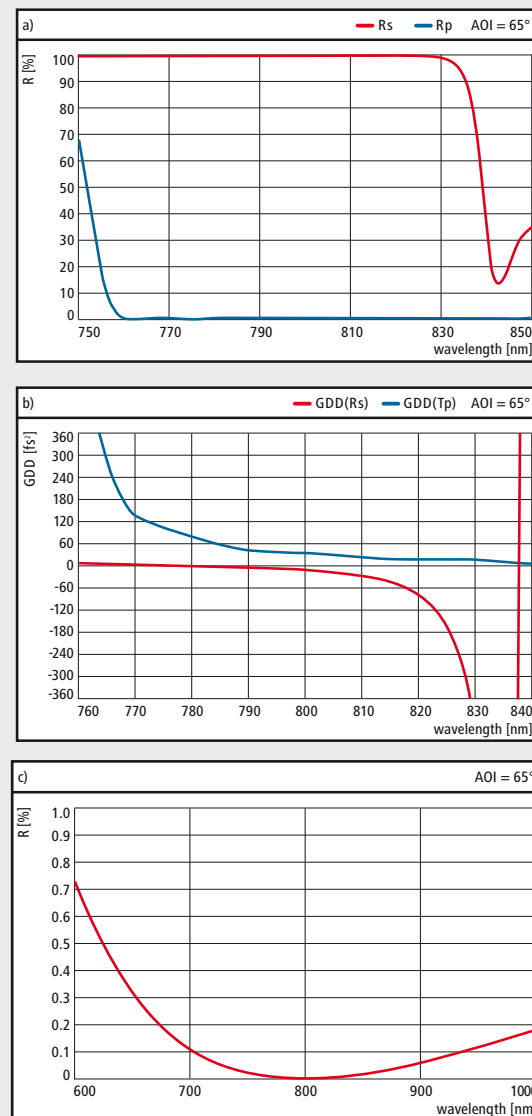


Figure 3: Reflectance and GDD spectra of a TFP (AOI = 65° to achieve a low GDD for Rs and Tp, bandwidth ~ 40 nm)
a) Reflectance vs. wavelength
b) GDD vs. wavelength
c) Back side ARp (65°, 750 – 850 nm)

120 – 150 nm BANDWIDTH

THIN FILM POLARIZERS FOR AOI = 80°

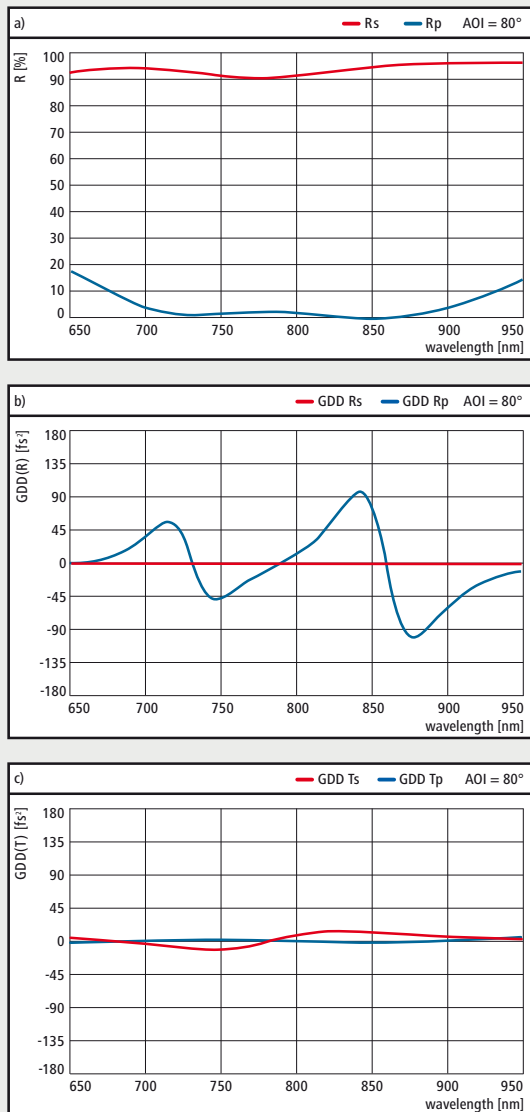


Figure 4: Reflectance and GDD spectra of a TFP (AOI = 80°, lower R_s -value to achieve a low GDD for R_s and T_p , bandwidth ~ 150 nm)

- a) Reflectance vs. wavelength
- b) GDD of the reflected light vs. wavelength
- c) GDD of the transmitted light vs. wavelength

NON-POLARIZING BEAM SPLITTERS FOR AOI = 45°

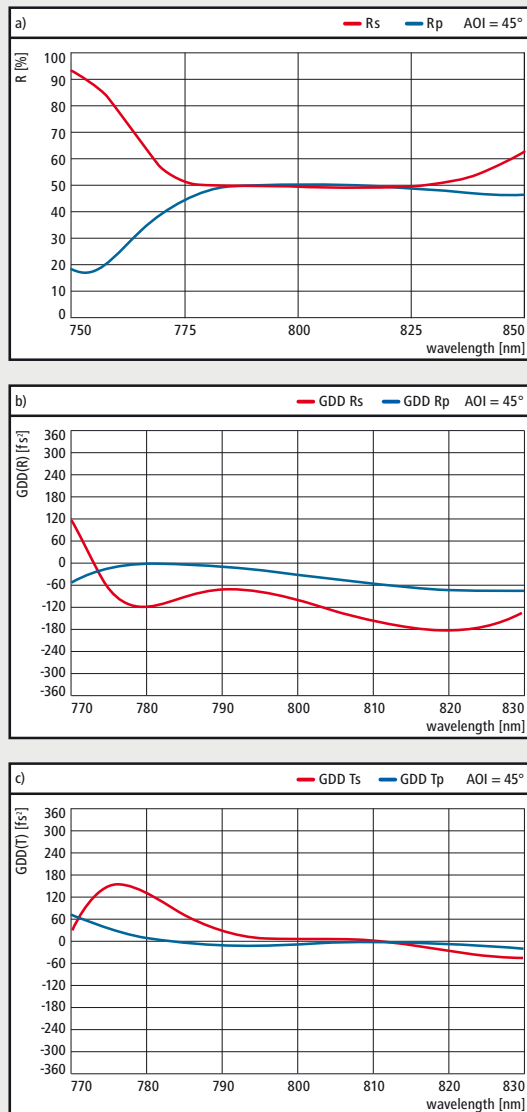


Figure 5: Reflectance and GDD spectra of a non-polarizing beam splitter

- a) Reflectance vs. wavelength
- b) GDD of the reflected light vs. wavelength
- c) GDD of the transmitted light vs. wavelength

ANTIREFLECTION COATINGS

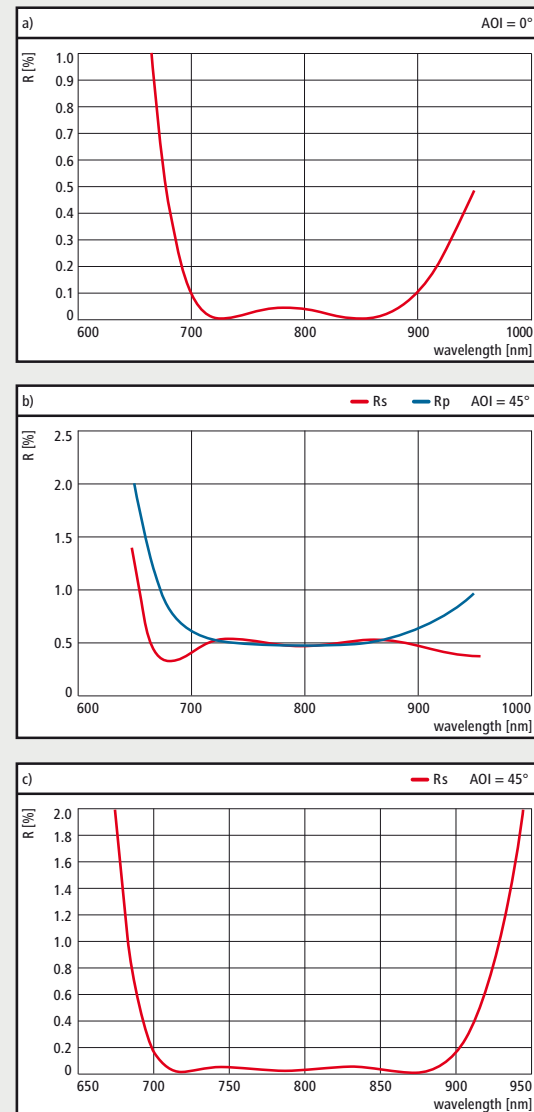


Figure 6: Reflectance of different antireflection coatings

- a) AOI = 0°
- b) AOI = 45° $R_s = R_p \sim 0.5$ %
- c) AOI = 45° $R_s < 0.2$ % (only possible for s- or p-polarized light)

Broadband antireflection coatings for AOI = 0° or a single polarization at AOI > 0° with $R < 0.1$ % on request.

BROADBAND FEMTOSECOND LASER OPTICS

- The coatings shown here are calculated for the wavelength range 700 – 1000 nm. Similar coatings are available for 600 – 900 nm or 650 – 950 nm.
- Very high reflectance of the mirrors ($R > 99.8\%$... $R > 99.95\%$ depending on the design).
- Center wavelength, bandwidth, GDD and TOD

according to customer specifications.

- Spectral tolerance $\pm 1\%$ of center wavelength.
- In-house design calculation and GDD measurement capabilities.
- GDD measurement reports are included in the delivery.

LIDT - INFO

$\approx 0.1 \text{ J/cm}^2$, 800 nm, 150 fs,

Measurements were performed at Laser Zentrum Hannover

MIRROR PAIRS FOR AOI = 0°

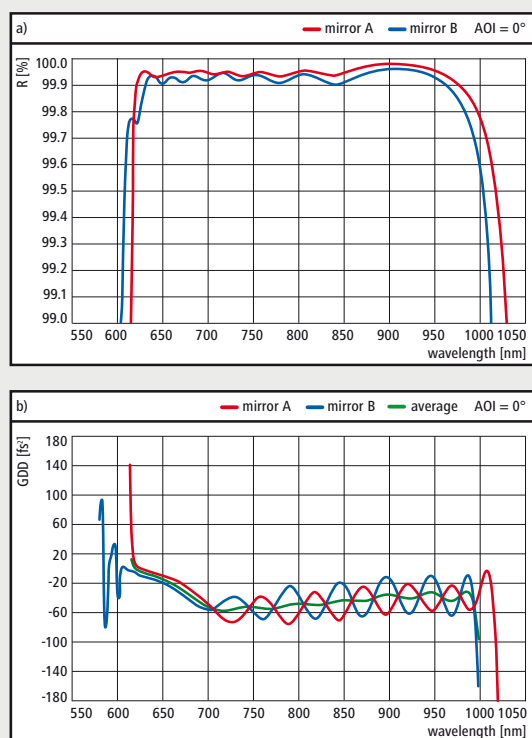


Figure 1: Reflectance and GDD spectra of a negative dispersion laser mirror pair

- a) Reflectance vs. wavelength
b) GDD versus wavelength

Mirror pairs show a very smooth average GDD spectrum, although the single broadband mirrors exhibit strong GDD oscillations. Pump mirror pairs, i.e. mirror pairs with at least one mirror showing high transmittance between 514 – 532 nm, are also available. (See page 82)

TURNING MIRRORS FOR S-POLARIZED LIGHT AT AOI = 45°

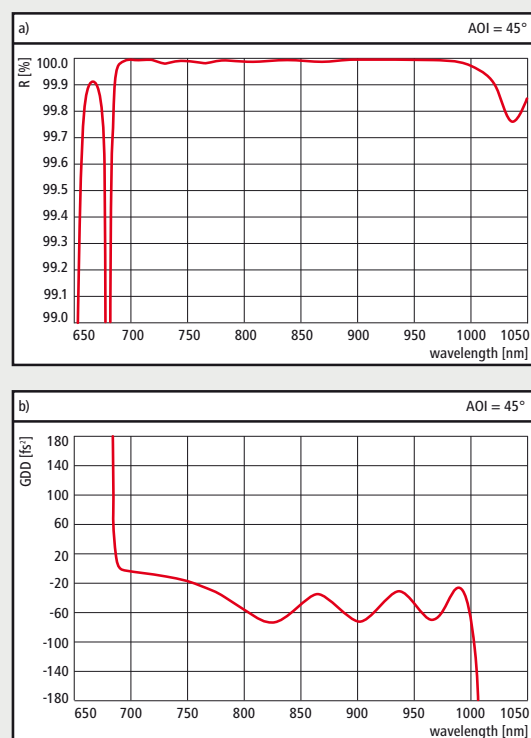


Figure 2: Reflectance and GDD spectra of a broadband turning mirror for s-polarized light

- a) Reflectance vs. wavelength
b) GDD vs. wavelength

TURNING MIRRORS FOR P-POLARIZED LIGHT AT AOI = 45°

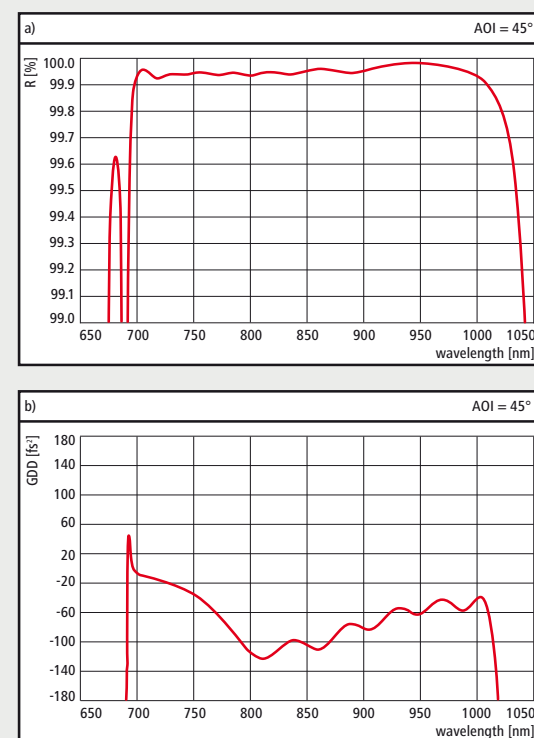


Figure 3: Reflectance and GDD spectra of a broadband turning mirror for p-polarized light

- a) Reflectance vs. wavelength
b) GDD vs. wavelength

200 – 300 nm BANDWIDTH

OUTPUT COUPLERS FOR AOI = 0°

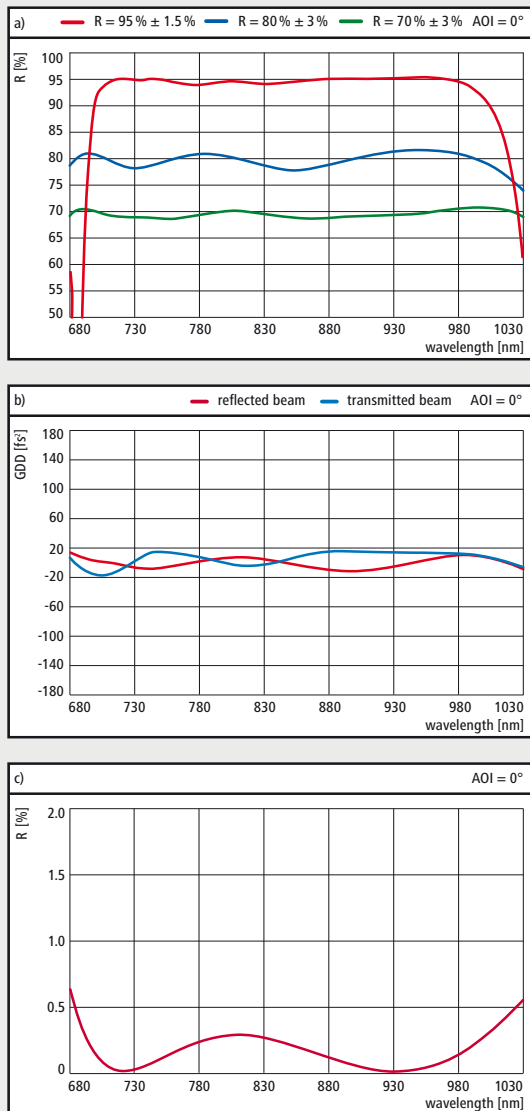


Figure 4: a) Reflectance spectra of several broadband output couplers
b) GDD spectra of the output coupler with $R = 80\%$; the GDD spectra are similar for all levels of reflectance
c) Reflectance spectrum of a broadband AR coating AR (0°, 680 - 1030 nm) < 0.5 %

BEAM SPLITTERS FOR P-POLARIZED LIGHT AT AOI = 45°

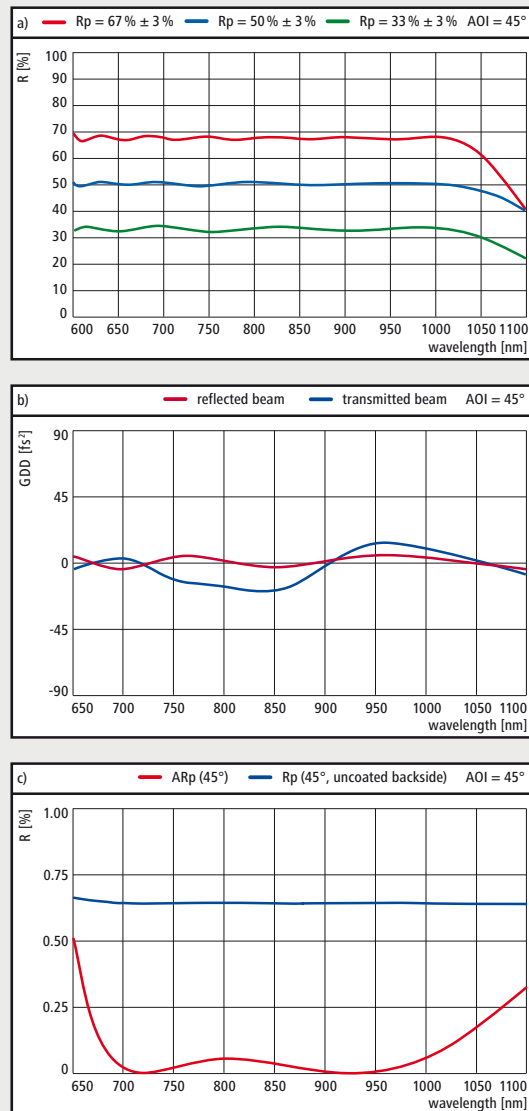


Figure 5: a) Reflectance of several broadband beam splitters for p-polarization
b) GDD spectra for the 50 % beam splitter
c) Reflectance spectrum of a broadband AR coating for p-polarized light

BEAM SPLITTERS FOR S-POLARIZED LIGHT AT AOI = 45°

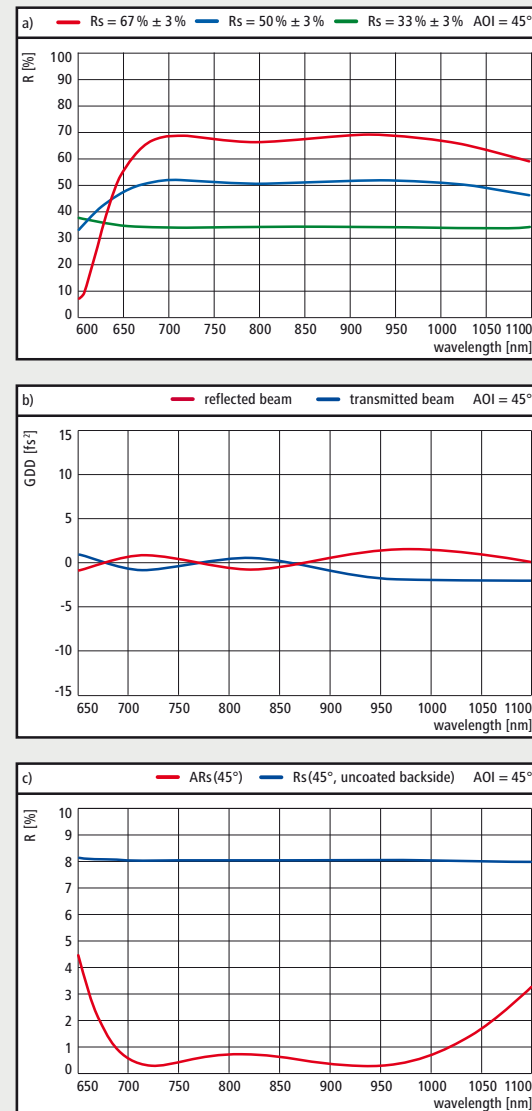


Figure 6: a) Reflectance of several broadband beam splitters for s-polarization
b) GDD spectra for the 50 % beam splitter
c) Reflectance spectrum of a broadband AR coating for s-polarized light

BROADBAND FEMTOSECOND LASER OPTICS

NEGATIVE DISPERSION PUMP MIRROR PAIRS FOR AOI = 0°

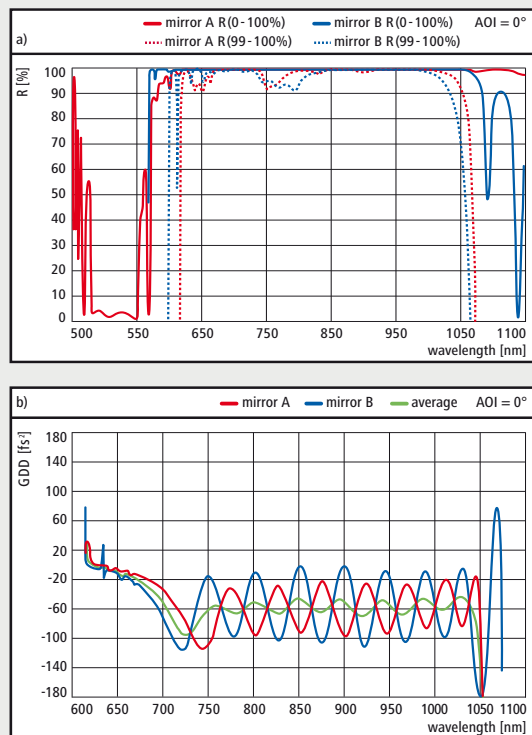


Figure 1: Reflectance and GDD spectra of a negative dispersion pump mirror pair (mirror 2 without HT- option)
a) Reflectance vs. wavelength
b) GDD vs. wavelength

MIRROR PAIRS WITH POSITIVE AVERAGE GDD

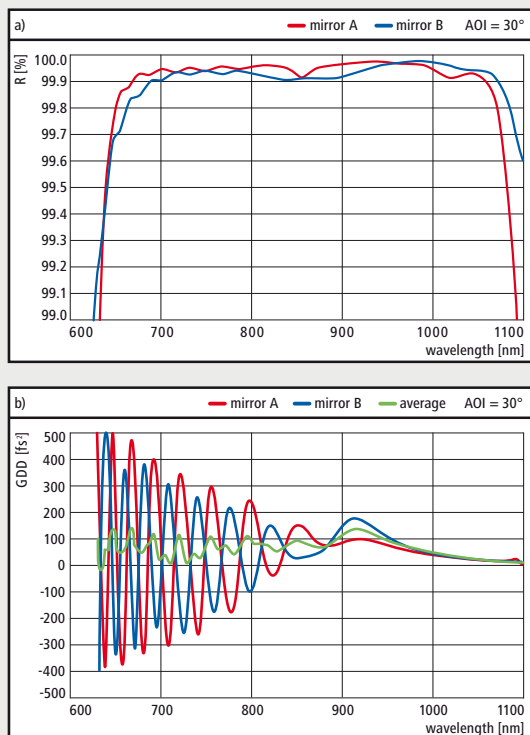


Figure 2: Reflectance and GDD spectra of a broadband mirror pair with positive average GDD for s-polarized light at AOI = 30°
a) Reflectance vs. wavelength
b) GDD vs. wavelength

THIN FILM POLARIZERS FOR AOI = 70°

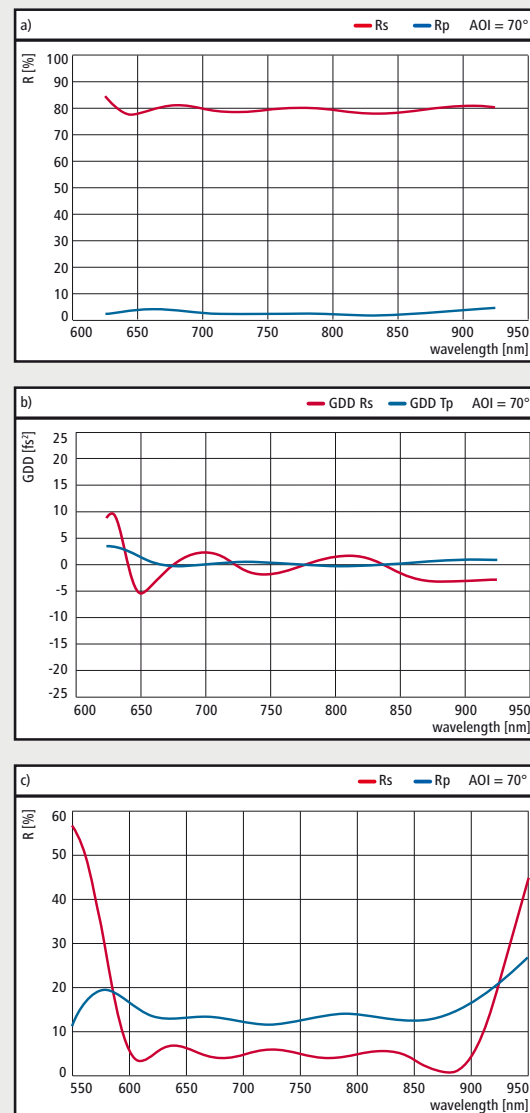
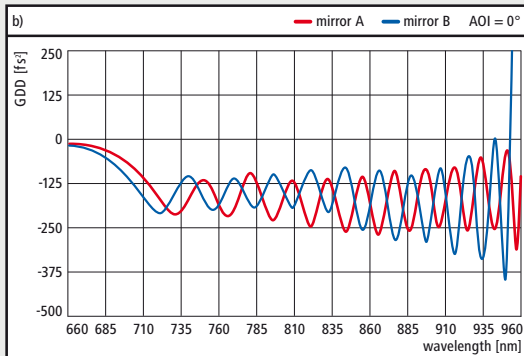
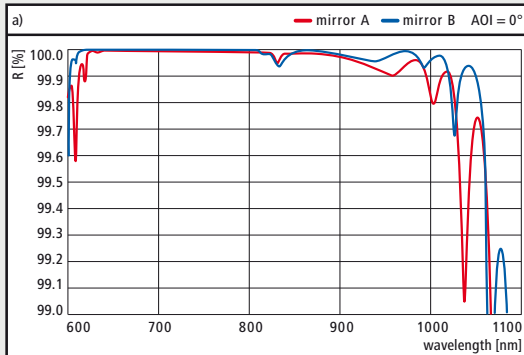


Figure 3: Reflectance and GDD spectra of a TFP (AOI = 70°), lower R_s to achieve "zero" GDD for R_s and T_p , bandwidth ≈ 300 nm
a) Reflectance vs. wavelength
b) GDD vs. wavelength
c) Back side AR coating for s-polarized light. Please note that this coating results in $R \sim 15\%$ for the p-polarization component. As an AR coating for the p-polarization LAYERTEC suggests the use of the design from fig. 3a.

200 – 300 nm BANDWIDTH

HIGH NEGATIVE DISPERSION MIRROR PAIRS FOR AOI = 0°



Measurement

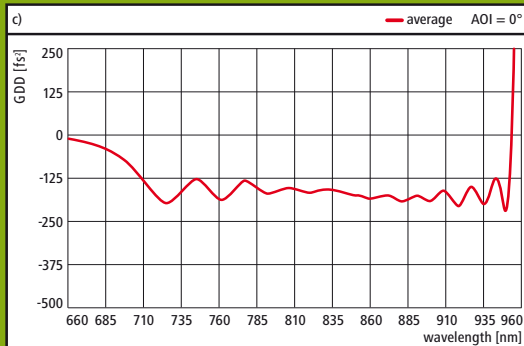


Figure 4: Reflectance and GDD spectra of a high dispersion mirror pair with a bandwidth of 250 nm and an average GDD of $-180 \text{ fs}^2 \pm 40 \text{ fs}^2$ per bounce in the 800 nm range

- Reflectance vs. wavelength
- Calculated GDD vs. wavelength
- Measured average GDD vs. wavelength

MIRROR PAIRS WITH OPTIMIZED THIRD ORDER DISPERSION FOR AOI = 0°

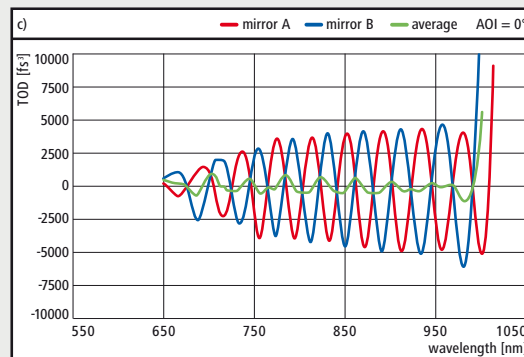
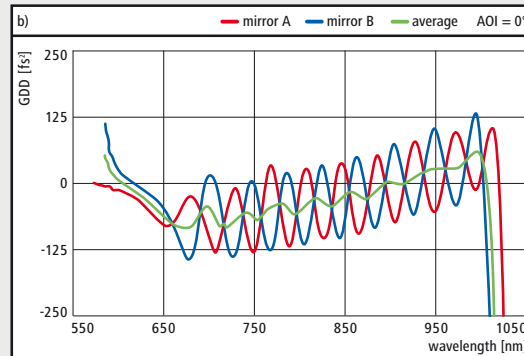
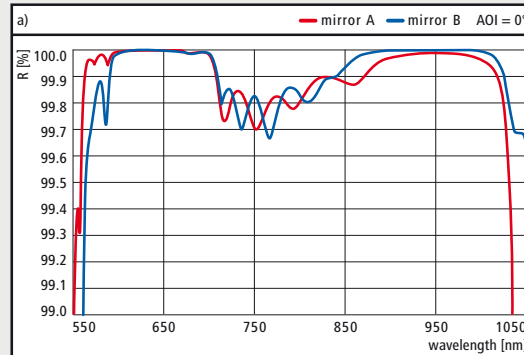


Figure 5: Reflectance, GDD and TOD spectra of a mirror pair optimized for broadband low third order dispersion

- Reflectance vs. wavelength
- GDD vs. wavelength
- TOD vs. wavelength

Special features:

- GDD of high dispersive mirrors between -50 fs^2 and -500 fs^2 .
- Very high reflectance.
- Center wavelength, bandwidth and GDD according to customer specifications.
- Please note that bandwidth and GDD are closely connected. High values of negative GDD result in a very narrow bandwidth.
- Spectral tolerance $\pm 1 \%$ of center wavelength.
- In-house design calculation and measurement capabilities (GDD 250 – 1700 nm, reflectance measurement by CRD 220 – 1800 nm).

LIDT - INFO

$\approx 0.1 \text{ J/cm}^2$, 800 nm, 150 fs,
Measurements were performed at Laser Zentrum Hannover

The mirror pair shows very smooth GDD and TOD spectra, although the single mirrors exhibit considerable GDD and TOD oscillations.

OCTAVE SPANNING FEMTOSECOND LASER OPTICS

- The coatings shown here are calculated for the wavelength range of one octave (e.g. 550 – 1100 nm). Similar coatings are possible for other wavelength ranges.
- Center wavelength, bandwidth, GDD and reflectance of output couplers and beam splitters

according to customer specifications.

- Spectral tolerance $\pm 1\%$ of center wavelength.
- In-house design calculation and GDD measurement capabilities.
- GDD measurement reports are included in the delivery.

LIDT - INFO

$\approx 0.1 \text{ J/cm}^2$, 800 nm, 150 fs,

Measurements were performed at Laser Zentrum Hannover

NEGATIVE DISPERSION LASER MIRROR PAIRS FOR AOI = 0°

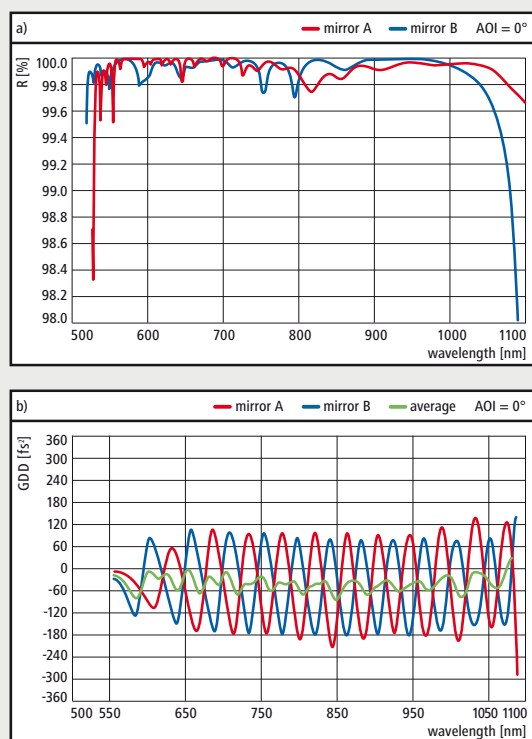


Figure 1: Reflectance and GDD spectra of an ultra broadband negative dispersion laser mirror pair
a) Reflectance vs. wavelength
b) GDD vs. wavelength

Mirror pairs designed by LAYERTEC show a very smooth average GDD spectrum even though the single broadband mirrors exhibit strong GDD oscillations.

NEGATIVE DISPERSION PUMP MIRROR PAIRS FOR AOI = 0°

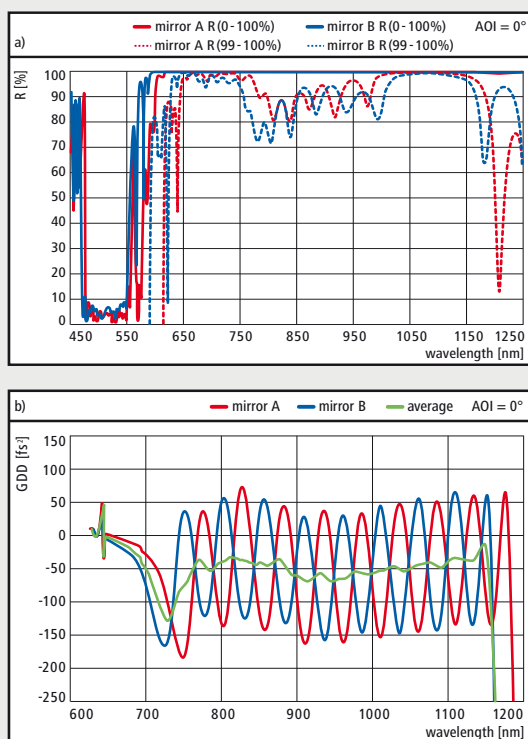


Figure 2: Reflectance and GDD spectra of an ultra broadband negative dispersion pump mirror pair
a) Reflectance vs. wavelength
b) GDD vs. wavelength

The pump mirror pair consists of two mirrors which both show a region of high transmittance around 500 nm.

NEGATIVE DISPERSION TURNING MIRROR PAIRS FOR P-POLARIZED LIGHT AOI = 45°

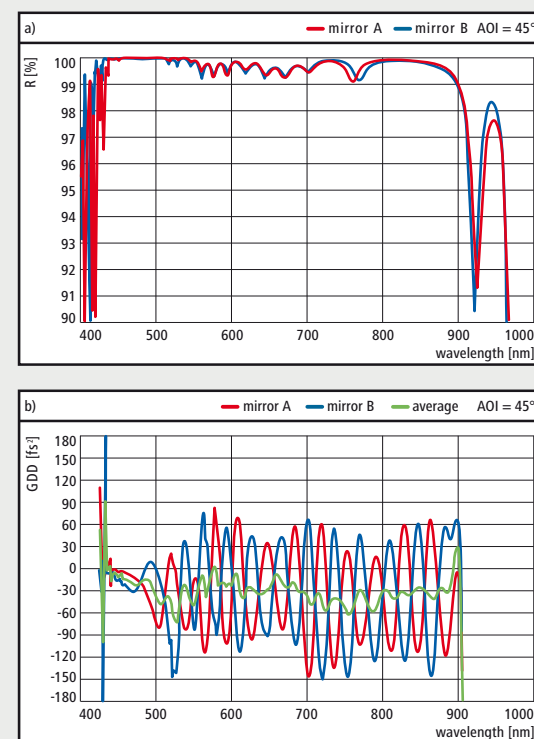


Figure 3: Reflectance and GDD spectra of an ultra broadband turning mirror pair for p-polarized light
a) Reflectance vs. wavelength
b) GDD vs. wavelength

400 – 500 nm BANDWIDTH

OUTPUT COUPLERS FOR AOI = 0°

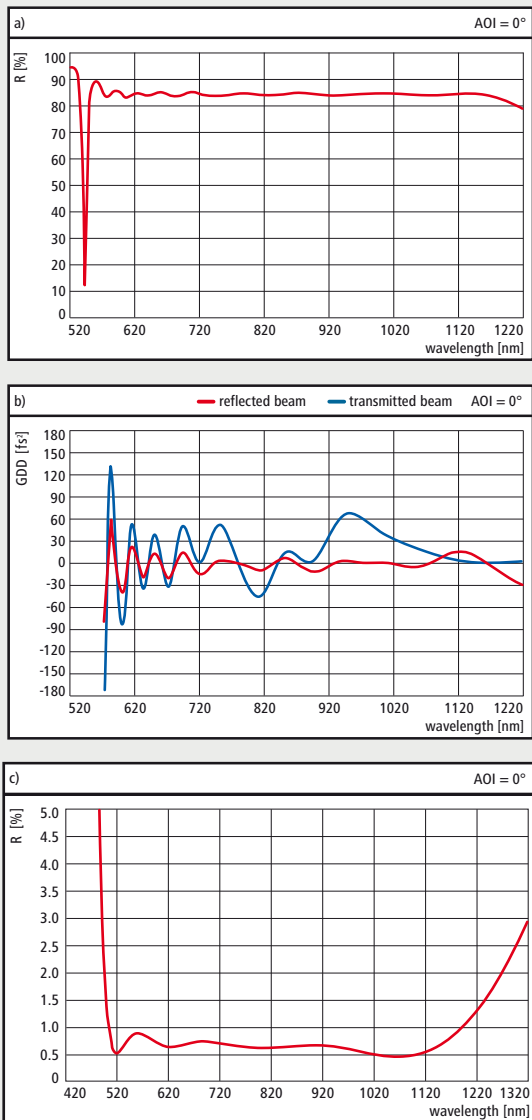


Figure 4: Reflectance and GDD spectra of an ultra broadband output coupler with $R = 85 \% \pm 3 \%$
a) Reflectance vs. wavelength
b) GDD vs. wavelength
c) Back side octave spanning AR coating

BEAM SPLITTERS FOR P-POLARIZED LIGHT AT AOI = 45°

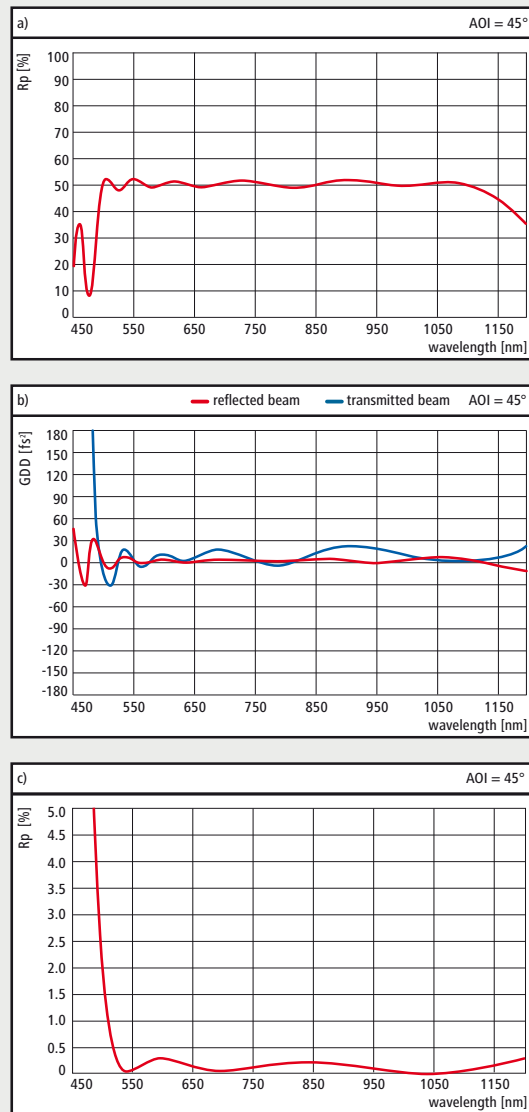


Figure 5: Reflectance and GDD spectra of an ultra broadband beam splitter for p-polarized light with $R_p = 50 \% \pm 4 \%$
a) Reflectance vs. wavelength
b) GDD vs. wavelength
c) Back side octave spanning AR coating for p-polarized light

BEAM SPLITTERS FOR S-POLARIZED LIGHT AT AOI = 45°

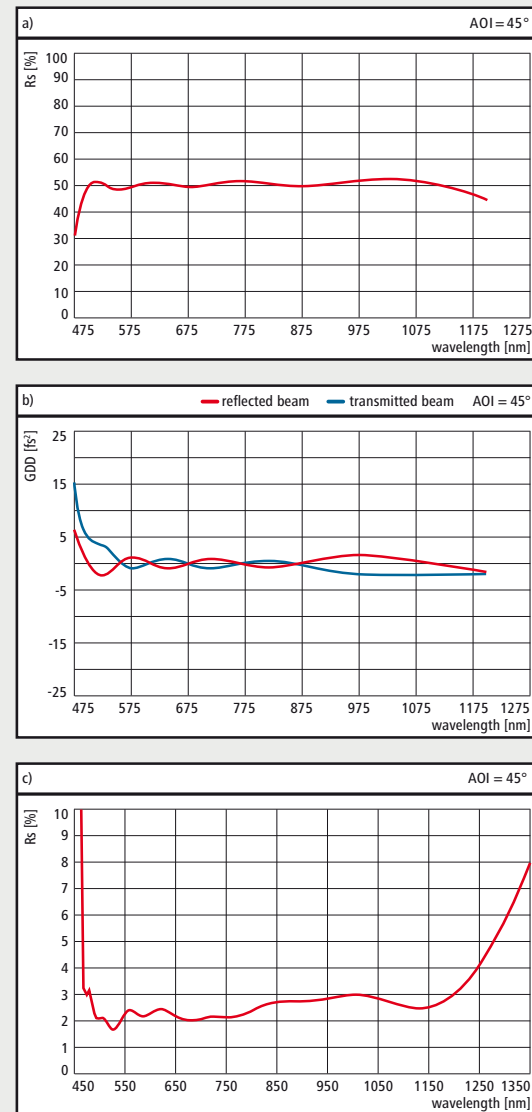


Figure 6: Reflectance and GDD spectra of an ultra broadband beam splitter for s-polarized light with $R_s = 50 \% \pm 5 \%$
a) Reflectance vs. wavelength
b) GDD vs. wavelength
c) Back side octave spanning AR coating for s-polarized light

SILVER MIRRORS FOR FEMTOSECOND LASERS

SILVER MIRRORS OPTIMIZED FOR FEMTOSECOND LASER APPLICATIONS

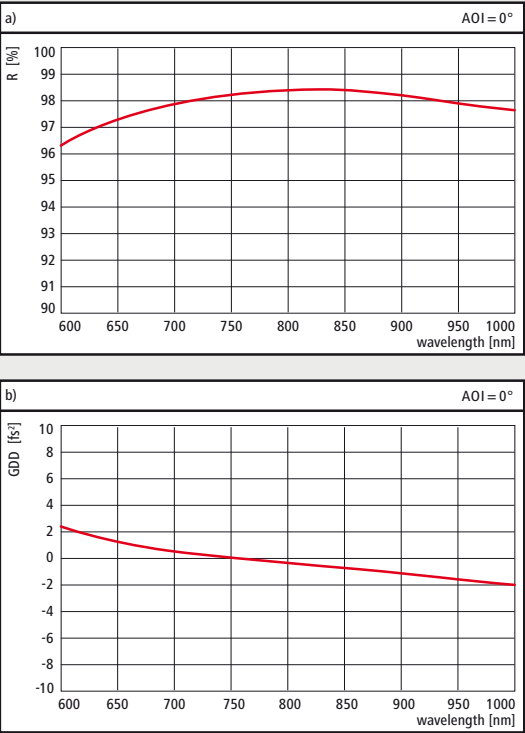


Figure 1: Reflectance and GDD-spectrum of a silver mirror optimized for use with fs-lasers in the wavelength range 600 – 1000 nm (AOI = 0°)

a) Reflectance vs. wavelength

b) GDD vs. wavelength

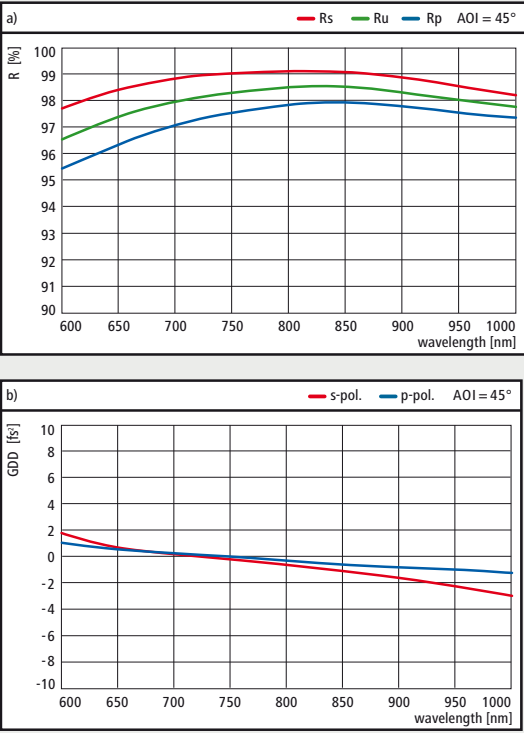


Figure 2: Reflectance and GDD-spectra of a silver mirror optimized for use with fs-lasers in the wavelength range 600 – 1000 nm (AOI = 45°)

a) Reflectance vs. wavelength

b) GDD vs. wavelength

- Special features:**
- High reflectance in the VIS and NIR.
 - Very broad reflectance band with GDD ≈ 0 fs².
 - Silver mirrors with defined transmittance (e.g. 0.01 %) exhibit high LIDT (see table) and the same reflectance and GDD values as shown in fig. 1 and 2.
 - Extremely low scattering losses (total scattering TS ≈ 30 ppm in the VIS and NIR).
 - Lifetimes of more than 10 years have been demonstrated in normal atmosphere.
 - Highly stable optical parameters due to sputtered protective layers.
 - Easy to clean (tested according to MIL-M-13508C § 4.4.5).

- Stock of standard components:**
- Standard and fs-optimized protected silver on substrates with $\varnothing = 12.7$ mm, $\varnothing = 25$ mm and $\varnothing = 50$ mm:
 - Plane,
 - Plano/concave and plano/convex with a variety of radii between 10 mm and 10000 mm.
 - Other sizes, shapes, radii and coatings for other wavelength ranges on request.

LIDT - INFO

Coating	Reflectance*	Wavelength range	LIDT [J / cm²] **
fs-optimized protected silver	R = 96.5 % ... 98.5 %	600 – 1000 nm	0.38
Enhanced silver 800nm	R > 99 %	700 – 900 nm	0.37
Broadband enhanced silver	R = 98 % ... 98.5 %	600 – 1200 nm	0.24
Partially transparent silver	R = 96.5 % ... 98.5 %	600 – 1000 nm	0.22

* For unpolarized light at AOI = 45°

** Measurements were performed at Laser Zentrum Hannover according to ISO 11254
measurement conditions: pulse duration: 150 fs, 30000 pulses, repetition rate: 1 kHz, $\lambda = 800$ nm

550 – 1100 nm

SILVER MIRRORS WITH ENHANCED REFLECTANCE

The reflectance of silver mirrors can be enhanced by an additional dielectric coating. The bandwidth of the enhanced reflectance must be exactly specified. Outside this band, the reflectance of the mirror may be lower than that of a standard silver mirror.

For the use with fs-lasers, the additional dielectric coating must be optimized for high reflectance and low GDD. The following figures show examples for silver mirrors with enhanced reflectance at a specified wavelength (fig. 3 and 4) and over the

wavelength range of the Ti:Sapphire laser (fig. 5). Enhanced silver mirrors can also be designed for a defined transmittance (e.g. $T = 0.01\%$).

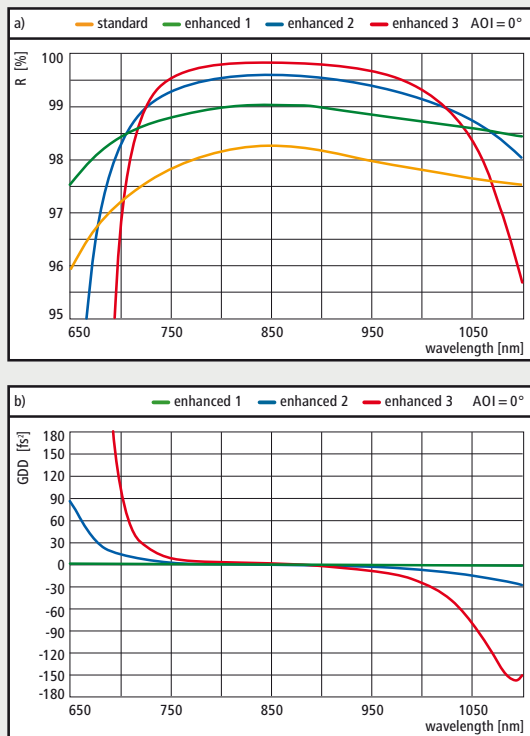


Figure 3: Reflectance and GDD spectra of silver mirrors with different designs for enhanced reflectance around 850 nm ($AOI = 0^\circ$)
a) Reflectance vs. wavelength
b) GDD vs. wavelength

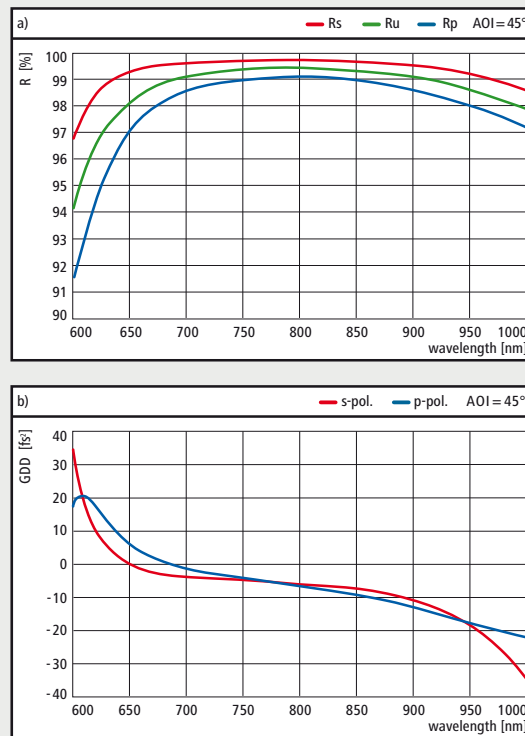


Figure 4: Reflectance and GDD spectra of silver mirrors with enhanced reflectance around 800 nm ($AOI = 45^\circ$)
a) Reflectance vs. wavelength
b) GDD vs. wavelength

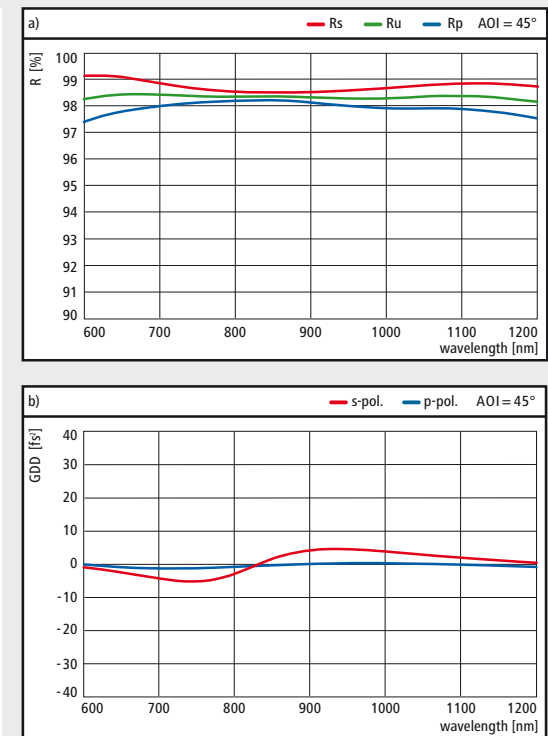


Figure 5: Reflectance and GDD spectra of silver mirrors with enhanced reflectance in the wavelength range 600 – 1200 nm ($AOI = 45^\circ$)
a) Reflectance vs. wavelength
b) GDD vs. wavelength

HIGH POWER FEMTOSECOND LASER OPTICS

Femtosecond lasers are widely used in measurement applications and materials science. Ultrafast lasers enable the machining of metals as well as of dielectric materials by cold, i.e. non-thermal, processes. The most important feature of these treatment steps is the avoidance of melt. That is why pieces machined with ultrafast lasers are of high accuracy and do not require mechanical postprocessing. The demands for efficient production processes drive the development of high-power fs lasers. In most cases, these lasers show pulse lengths between 100 fs and 1 ps (for high power ps lasers see page 55).

Moreover, high-power ultrafast lasers with power levels in the terawatt and petawatt range become more and more important in basic research on light-material-interaction, particle physics and even for medical applications. The pulse duration of these lasers is considerably shorter than that of lasers for material processing. Typical pulse durations range from 20 fs to 50 fs.

The laser types mentioned above require optics with high laser-induced damage thresholds (LIDT). High-power coatings for ultrafast lasers were the topic of a number of scientific investigations in the last years [1, 2]. Research institutes as well as optics manufacturers have spent much effort on the improvement of the LIDT of fs laser optics. LAYERTEC has dealt with this issue for nearly 20 years (please see LAYERTEC's catalogs of 2001 – 2015).

The main result of the investigations mentioned above was that the LIDT of optical coatings in the fs regime is strongly related to the band gap of the coating materials as well as the coating designs. Materials with larger band gaps exhibit larger LIDT. However, there is a trade-off between damage threshold and bandwidth, as large band gaps also translate into a smaller difference of the refractive indices. Thus, turning mirrors made of these materi-

als only have a bandwidth of about 100 nm for p-polarized light at AOI = 45°. This bandwidth is sufficient for pulse lengths as low as 25 fs. Please note that all LAYERTEC high-power designs are optimized for $GDD < 50 \text{ fs}^2$.

In contrast, materials with a large difference of the refractive indices may be used in order to achieve large bandwidths. Designs for standard low-GDD components exhibit medium LIDT values, whereas broadband designs result in low damage thresholds. This is also the case when considering mirrors with dispersion control, such as chirped mirror pairs or GTI mirrors. Here, bandwidth and phase requirements outweigh LIDT. However, depending on the complexity of the overall constraints, some optimization of damage thresholds may be possible.

The investigations have also shown that LAYERTEC's optimized silver mirrors possess significant LIDT values in the fs range. Another advantage of silver mirrors is their extremely broad zero-GDD reflectance band with reflectance up to 98.5 % at normal incidence. Even silver mirrors with a defined transmission of 0.01 % exhibit considerable damage thresholds, especially with respect to dielectric ultra-broadband components. For more information on silver mirrors see pages 86 – 87.

- 1) Femtosecond laser damage resistance of oxide and mixture oxide optical coatings
Author(s): B. Mangote, L. Gallais, M. Commandré, M. Mende, L. O. Jensen, H. Ehlers, M. Jupé, D. Ristau, A. Melninkaitis, J. Mirauskas, V. Sirutkaitis, S. Kicas, T. Tolenis, R. Drazdys
Optics Letters 9 (37), 1478/u20131480 (2012)
- 2) 40-fs broadband low dispersion mirror thin film damage competition
Author(s): Raluca A. Negres; Christopher J. Stolz; Kyle R. P. Kafka; Enam A. Chowdhury; Matt Kirchner; Kevin Shea; Meaghan Daly
Proc. SPIE 10014, Laser-Induced Damage in Optical Materials 2016, 100140E (6 December 2016); doi: 10.1117/12.2244758

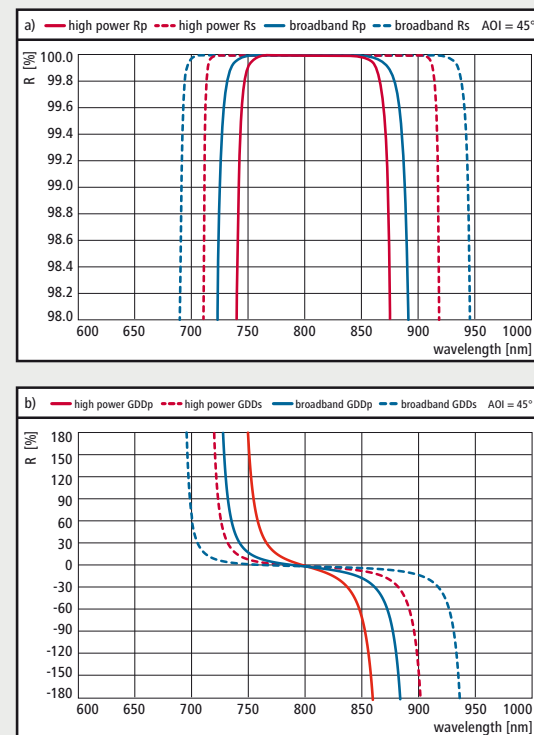
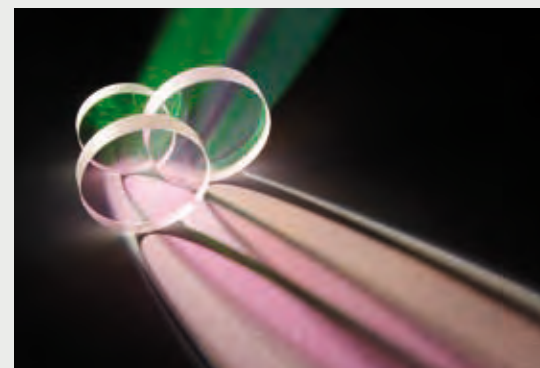


Figure 1: Reflectance (a) and GDD (b) spectra of a high power fs laser turning mirror (red) and a broadband fs laser turning mirror (blue)



550 – 1100 nm BANDWIDTH

OVERVIEW ABOUT LASER INDUCED DAMAGE THRESHOLDS OF FEMTOSECOND LASER OPTICS

LIDT - INFO

Coating	Reflectance [%] at 800 nm	LIDT [J / cm²] at 800 nm	Pulse duration Repetition rate
Unprotected gold	97.5	0.33 ¹⁾ 0.33 ²⁾	50 fs, 1 kHz 150 fs, 1 kHz
fs-optimized silver	98.5	0.38 ¹⁾ 0.38 ²⁾	50 fs, 1 kHz 150 fs, 1 kHz
Enhanced silver (800 nm)	99.7	0.37 ²⁾	150 fs, 1 kHz
Enhanced silver (600 – 1200 nm)	98.5	0.24 ²⁾	150 fs, 1 kHz
Partially transparent silver (T = 0.01 % @ 800 nm)	98.5	0.22 ²⁾	150 fs, 1 kHz
Negative-dispersion mirrors *	> 99.9	0.10 ²⁾	150 fs, 1 kHz
Broadband low-GDD mirrors *	> 99.9	0.15 ¹⁾ 0.10 ²⁾	6 fs, 1 kHz 150 fs, 4 kHz
Standard low-GDD mirrors	> 99.9	0.50 ³⁾ 2.40 ⁴⁾ 0.30 ²⁾ 0.55 ²⁾	42 fs, 1 kHz 70 fs, 10 kHz 150 fs, 1 kHz 1 ps, 1 kHz
High-power mirror for ps pulses	> 99.9	0.35 ¹⁾ 0.44 ²⁾ 0.65 ²⁾	50 fs, 1 kHz 150 fs, 1 kHz 1 ps, 1 kHz
High-power mirror for fs pulses	> 99.5	0.90 ³⁾ 3.60 ⁴⁾	42 fs, 1 kHz 70 fs, 1 kHz
Single-wavelength AR coating **	< 0.2	1.10 ³⁾ 1.20 ²⁾	42 fs, 1 kHz 1 ps, 1 kHz
Broadband AR coating **	< 0.5	1.20 ²⁾	1 ps, 1 kHz

1) Measurements were performed at Friedrich-Schiller Universität Jena

2) Measurements were performed at Laser Zentrum Hannover

3) Measurements were performed at Wigner Research Centre for Physics, Budapest

4) Measurements were performed at Helmholtz-Zentrum Dresden-Rossendorf

*

A significant number of designs were tested. The LIDT values stated here are typical for the corresponding test conditions.

** Self-focusing effects may destroy the substrate while the AR coating is still intact.

METALLIC HIGH POWER MIRRORS

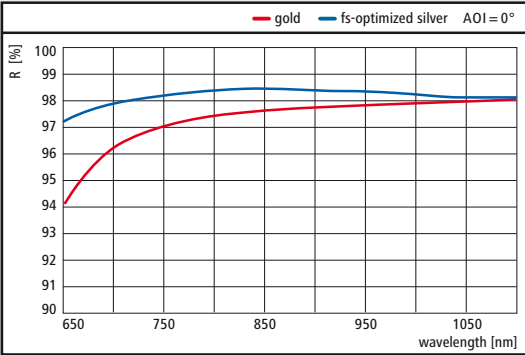


Figure 2: Reflectance spectra of unprotected gold and fs-optimized silver (optimized for high reflectance at 800 nm)

GDD OF HIGH POWER FEMTOSECOND LASER MIRRORS

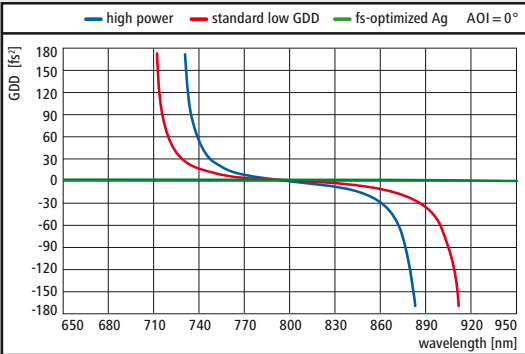


Figure 3: Group delay dispersion (GDD) of standard and high-power dielectric mirrors and fs-optimized silver mirrors

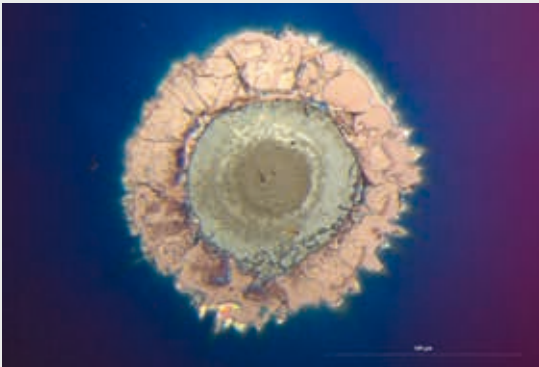


Figure 4: Laser-induced damage of a coated surface

COMPONENTS FOR THE SECOND HARMONIC OF THE Ti:SAPPHIRE LASER

DUAL WAVELENGTH MIRRORS

The second harmonic of the Ti:Sapphire laser provides fs-pulses in the NUV and VIS spectral range. This aspect offers a variety of applications in spectroscopy and materials science. Optics for these special applications must be optimized for both high reflectance and low dispersion. Also, negative dispersion mirrors for pulse compression are of interest.

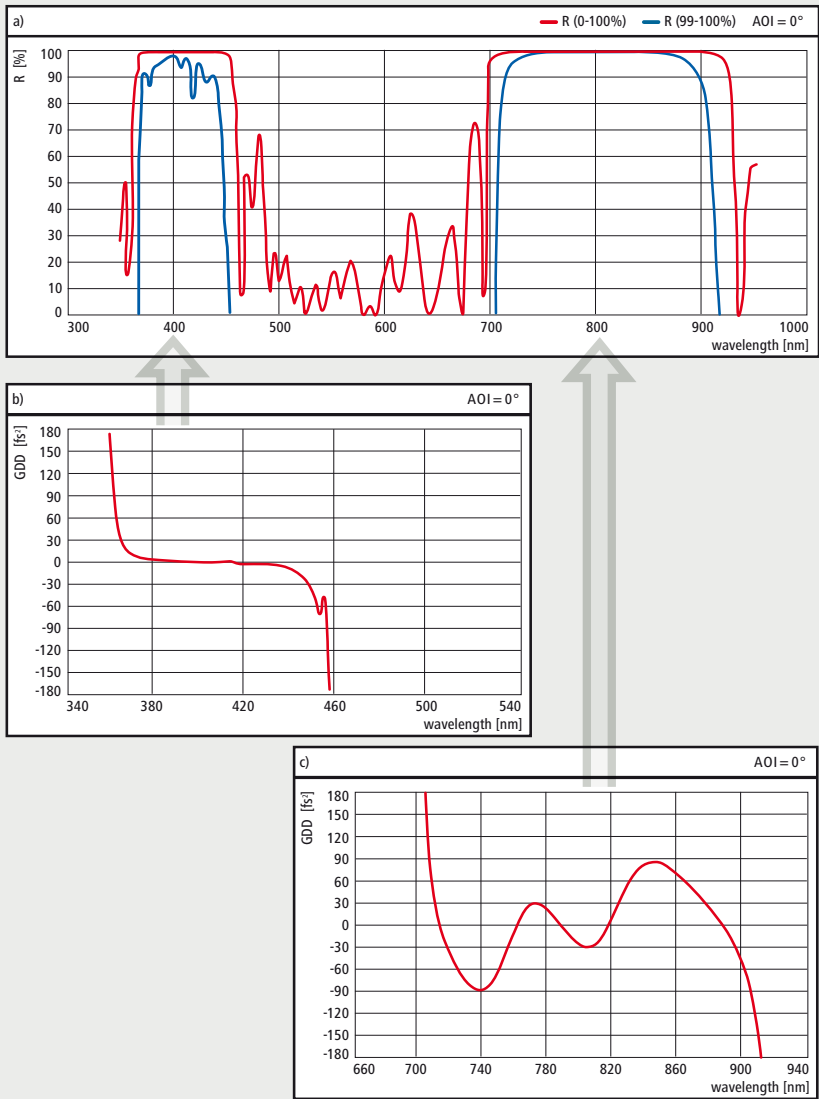


Figure 1: Reflectance and GDD spectra of a fs-optimized dual wavelength mirror for 400 nm + 800 nm at AOI = 0°
a) Reflectance vs. wavelength b, c) GDD vs. wavelength

Special features:

- Very high reflectance ($R > 99.9\%$).
- Center wavelength and bandwidth according to customer specifications.
- Spectral tolerance $\pm 1\%$ of center wavelength.

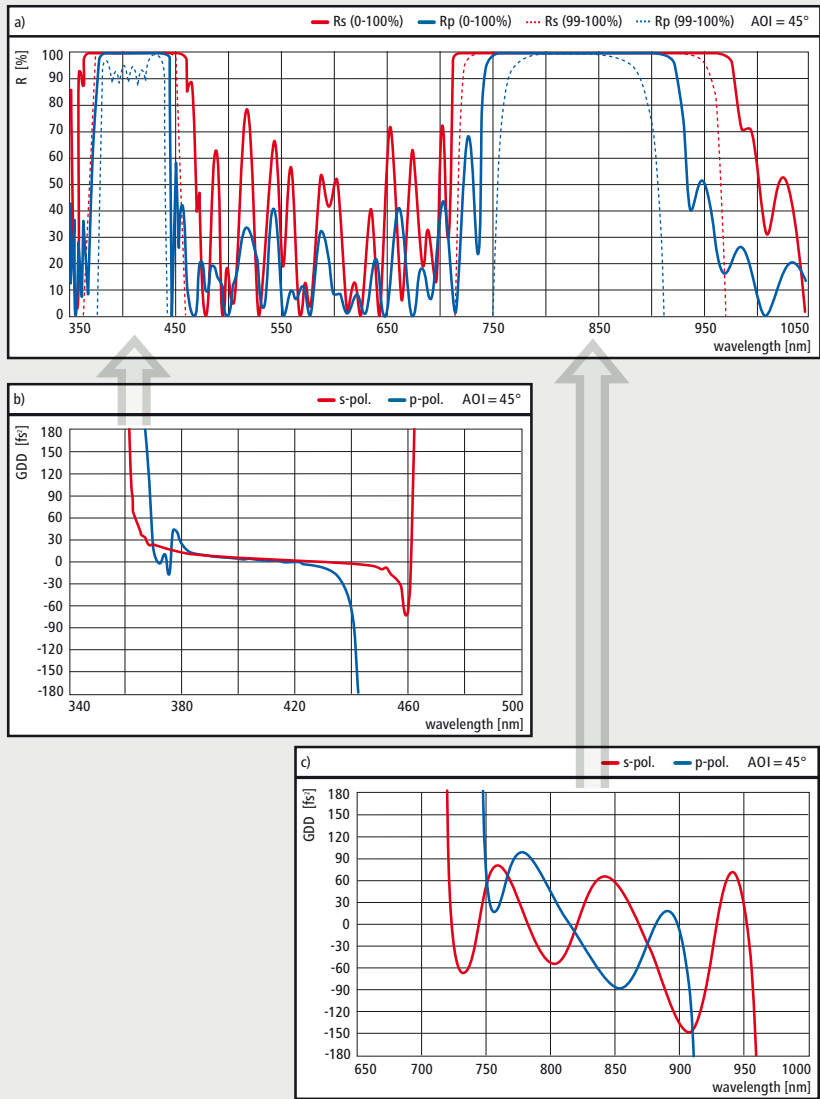


Figure 2: Reflectance and GDD spectra of a fs-optimized dual wavelength turning mirror for 400 nm + 800 nm at AOI = 45°
a) Reflectance vs. wavelength b, c) GDD vs. wavelength

300 – 600 nm

SEPARATORS FOR THE SECOND HARMONIC FROM THE FUNDAMENTAL FOR AOI = 45°

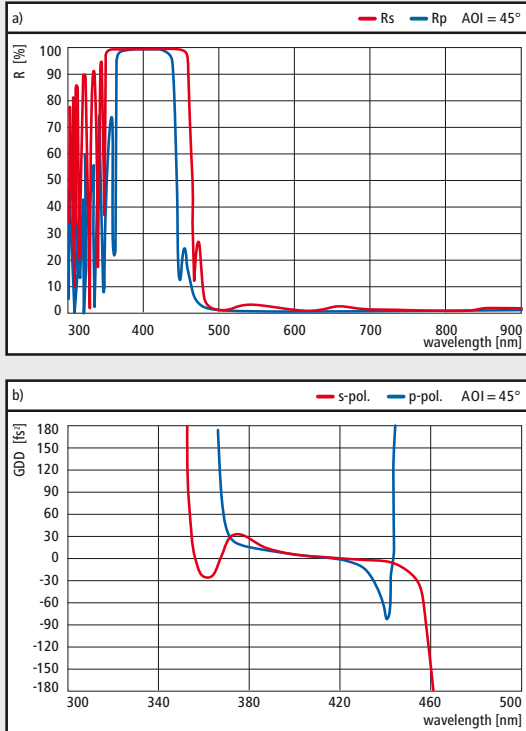


Figure 3: Reflectance and GDD spectra of a separator
 $HR_{s,p}(45^\circ, 400 \text{ nm}) > 99.9\%$ + $Rs,p(45^\circ, 800 \text{ nm}) < 2\%$
 a) Reflectance vs. wavelength
 b) GDD vs. wavelength

- Reflectance $R > 99.9\%$ for s- and p-polarization in the reflectance band.
- Transmittance $T > 95\%$ for s- and p-polarization in the transmittance band.
- These components work for p- and s- polarization, but performance can be optimized if the polarization is clearly specified.

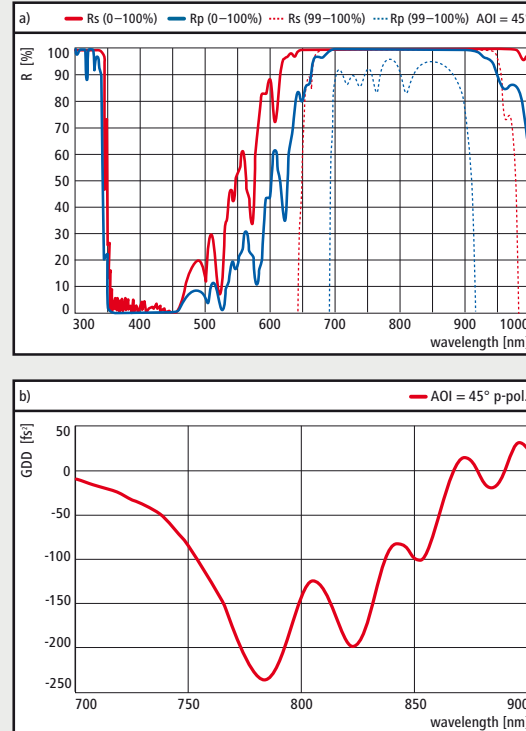


Figure 4: Reflectance and GDD spectra of a separator
 $HR_p(45^\circ, 800 \text{ nm}) > 99.9\%$ + $R_p(45^\circ, 400 \text{ nm}) < 2\%$
 a) Reflectance vs. wavelength
 b) GDD vs. wavelength

- Bandwidth of the 800 nm reflectance band $> 200 \text{ nm}$ for p-polarization.
- All separators exhibit $|GDD| < 20 \text{ fs}^2$ in the transmittance band.

NEGATIVE DISPERSION MIRROR PAIR FOR THE 400 nm SPECTRAL RANGE AT AOI = 0°

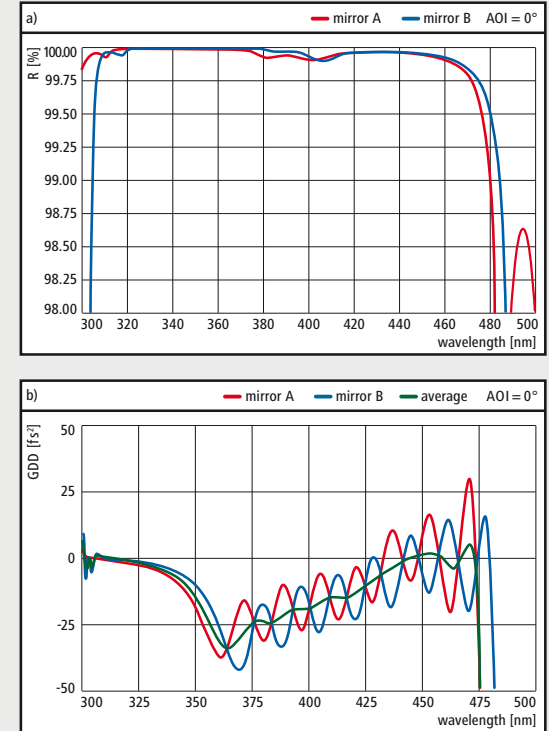


Figure 5: Reflectance and GDD spectra of a negative dispersion mirror pair for 350 – 480 nm with an average GDD varying from -30 fs^2 at 350 nm to 0 fs^2 at 480 nm (TOD optimized)
 a) Reflectance vs. wavelength
 b) GDD vs. wavelength

- Prototype production according to customer specifications.
- In-house design calculation and measurement capabilities.

COMPONENTS FOR THE THIRD HARMONIC OF THE Ti:SAPPHIRE LASER

DUAL WAVELENGTH TURNING MIRRORS FOR AOI = 45°

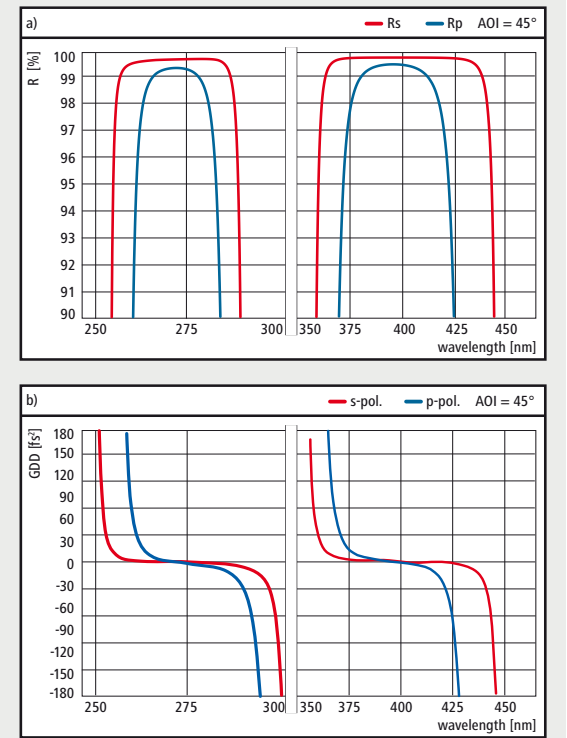


Figure 1: Reflectance and GDD spectra of a fs-optimized dual wavelength turning mirror for 270 nm and 405 nm
a) Reflectance vs. wavelength
b) GDD vs. wavelength

TRIPLE WAVELENGTH TURNING MIRRORS FOR AOI = 45°

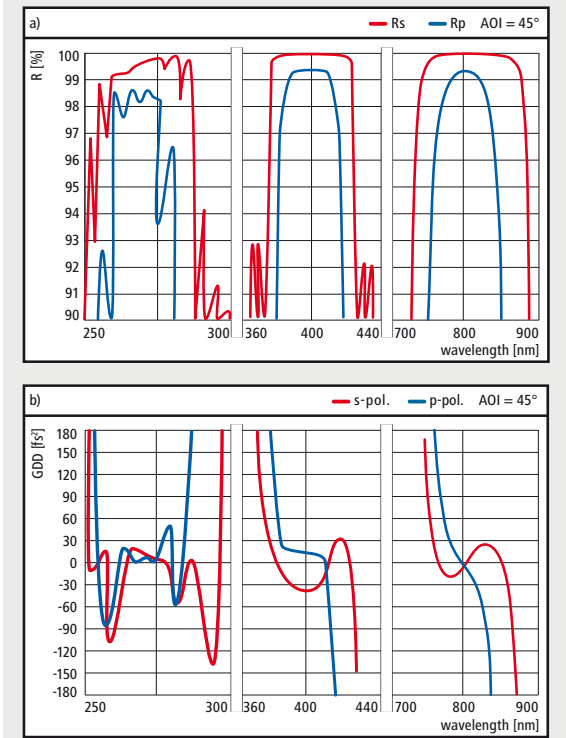


Figure 2: Reflectance and GDD spectra of a fs-optimized turning mirror for the 266 nm, 400 nm and 800 nm wavelength regions
a) Reflectance vs. wavelength
b) GDD vs. wavelength

Please note that this triple wavelength turning mirror exhibits $|GDD| < 50 \text{ fs}^2$ in all three wavelength regions of interest.

BROADBAND LOW DISPERSION MIRRORS FOR AOI = 45°

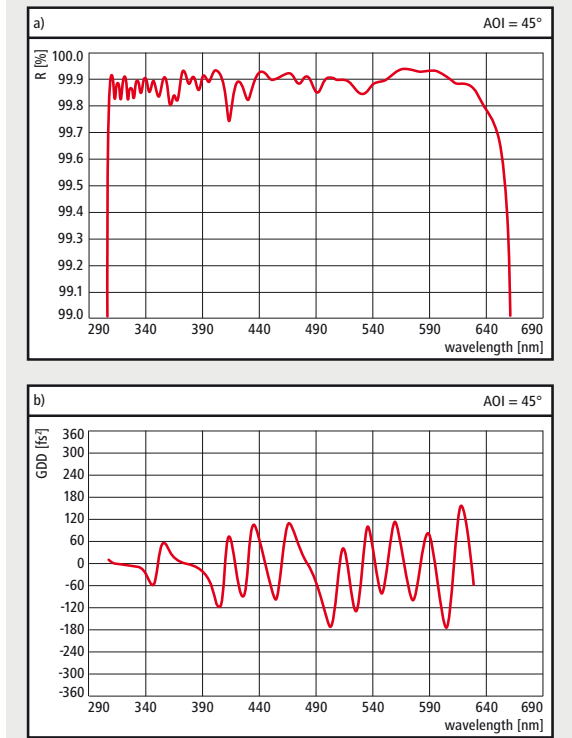


Figure 3: Reflectance and GDD spectra of a broadband negative dispersion mirror HRs (45°, 325 – 600 nm) > 99.7 % with low GDD
a) Reflectance vs. wavelength
b) GDD vs. wavelength

250 – 400 nm

SEPARATORS FOR THE THIRD HARMONIC FROM THE SECOND HARMONIC AND THE FUNDAMENTAL WAVE FOR AOI = 45°

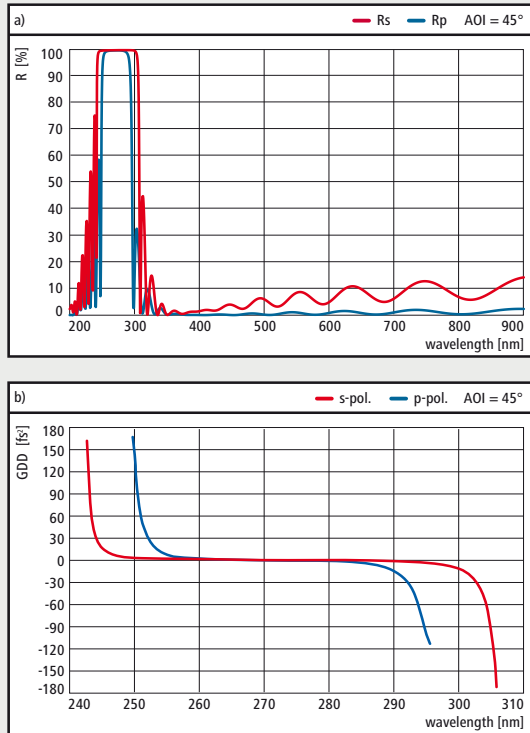


Figure 4: Reflectance and GDD spectra of a standard separator reflecting the third harmonic and transmitting the second harmonic and the fundamental
a) Reflectance vs. wavelength
b) GDD vs. wavelength

For the bandwidth of the reflectance and low-GDD ranges, please see table on page 95.

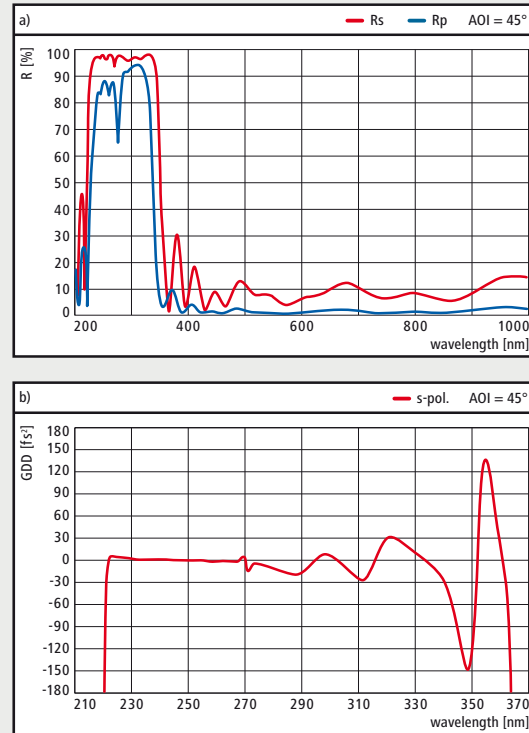


Figure 5: Reflectance and GDD spectra of a broadband separator with high reflectance for s-polarized light throughout the wavelength range of the third harmonic of the Ti:Sapphire laser and high transmittance for p-polarized light in the VIS and NIR:
HRs (45°, 250 – 330 nm) > 95 %
+ Rp (45°, 440 – 1000 nm) < 3 %
a) Reflectance vs. wavelength
b) GDD vs. wavelength

NEGATIVE DISPERSION MIRROR PAIR FOR AOI = 0°

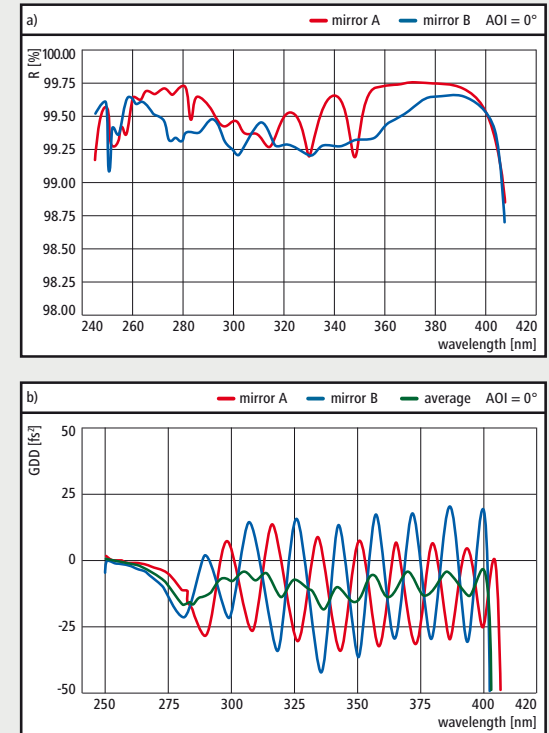


Figure 6: Reflectance and GDD spectra of a broadband negative dispersion mirror pair HR (0°, 275 – 400 nm) > 99 % with an average GDD of ≈ -10 fs² per bounce
a) Reflectance vs. wavelength
b) GDD vs. wavelength

COMPONENTS FOR THE HIGHER HARMONICS OF THE Ti:SAPPHIRE LASER

TURNING MIRRORS AND SEPARATORS FOR THE FOURTH HARMONIC AT AOI = 45°

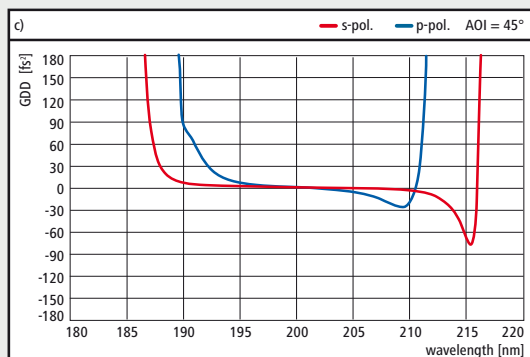
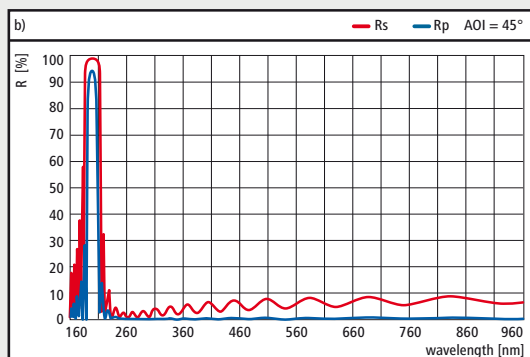
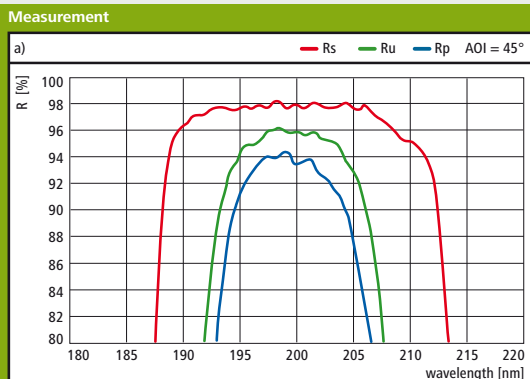


Figure 1: Reflectance and GDD spectra of a separator for the fourth harmonic from the longer wavelength harmonics and the fundamental wave (AOI = 45°)

- a) Reflectance vs. wavelength (measured)
- b) Reflectance vs. wavelength (calculated)
- c) GDD vs. wavelength (calculated)

The fourth, fifth and sixth harmonics of the Ti:Sapphire laser provide fs-pulses in the DUV / VUV range. These harmonics offer a variety of applications in spectroscopy as well as in materials science. Optics for these very special applications must be optimized for high reflectance and low dispersion.

Mirrors and separators for the wavelength range 125 – 215 nm consist of fluoride layer systems on CaF_2

COMPONENTS FOR THE FIFTH HARMONIC AT AOI = 45°

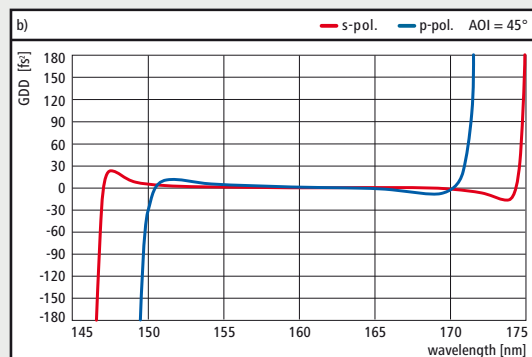
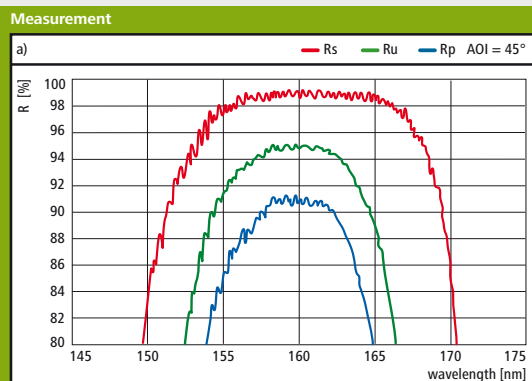


Figure 2: Reflectance and GDD spectra of a turning mirror for 160 nm (AOI = 45°)

- a) Reflectance vs. wavelength (measured)
- b) GDD vs. wavelength (calculated)

substrates while components for longer wavelengths can be made of oxides.

For mirrors, LAYERTEC recommends substrates with a thickness of 3 mm or 6.35 mm to achieve good flatness values. For special separators, LAYERTEC offers substrates of fused silica or calcium fluoride as thin as 1 mm or 0.5 mm.

COMPONENTS FOR THE SIXTH HARMONIC AT AOI = 45°

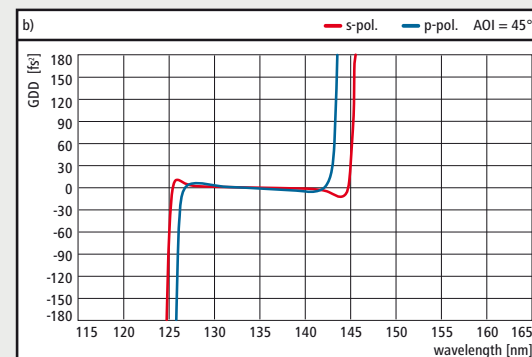
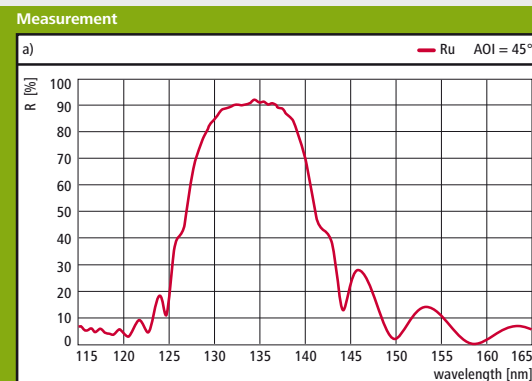


Figure 3: Reflectance and GDD spectra of a turning mirror for 133 nm (AOI = 45°)

- a) Reflectance vs. wavelength (measured for unpolarized light)
- b) GDD vs. wavelength (calculated)

140 – 250 nm

BANDWIDTH OF THE REFLECTANCE AND LOW-GDD RANGE OF STANDARD COMPONENTS

- The coatings described in the data sheets on pages 92 – 95 can be used to achieve center wavelengths as given in the following table. Different coating materials are used for different wavelength ranges.
- All coatings are optimized for broad reflection bands, high reflectance and low GDD.

Component	Wavelength range	P-polarization	S-polarization
		GDD < 20 fs ²	GDD < 20 fs ²
Turning mirror or separator 3rd harmonic	250 nm – 330 nm	30 nm (R > 99 %)	50 nm (R > 99 %)
Dual wavelength turning mirror	250 nm – 330 nm	15 nm (R > 99 %)	26 nm (R > 99 %)
	370 nm – 500 nm	34 nm (R > 99 %)	72 nm (R > 99 %)
Turning mirror or separator 4th harmonic	180 nm – 250 nm	5 nm (R > 93 %)	15 nm (R > 97 %)
Turning mirror or separator 5th harmonic	140 nm – 180 nm	4 nm (R > 90 %)	12 nm (R > 97 %)
Turning mirror or separator 6th harmonic	125 nm – 140 nm	8 nm (R > 85 % unpolarized)	

BROADBAND REFLECTORS FOR THE 200 – 250 nm WAVELENGTH RANGE

Advanced sputtering techniques enable LAYERTEC to produce broadband mirrors and separators for the wavelength range of the fourth harmonic of the Ti:Sapphire laser. These components consist of oxide coatings on fused silica substrates. Please note that oxide coatings show considerable absorption losses between 200 nm and 215 nm. That is why LAYERTEC only specifies R > 80 – 90 % in this wavelength range. Nevertheless, this is the only way to produce broadband low dispersion components for the UV with high transmittance in the VIS and NIR.

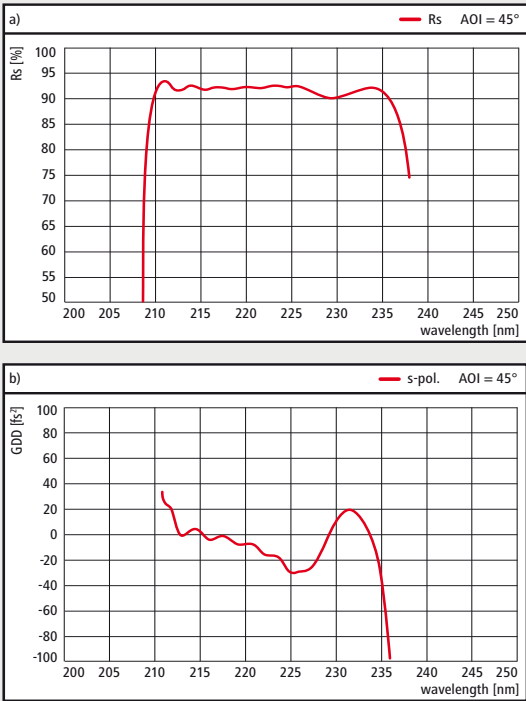


Figure 4: Reflectance and GDD spectra of a broadband mirror HRs (45°, 210 – 235 nm) > 90 %
a) Reflectance vs. wavelength
b) GDD vs. wavelength

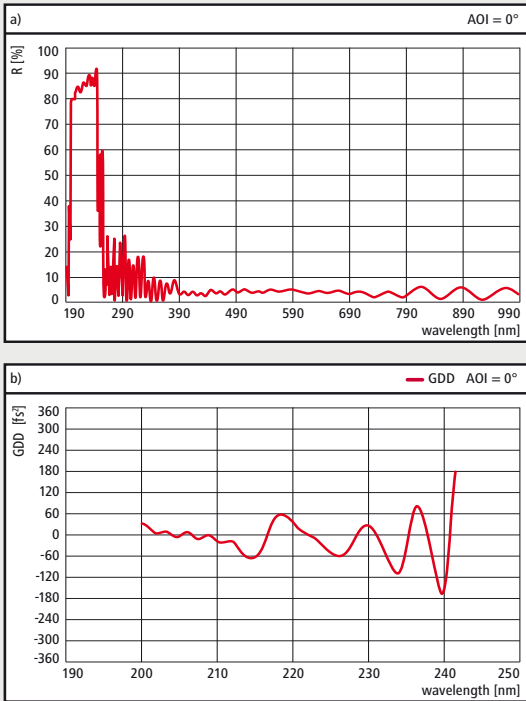


Figure 5: Reflectance and GDD spectra of a broadband separator HR (0°, 200 – 245 nm) > 80 % + R (0°, 300 – 1000 nm) < 10 %
a) Reflectance vs. wavelength
b) GDD vs. wavelength

GIRES-TOURNOIS-INTERFEROMETER (GTI) MIRRORS

Gires-Tournois- Interferometer (GTI) mirrors are used for pulse compression in short pulse lasers such as Yb:YAG- or Yb:KGW-lasers. LAYERTEC also offers GTI mirrors for the Ti:Sapphire wavelength range and for other femtosecond lasers in the NIR spectral range. Compared to prism compressors, GTI mirrors reduce the intra-cavity losses resulting in higher output power of the laser.

Special features:

- Very high reflectance.
- Center wavelength, bandwidth and GDD according to customer specifications.
- Please note that bandwidth and GDD are closely connected. A high value of negative GDD results in a very narrow bandwidth.
- Spectral tolerance $\pm 1\%$ of center wavelength.
- In-house design calculation and measurement capabilities (GDD 250 – 1700 nm, reflectance measurement by CRD 210 – 1800 nm).

LIDT - INFO

$\approx 0.1\text{ J/cm}^2$, 800 nm, 150 fs,
Measurements were performed at Laser Zentrum Hannover

GTI - MIRRORS FOR Yb:YAG- AND Yb:KGW-LASERS

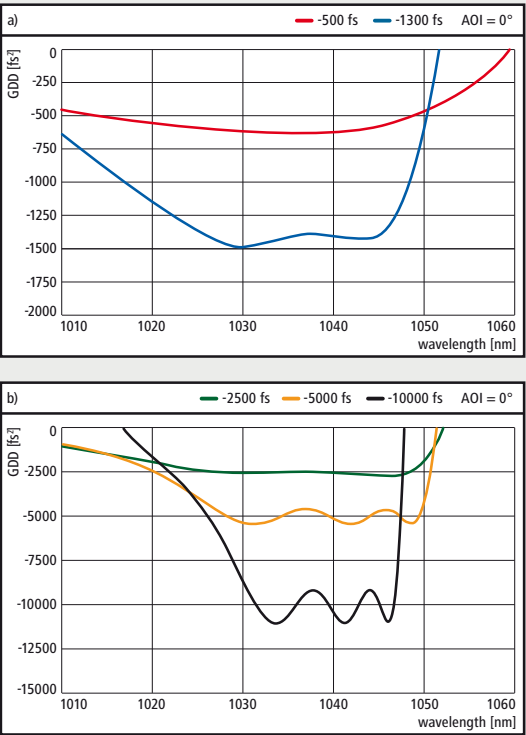


Figure 1: GDD spectra of GTI-mirrors for 1040 nm with different GDD Values

GDD [fs²]	Reflectance [%] measured by CRD
-500	99.99
-1300	99.98
-2500	99.97
-5000	99.95
-10000	99.95

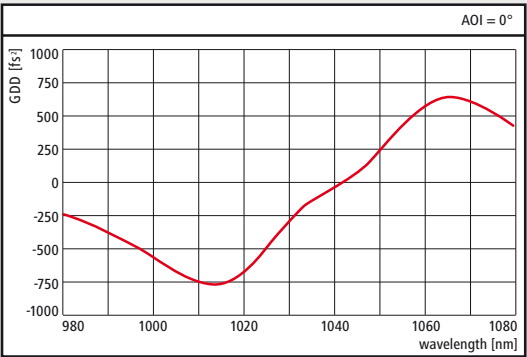


Figure 2: GTI mirror with nearly constant TOD

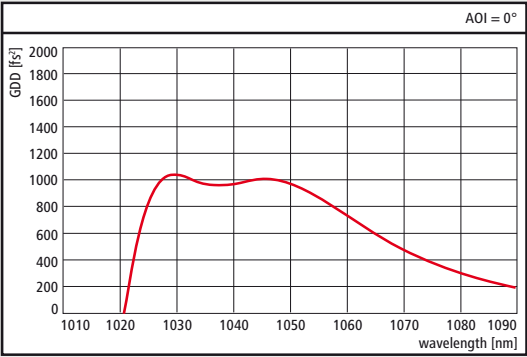


Figure 3: GTI mirror with positive GDD

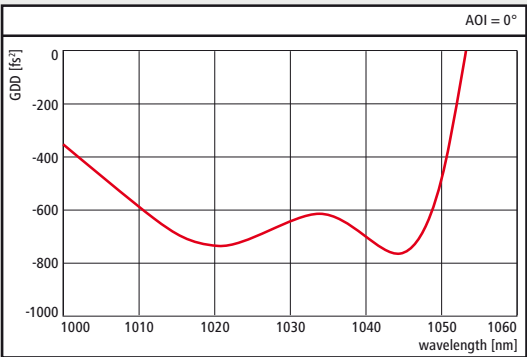


Figure 4: GDD spectrum of a rear side GTI mirror with GDD (0°- 10°, 1030 nm) $\sim -700\text{ fs}^2$. The mirror is irradiated through the substrate which has an AR coating on the front side. Back side GTI mirrors are insensitive against surface contaminations which sometimes distort the GDD spectrum of common front side GTI mirrors

600 – 1600 nm

OPTICAL LOSSES OF GTI MIRRORS

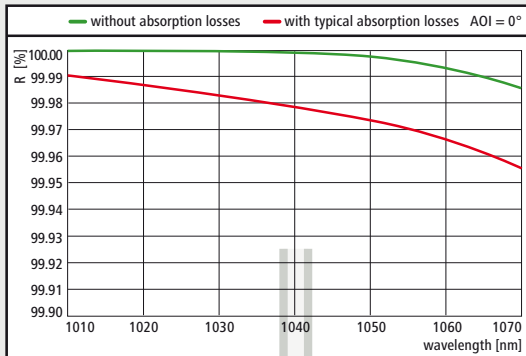


Figure 5: Calculated reflectance spectra of a GTI mirror without absorption losses (green) and with typical absorption losses (red)

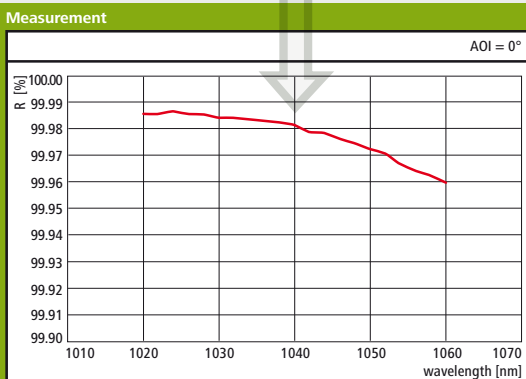


Figure 6: Measured reflectance spectrum of a GTI mirror (design as calculated in fig. 5)

GTI mirrors of LAYERTEC show high reflectance values (e.g. $R > 99.98\%$ at 1030 nm). The reflectance can be measured exactly by CRD. The high reflectance proves that the absorption losses in the GTI mirrors are very small. This also results in very small thermal lensing inside these GTI mirrors if they are used in high power lasers.

COATING HOMOGENITY AND REPRODUCIBILITY OF GTI MIRRORS

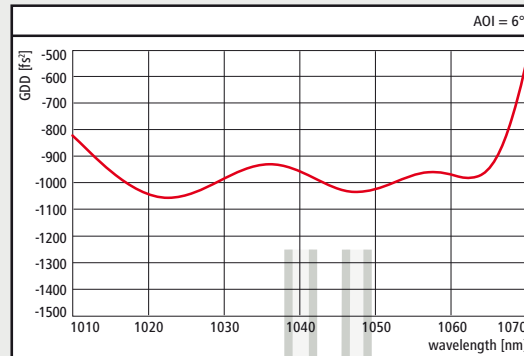


Figure 7: Calculated GDD spectrum of a GTI mirror:
GDDr (6°, 1020 – 1060 nm) $\sim -1000 \pm 200 \text{ fs}^2$

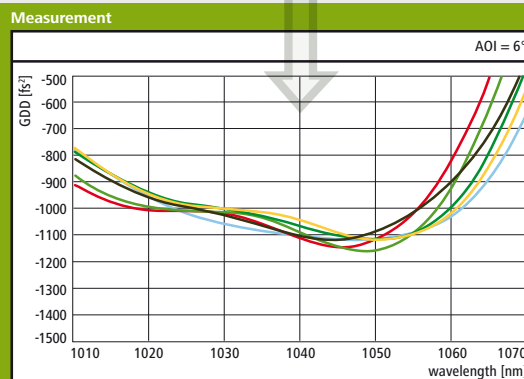


Figure 8: Measured GDD spectra of 6 GTI mirrors which were coated in the same batch according to the design of fig. 7

Fig. 8 and 9 show that all GTI mirrors which were produced in these batches meet the specifications given in fig. 7. Comparing mirrors from two batches the variation within a batch and between batches are much smaller than what is allowed by the specifications. The excellent reproduction of complex coating designs is the basis for the use of GTI mirrors in industrial short pulse lasers.

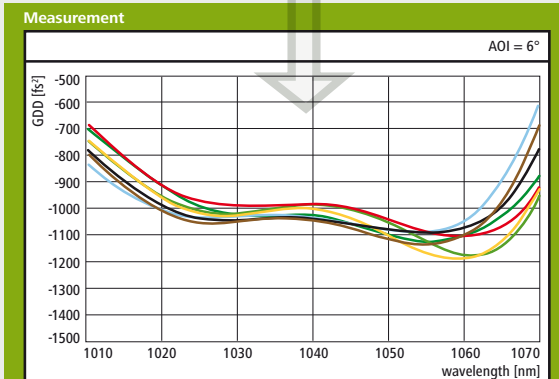


Figure 9: Measured GDD spectra of 6 GTI mirrors which were coated in a second batch according to the design of fig. 7

OPTICS FOR FEMTOSECOND LASERS IN THE 1100 – 1600 nm WAVELENGTH RANGE

Although Ti:Sapphire lasers are currently the most important femtosecond lasers, many applications require femtosecond pulses at considerably longer wavelengths. Several lasers emitting light between 1100 nm and 1600 nm have been developed in recent years, such as the Cr:Forsterite laser (1150 – 1350 nm) or the Er:Fiber laser (1550 nm). Some examples of coatings such as negative dispersion mirrors and mirror pairs for these wavelength ranges are presented.

Special features:

- Very high reflectance of the mirrors ($R > 99.8\%$... $R > 99.99\%$ depending on the design).
- Center wavelength, bandwidth, GDD and TOD according to customer specifications.
- Spectral tolerance 1 % of center wavelength.
- In-house design calculation and measurement capabilities (GDD 250 – 1700 nm, reflectance 210 – 1800 nm).

LIDT - INFO

$\approx 0.1 \text{ J/cm}^2$ (estimated)

NEGATIVE DISPERSION LASER AND PUMP MIRRORS FOR AOI = 0°

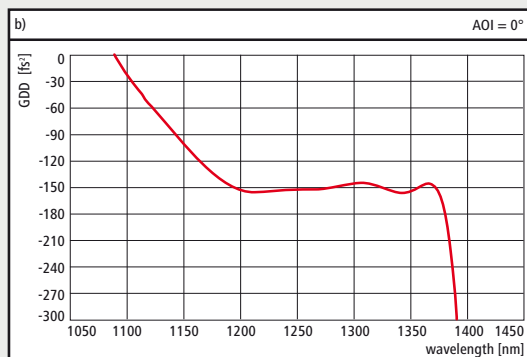
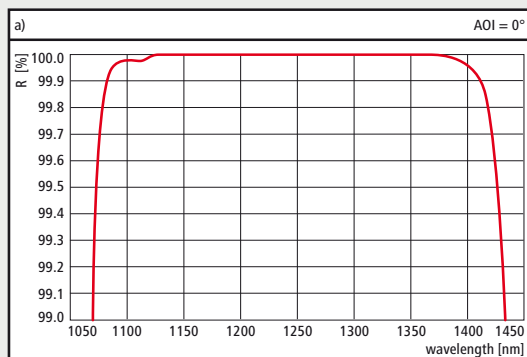


Figure 1: Reflectance and GDD spectra of a negative dispersion laser mirror (GDD $\approx -150 \text{ fs}^2$ for 1200 – 1370 nm)

a) Reflectance vs. wavelength
b) GDD vs. wavelength

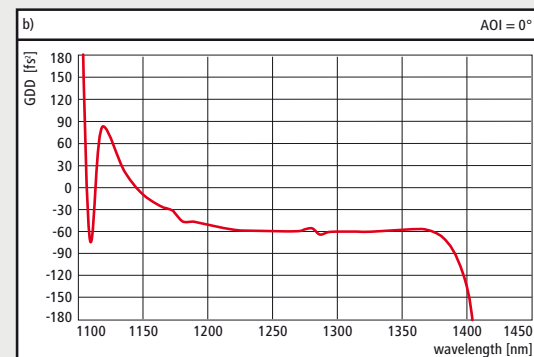
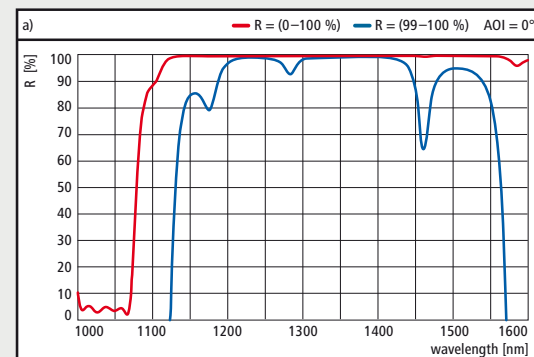


Figure 2: Reflectance and GDD spectra of a negative dispersion pump mirror:

HR (0°, 1180 – 1380 nm) $> 99.8\%$
+ R (0°, 1020 – 1070 nm) $< 5\%$,
GDD-R (0°, 1180 – 1380 nm) $\approx -60 \text{ fs}^2$
a) Reflectance vs. wavelength
b) GDD vs. wavelength

GTI MIRRORS FOR AOI = 0°

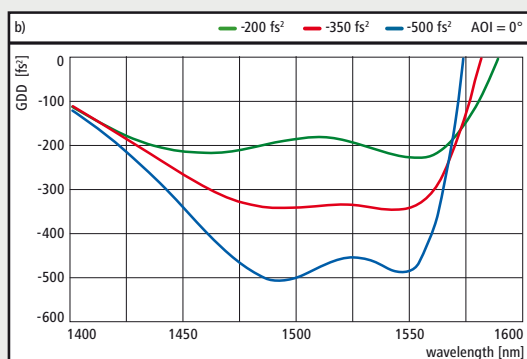
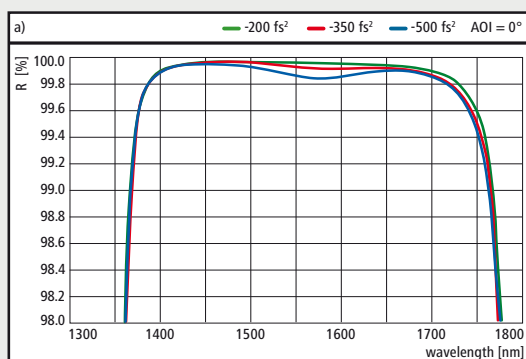


Figure 3: Reflectance and GDD spectra of GTI mirrors for 1500 nm with different GDD values

a) Reflectance vs. wavelength b) GDD vs. wavelength

1100 – 1600 nm

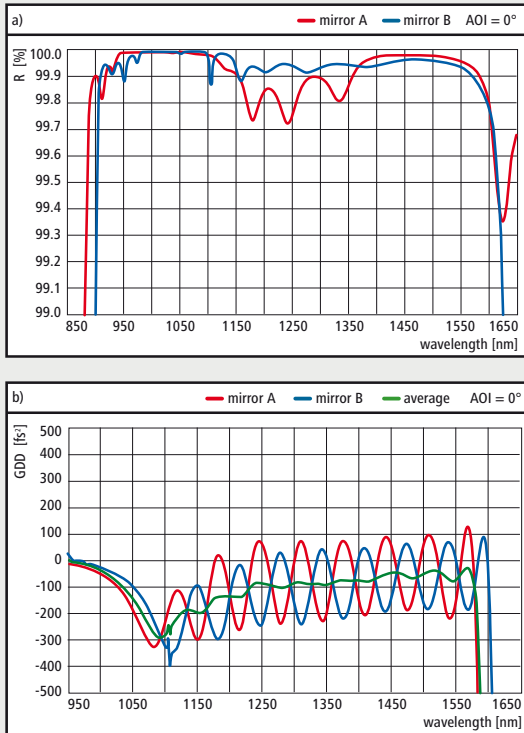
BROADBAND NEGATIVE DISPERSION
MIRROR PAIRS FOR AOI = 0°

Figure 4: Reflectance and GDD spectra of a broadband negative dispersion mirror pair; single mirrors with $R > 99.7\%$ (mirror A) and $R > 99.85\%$ (mirror B)
a) Reflectance vs. wavelength
b) GDD vs. wavelength

Specially designed mirror pairs show a very smooth average GDD spectrum, although the single broadband mirrors exhibit strong GDD oscillations. Pump mirror pairs (i.e. mirror pairs with one mirror showing high transmittance at the pump wavelength of the respective laser type) are also available.

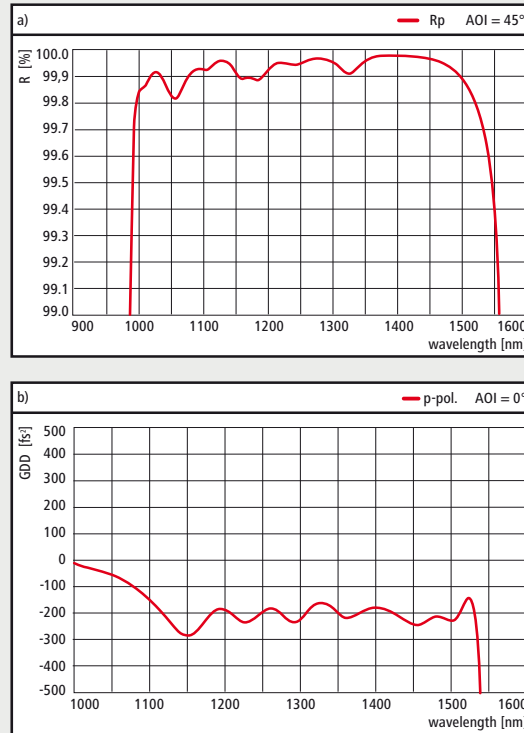
BROADBAND NEGATIVE DISPERSION
TURNING MIRRORS FOR AOI = 45°

Figure 5: Reflectance and GDD spectra of a broadband negative dispersion turning mirror for p-polarized light
a) Reflectance vs. wavelength
b) GDD vs. wavelength

Please note the large bandwidth of this mirror. Low dispersion turning mirrors are available with bandwidths of about 200 nm for p-polarization and about 400 nm for s-polarization in this wavelength range.

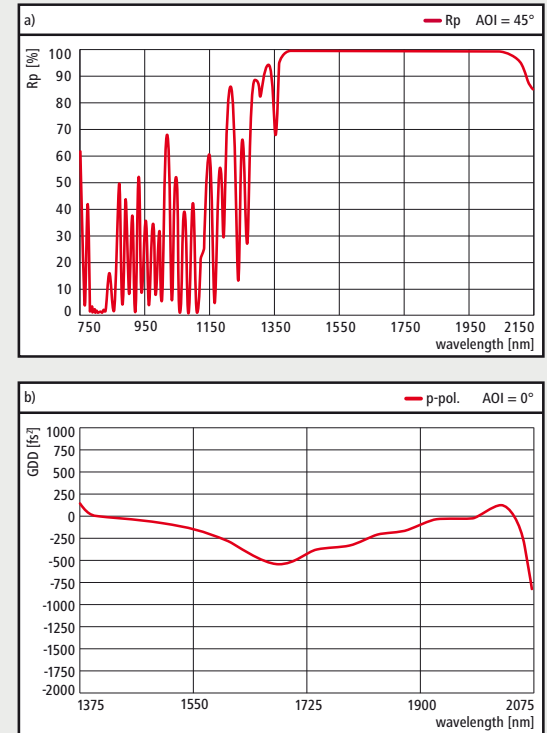
SEPARATORS/COMBINERS WITH NEGATIVE
GDD FOR AOI = 45°

Figure 6: Reflectance and GDD spectra of a beam combiner HRp (45°, 1500 – 2000 nm) + Rp (45°, 800 nm) with negative GDD in the reflection band
a) Reflectance vs. wavelength
b) GDD vs. wavelength

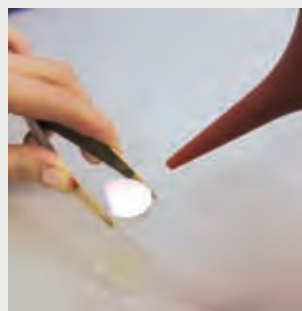
CLEANING OF OPTICAL SURFACES



1

Prerequisites:

- An air blower
- Optical cleaning tissue (e.g. Whatman®)
- Nonslip tweezers (e.g. with cork)
- Spectroscopy grade acetone*



2

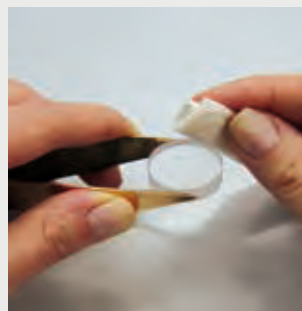
Pre-cleaning:

- Clean hands with soap or use clean gloves (latex, nitrile)
- Blow off dust from all sides of the sample (2)



3

- Moisten tissue with acetone (3)
- Remove coarse dirt from the edge and the chamfer (4)



4

* Compared to alcohol acetone is the better solvent as it significantly reduces the formation of streaks



5

Preparation of the cleaning tissue:

- Fold a new tissue along the long side several times (5, 6)
- Fold across until you have a round edge (7)
- Grab the tissue as shown in (8)



6



7



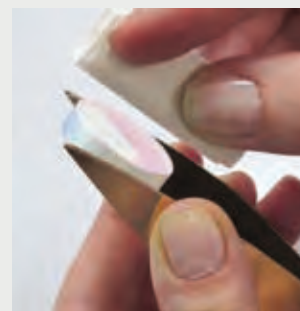
8



9

Cleaning of the optical surface:

- Moisten the tissue with acetone (9)
- A wet tissue will result in streaks
- Hold the sample with tweezers (10)
- Slide the curved tissue from one edge of the sample to the other **once** (10 ... 12)
- The tissue may be turned inside out and used again once
- Repeat steps 9 ... 12 with a new tissue until the sample is clean



10



11



12

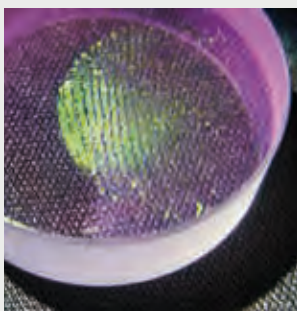
HINTS



13

Small samples:

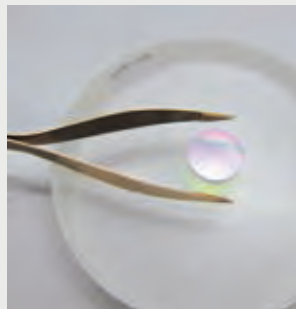
- Put sample onto a concave polished glass support to pick it up easily (13)
- Use special tweezers



14

Fingerprints on sputtered coatings (14):

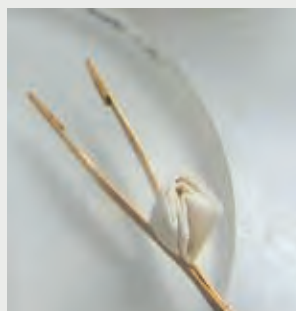
- Moisten the surface by breathing upon it
- Slide (acetone) moistened tissue over the surface as long as the water film is visible
- Exception: Never do this with hygroscopic materials (CaF_2 ...)



15

Storage:

- It works best to store the samples on a polished curved glass support (15)
- Clean the support like an optical surface before use



16

Holding the tissue:

- Use the tweezers to hold the moistened tissue (16)



17

Cleaning of concave surfaces:

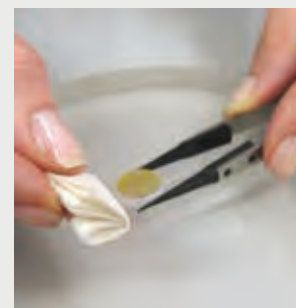
- Use a less often folded tissue that can be slidably bent (17)
- Clean analog to (9) ... (12)
- Use your thumb to gently press the tissue onto the curved surface (18, 19)
- Use tissue only one time
- A concave support helps holding the sample (20)



18



19



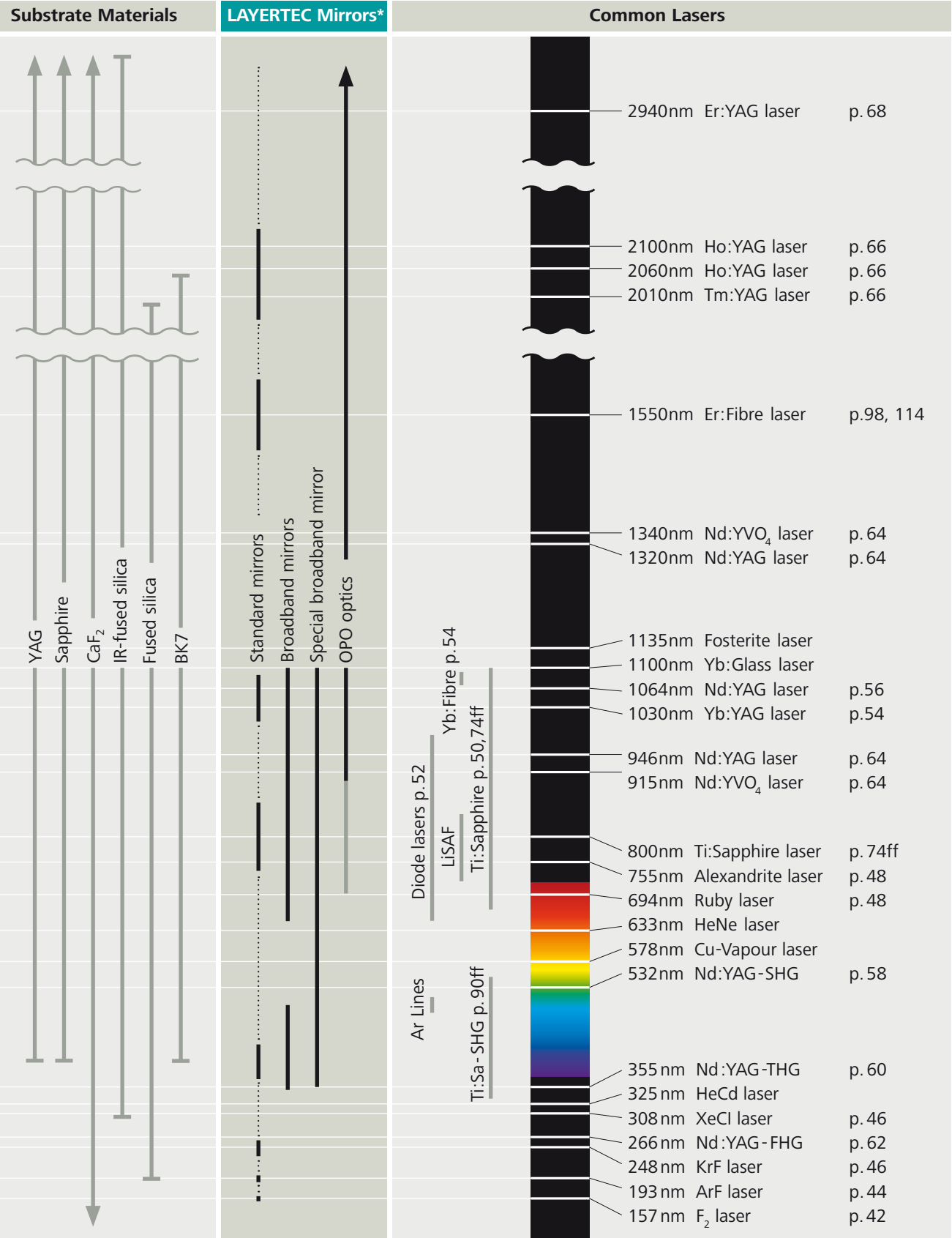
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*Bandwidths of selected LAYERTEC mirrors

Interference Optics



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