CONTENTS

CONTENTS

INTRODUCTION TO FEMTOSECOND LASER OPTICS

Short pulse lasers are used in numerous applications such as time-resolved spectroscopy, precision material processing and large bandwidth telecommunication. Driven by these applications, recent developments in this field are directed to lasers generating higher output power and shorter pulses. Nowadays most of the work in short pulse physics is done with Ti:Sapphire lasers but also dye lasers and solid state lasers on the basis of other transition metal doped crystals such as Cr:LiSAF and Cr:LiSGaF are used for the generation of femtosecond pulses. The reproducible generation of sub-100 fs-pulses is closely connected with the development of broadband low loss dispersive delay lines consisting of prism or grating pairs or of dispersive multilayer reflectors.
In the sub-100 fs-regime it is essential to control the group velocity dispersion (GVD) of each optical element not only in the stretcher and compressor units but also at the cavity mirrors, output couplers and in the beam propagation system. Femtosecond laser optics must be specially designed to control the phase characteristic of the optical system over the extremely wide bandwidth of the fs-lasers. In addition to the power spectrum, i.e. reflectance or transmittance, also the phase relationship among the Fourier components of the pulse must be preserved in order to avoid broadening or distortion of the pulse or the phase relationship is to be changed in a defined way to achieve desired changes (broadening or narrowing) of the pulse.
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 centre frequency ω_0 may be expanded in a Taylor series for frequencies near ω_0:

$$\Phi(\omega) = \Phi(\omega_0) + \Phi'(\omega_0)(\omega-\omega_0) + \Phi''(\omega_0)(\omega-\omega_0)^2/2 + \Phi'''(\omega_0)(\omega-\omega_0)^3/6 + \ldots$$

The derivatives are, respectively, the group delay $\Phi'(\omega_0)$, the **G**roup **V**elocity **D**ispersion (GVD) $\Phi''(\omega_0)$, and the **T**hird **O**rder **D**ispersion (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 shows clearly the physical meaning of the single terms:
Provided the phase shift is linear in frequency (i.e. $\Phi'(\omega_0) \neq 0$, GVD = 0 and 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 GVD≠0, two important effect are observed:

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

The TOD determines also pulse length and pulse shape (distortion of the pulse).
LAYERTEC produces a variety of femtosecond optical components which are shown on the following pages. Most of the components were developed for Ti:Sapphire lasers but the fundamental concepts can be used for other lasers, too.

INTRODUCTION TO FEMTOSECOND LASER OPTICS

Femtosecond laser optics for Ti:Sapphire and related lasers (pages 34–43)
Ti:Sapphire lasers are the most common lasers to produce fs pulses. This chapter introduces optics for the wavelength range of the groundwave of the Ti:Sapphire laser, i.e. 600–1100nm. These components can of course also be used for other lasers working at the same wavelengths. Three sub-chapters present optics with different bandwidths within the Ti:Sapphire range: standard components with a bandwidth of about 120 nm, broadband components (bandwidth about 300 nm) and ultra broadband components (bandwidth of 1 octave). Each of these subchapters shows low dispersion laser and turning mirrors, negative dispersion mirrors or mirrors pairs, output couplers and beam splitters of the corresponding bandwidth. The fourth sub-chapter presents silver mirrors for fs applications which are the components with the broadest low-GVD wavelength region available.

The chapter on **pages 42–43** presents components which are also optimized for **third order dispersion.**

High power femtosecond laser optics / Laser damage thresholds (pages 44–45)
In this chapter we present optics with increased laser damage threshold which is for dielectric mirrors connected with a reduced bandwidth. These mirrors are especially useful for pulslengths >100 fs. However, we found that silver mirrors have LIDT values well above that of standard and broadband dielectric mirrors. On page 45 we present an overview about the laser induced damage thresholds of several components for short pulse lasers.

Components for the harmonics of the Ti:Sapphire laser (pages 46–49)
Phase control for femtosecond pulses in the VIS and UV range becomes more and more important. LAYERTEC provides low dispersive components down to wavelengths around 150–160nm (fifth harmonic). Negative dispersive mirrors are available for the second harmonic (between about 360–440nm)

Gires-Tournois-Interferometer mirrors (pages 50–51)
This section introduces mirrors with a relatively high value of negative GVD and rather small bandwidths. The examples shown here are successfully used in Ti:Sapphire lasers, Yb:YAG- and Yb:KGW-oscillators and Er:fibre lasers. Pulse compression in Yb:YAG- and Yb:KGW-oscillators provided pulses of some hundred femtoseconds pulse length.
For each wavelength, components with different amounts of negative GVD are presented. Some designs are based on the ideas of Gires and Tournois from the early 1960s which gives the name for this kind of mirrors, other designs with similar properties are rather similar to the negative dispersive mirrrors introduced on pages 34–43.

Femtosecond laser optics for other NIR wavelengths (pages 52–53)
On these pages we present e.g. optics for Cr:Forsterite and Er:fibre lasers.

Calculation of designs and GVD measurement
LAYERTEC has own capabilities for design calculation and also for GVD measurements in the wavelength range from 650–1100 nm.

References:
H. Holzwarth, M. Zimmermann, Th. Udem, T. W. Hänsch, P. Russbüldt, 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 (BANDWIDTH ~120 nm)

- The coatings shown here are calculated for a bandwidth of 120–150nm in the wavelength range between 600nm and 1000nm.
- Very high reflectivity of the mirrors (R>99.9 ... 99.97%)
- Spectral tolerance 1% of centre wavelength
- LIDT = 0.1 ... 0.3J/cm² depending on the coating design
- In house design calculation and GVD measurement capabilities
- **OEM-production:**
  Centre wavelength, GVD and TOD according to customer specification

STANDARD MIRRORS FOR FEMTOSECOND LASERS

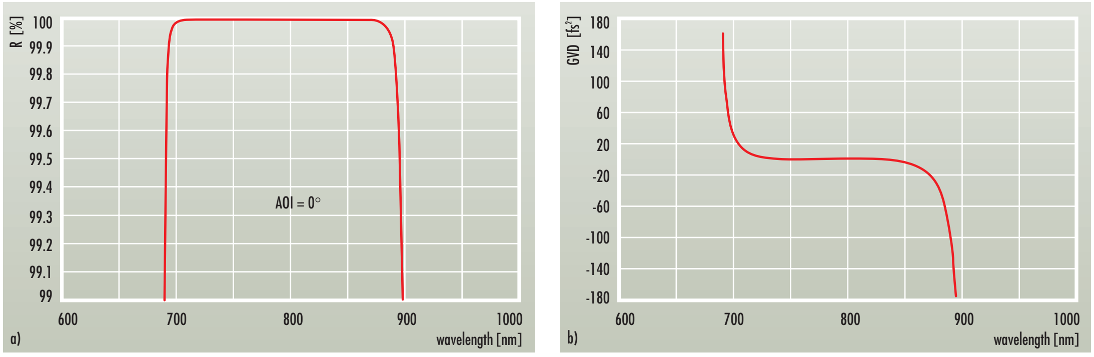

Figure 1: Reflectance (a) and GVD (b) spectra of a standard low dispersion femtosecond laser mirror

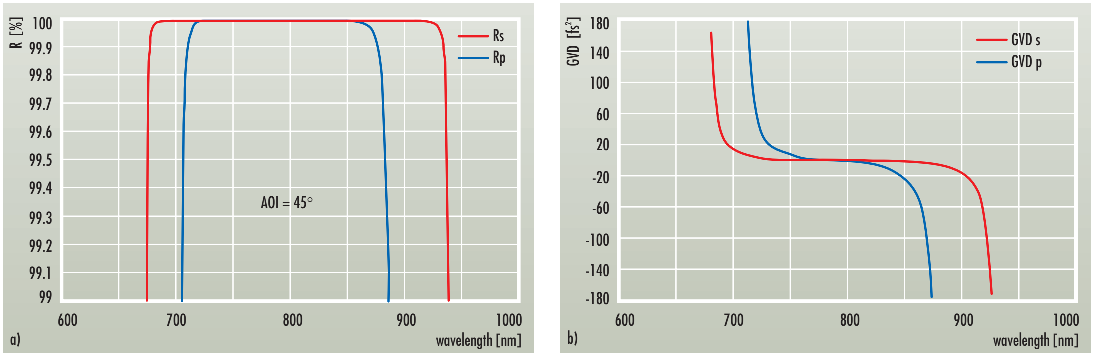

Figure 2: Reflectance (a) and GVD (b) spectra of a standard low dispersion turning mirror

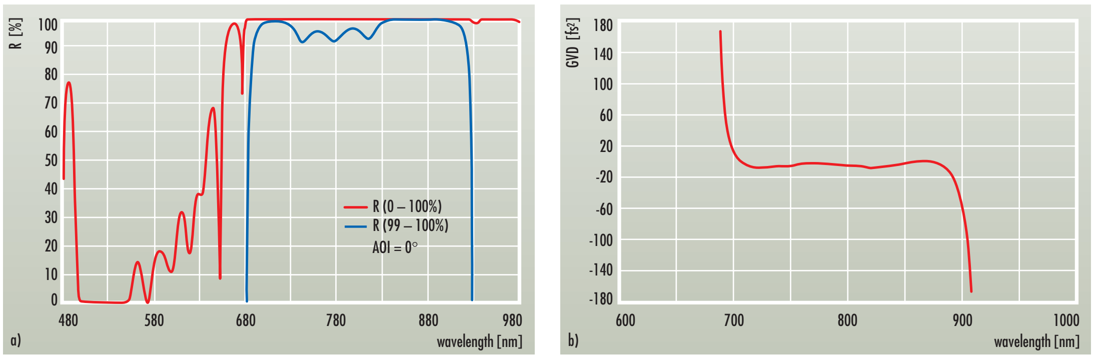

Figure 3: Reflectance (a) and GVD (b) spectra of a standard low dispersion pump laser mirror

All types of mirrors are also available with negative GVD (e.g. – 40fs²). For GTI mirrors see page 50.

NEGATIVE DISPERSION MIRRORS

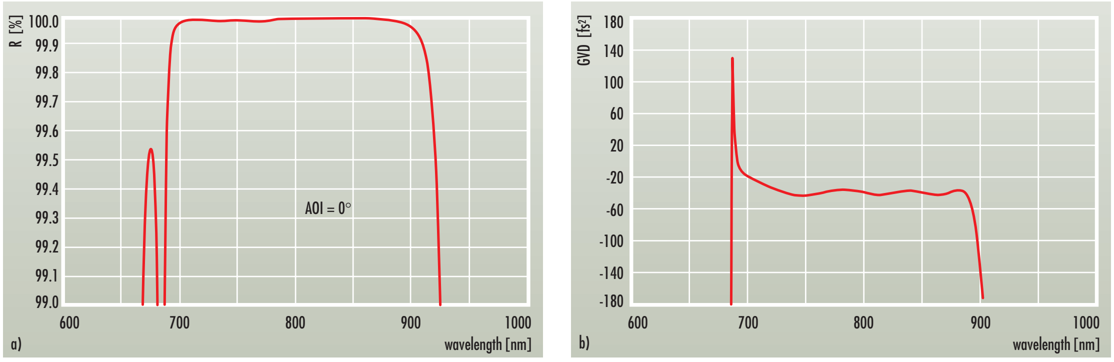

Figure 4: Reflectance (a) and GVD (b) spectrum of a standard negative dispersion mirror with GVD = -40±10fs²

OUTPUT COUPLERS AND BEAM SPLITTERS

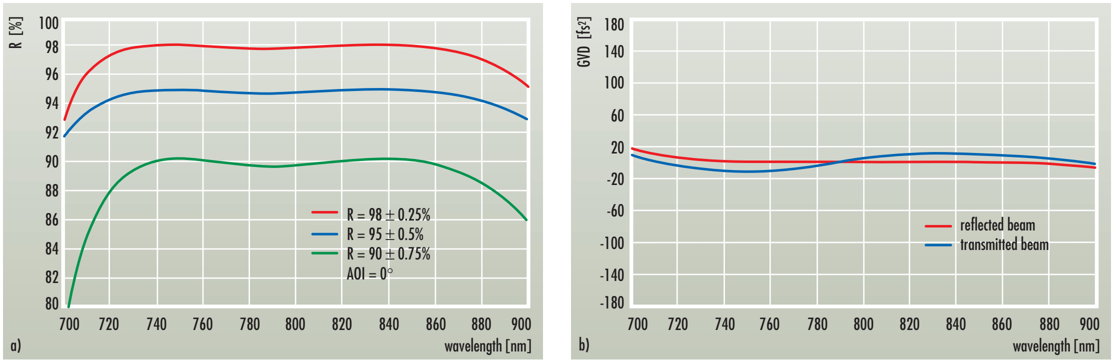

Figure 5: Reflectance (a) and GVD (b) spectra of several standard output couplers

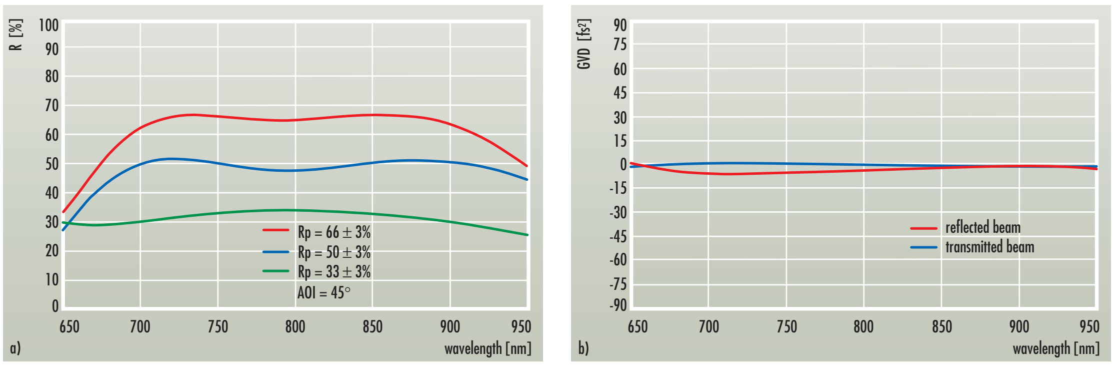

Figure 6: Reflectance (a) and GVD (b) spectra of several standard beam splitters for AOI = 45° and p-polarized light

- Beam splitters for s-polarization are available as well
- Reflectance and transmittance of output couplers and beam splitters can be adjusted according to customer specifications.
- Tolerances:
  - R = 10 … 70% ±2.5%
  - R = 70 … 90% ±1.5%
  - R = 90 … 95% ±0.75%
  - R = 95 … 98% ±0.5%
  - R > 98% ±0.25%
- Standard AR coatings:
  - AOI=0°: R<0.2%
  - AOI=45°, s-pol: R<0.5%; p-pol: rear side uncoated, R<0.6%

BROADBAND FEMTOSECOND LASER OPTICS (BANDWIDTH ~300nm)

- The coatings shown here are calculated for the wavelength range 700–1000nm. Similar coatings are available for 600–900nm and 650–950nm.
- Very high reflectivity of the mirrors (R>99.8% ... R>99.95% depending on the design)
- **OEM-production:** Centre wavelength, bandwidth, GVD and TOD according to customer specification
- Spectral tolerance 1% of centre wavelength
- LIDT $\approx 0.1 J/cm^2$
- In house design calculation and GVD measurement capabilities

NEGATIVE DISPERSION LASER MIRROR PAIR

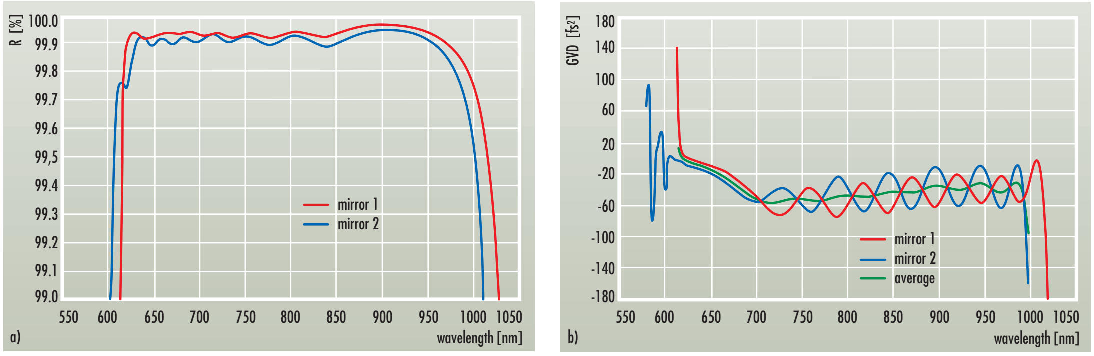

Figure 1:

Reflectance (a) and GVD (b) spectra of a negative dispersion laser mirror pair

Mirror pairs show a very smooth average GVD spectrum, although the single broadband mirrors exhibit strong GVD oscillations. Pump mirror pairs (i.e. mirror pairs with one mirror showing high transmission around 500nm) are also available.

NEGATIVE DISPERSION PUMP MIRROR PAIR

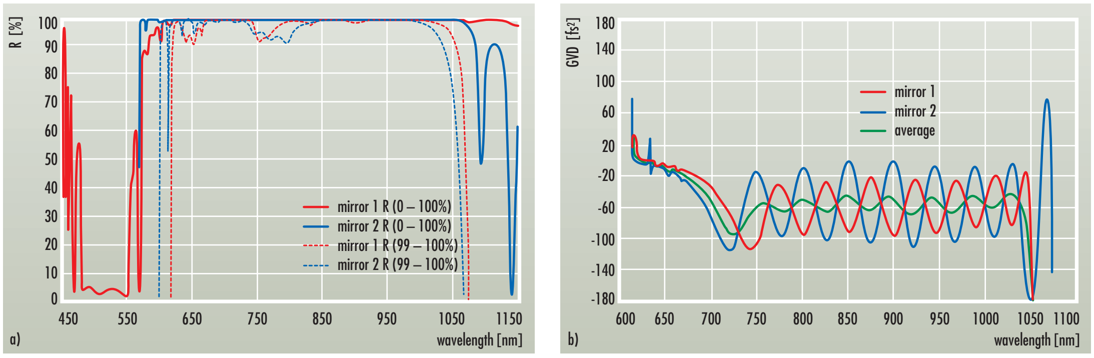

Figure 2:

Reflectance (a) and GVD (b) spectra of a negative dispersion pump mirror pair

BROADBAND SCANNING MIRROR WITH SMOOTH GVD SPECTRUM

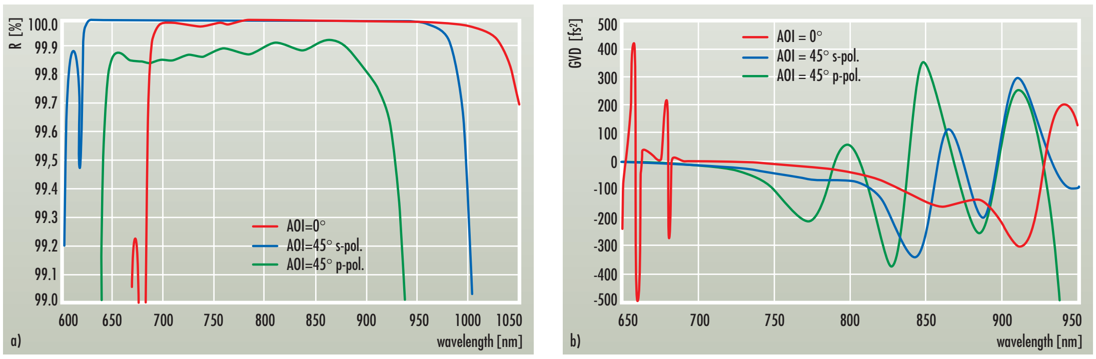

Figure 3:

Reflectance (a) and GVD (b) spectra of a broadband 0°– 45° scanning mirror for s- and p-polarized light

BROADBAND FEMTOSECOND LASER OPTICS (BANDWIDTH ~300nm)

BROADBAND NEGATIVE DISPERSION TURNING MIRRORS

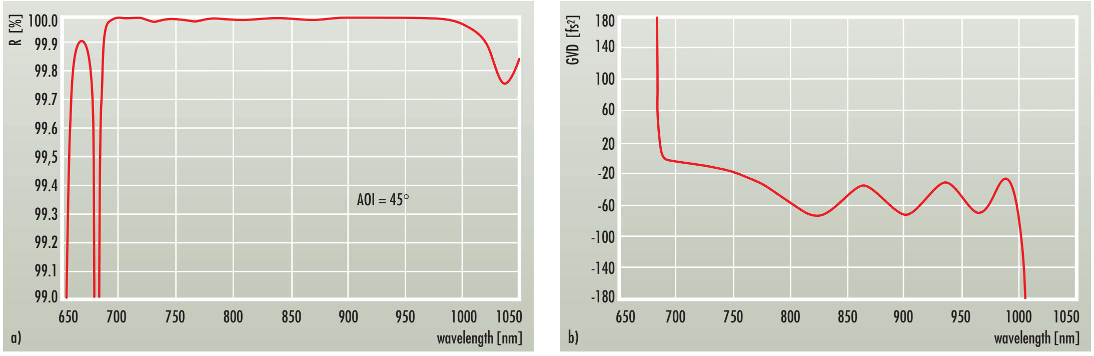

Figure 4:

Reflectance (a) and GVD (b) spectrum of a broadband turning mirror for s-polarized light

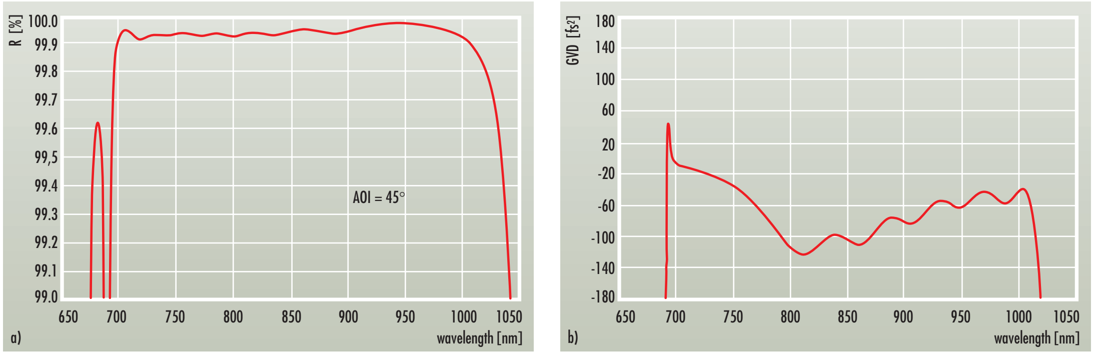

Figure 5:

Reflectance (a) and GVD (b) spectrum of a broadband turning mirror for p-polarized light

BROADBAND OUTPUT COUPLERS

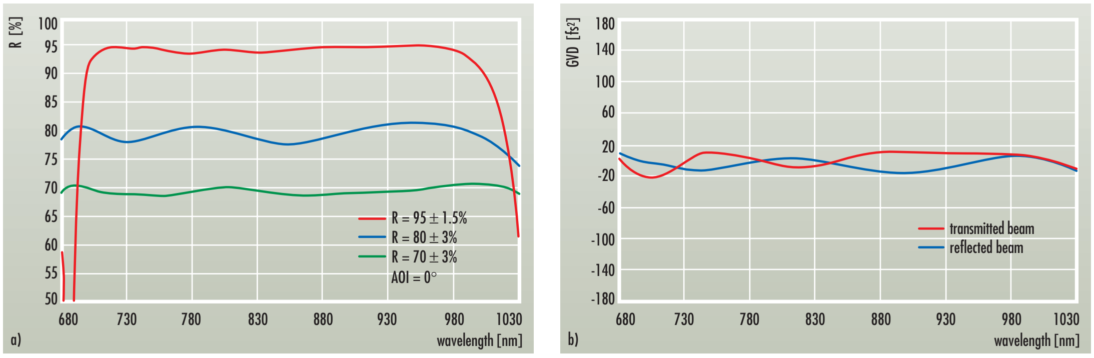

Figure 6:

Reflectance (a) and GVD (b) spectra of several broadband output couplers. The GVD spectra are similar for all these components. Figure 6b shows the GVD spectra for the 80% output coupler.

BROADBAND BEAM SPLITTERS

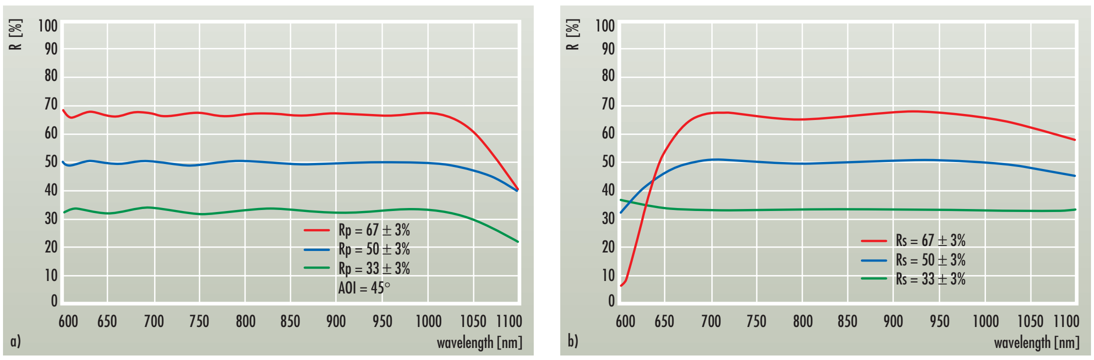

Figure 7:

Reflectance spectra of several broadband beam splitters for p- (a) and s-polarization (b). The GVD values for reflected and transmitted light are in the range of ± 30fs²

ULTRA BROADBAND FEMTOSECOND LASER OPTICS (BANDWIDTH ~ONE OCTAVE)

- The coatings shown here are calculated for the wavelength of one octave (either 440–880nm or 550–1100nm). Similar coatings are possible for intermediate wavelength ranges.
- **OEM-production:**
  Centre wavelength, bandwidth, GVD and reflectance of output couplers and beam splitters according to customer specification
- Spectral tolerance 1% of centre wavelength
- LIDT ~0.1 J/cm²
- In house design calculation and GVD measurement capabilities

NEGATIVE DISPERSION LASER MIRROR PAIR

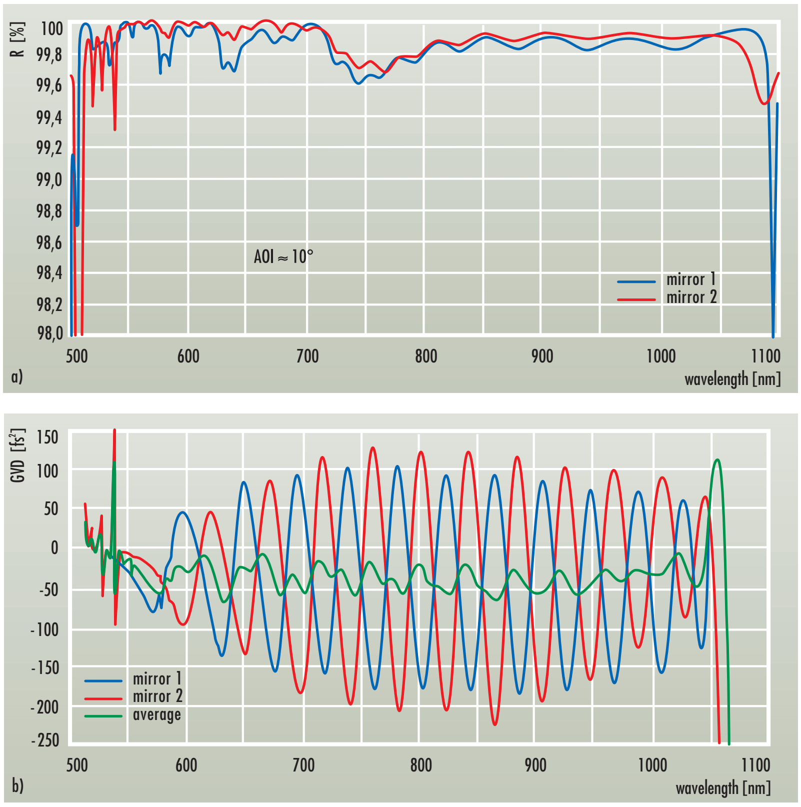

Figure 1: Reflectance (a) and GVD (b) spectra of an ultra broadband negative dispersion laser mirror pair

Mirror pairs designed by LAYERTEC show a very smooth average GVD spectrum, although the single broadband mirrors exhibit strong GVD oscillations.

ULTRA BROADBAND NEGATIVE DISPERSION TURNING MIRROR PAIRS

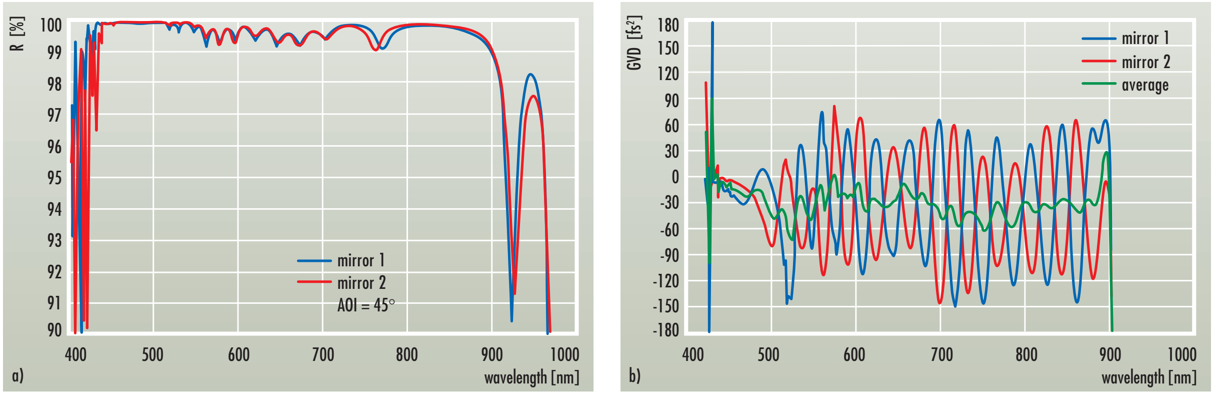

Figure 2: Reflectance (a) and GVD (b) spectra of an broadband turning mirror pair for p-polarized light

ULTRA BROADBAND OUTPUT COUPLERS

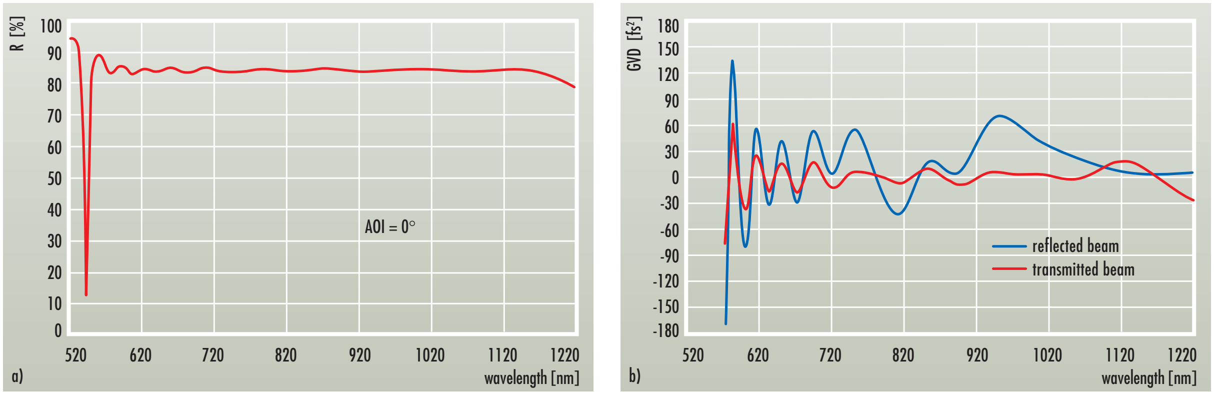

Figure 3: Reflectance (a) and GVD (b) spectra of an ultra broadband output coupler with R = 85 ± 3 %

ULTRA BROADBAND BEAMSPLITTERS

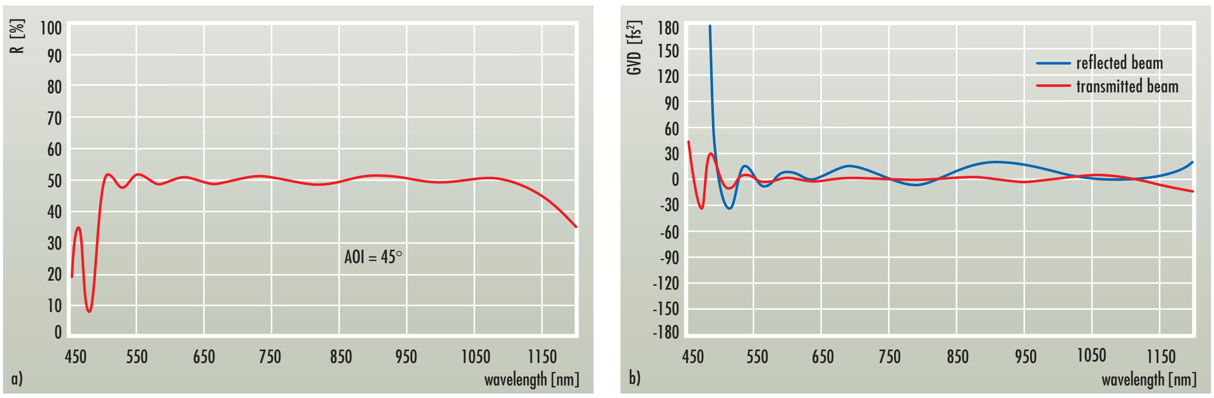

Figure 4: Reflectance (a) and GVD (b) spectra of an ultra broadband beamsplitter for p-polarized light with Rp = 50 ± 4 %

SILVER MIRRORS FOR FEMTOSECOND LASERS

SILVER MIRRORS OPTIMIZED FOR FEMTOSECOND APPLICATIONS

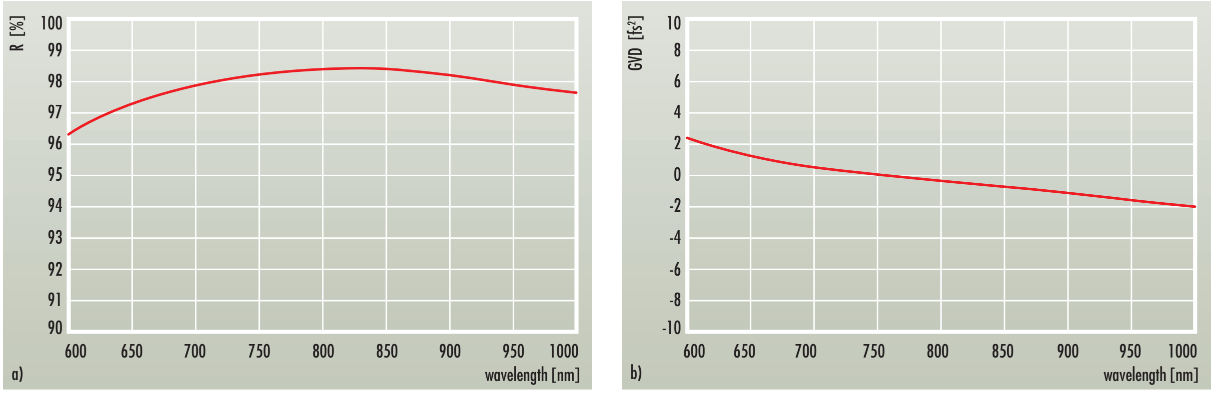

Figure 1: Reflectance (a) and GVD-spectrum (b) of a silver mirror optimized for use with fs-lasers in the wavelength range 600 –1000nm (AOI=0°)

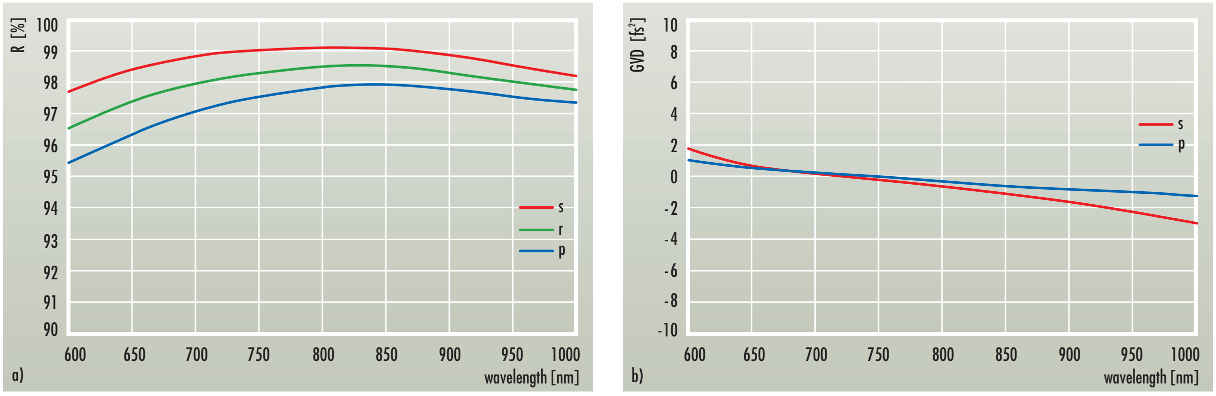

Figure 2: Reflectance (a) and GVD-spectra (b) of a silver mirror optimized for use with fs-lasers in the wavelength range 600–1000nm (AOI=45°)

Special features:

- High reflectance in the VIS and NIR
- Very broad reflectance band with GVD ~ 0 fs^2
- Extremely low straylight losses (TS < 10^{-4} at 633nm)
- Protected silver mirrors have a lifetime of more than 4 years in normal atmosphere
- Highly stable optical parameters because of sputtered protective layers
- Good cleanability (tested according to MIL-M-13508C § 4.4.5)
- Laser induced damage threshold for fs-pulses:

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

* For unpolarized light at AOI = 45°
** Measurements were performed at Laser Zentrum Hannover according to ISO 11254
measurement conditions: pulse duration: 150 fs, 30 000 pulses, repetition rate 1 kHz, λ = 800 nm

Stock of standard components

- Standard and fs-optimized protected silver on substrates with Ø = 12.7mm and Ø = 25.0mm:
  - Plano
  - Plano/concave and plano/convex with r = 50, 100, 200, 300, 500, 750 and 1000mm
- Other sizes, shapes, radii and coatings for other wavelengths ranges on request

SILVER MIRRORS WITH ENHANCED REFLECTIVITY

The reflectance of silver mirrors can be enhanced by a dielectric overcoat. The bandwidth of the enhanced reflectivity must be exactly specified. Outside this band the reflectivity of the mirror may be lower than that of a standard silver mirror.
For use with fs-lasers, the dielectric overcoat must be optimized for high reflectivity and low GVD. The following figures show examples for silver mirrors with enhanced reflectivity at a specified wavelength (figure 2) and over the wavelength range of the Ti:Sapphire laser (figure 3).

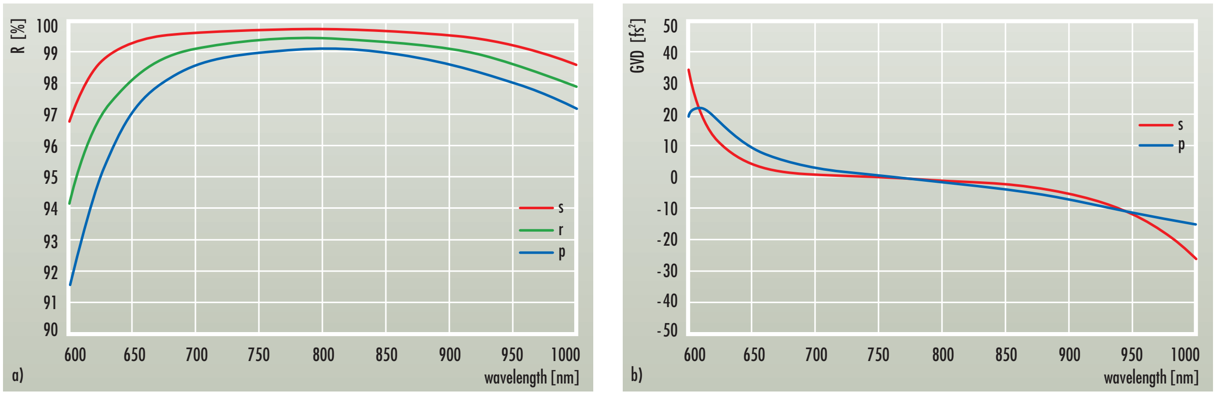

Figure 3: Reflectance (a) and GVD-spectra (b) of silver mirrors with enhanced reflectivity around 800nm

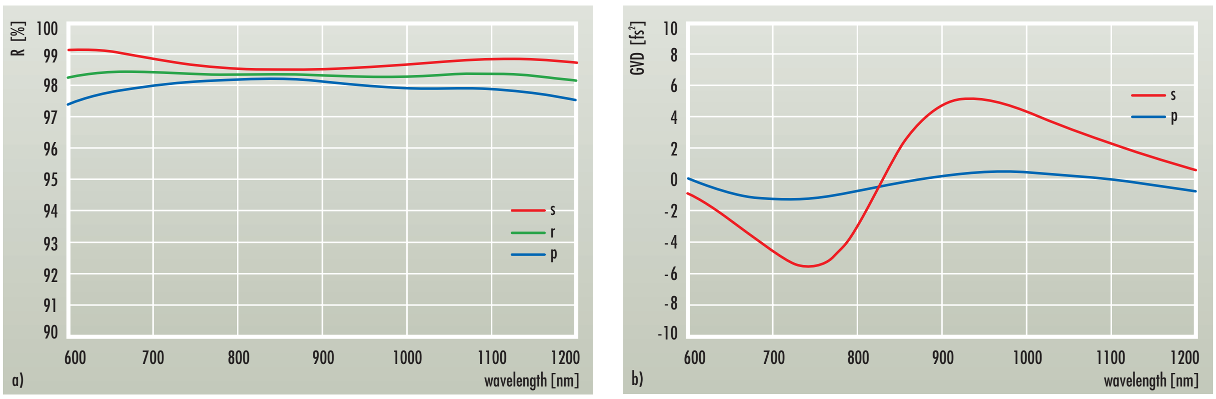

Figure 4: Reflectance (a) and GVD-spectra (b) of silver mirrors with enhanced reflectivity in the wavelength range 600–1200nm

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FEMTOSECOND LASER OPTICS OPTIMIZED FOR THIRD ORDER DISPERSION

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 as 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 in the order of some thousands of fs^3. If low TOD over a broad wavelength range is required we recommend to use optimized silver mirrors (see fig. 3).

MIRRORS OPTIMIZED FOR NEGATIVE THIRD ORDER DISPERSION

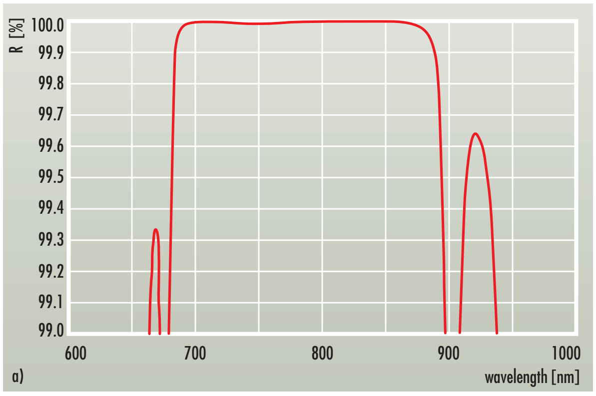
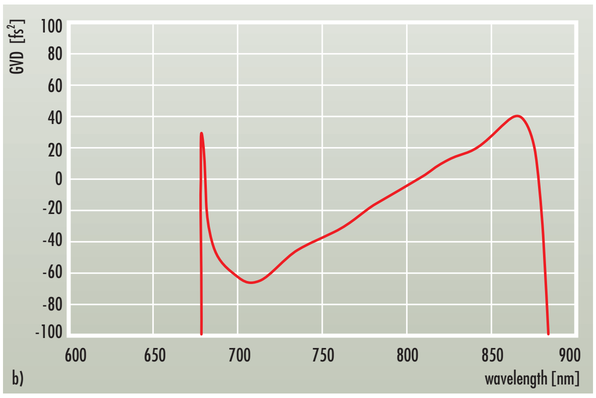
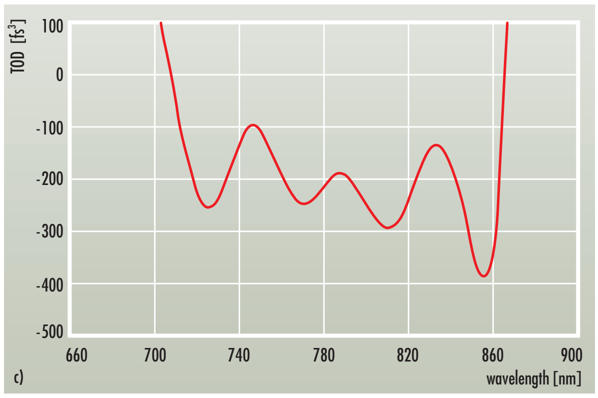


Figure 1: Reflectance (a), GVD (b) and TOD spectra (c) of a mirror optimized for nearly constant negative third order dispersion





OEM - production:

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

MIRRORS OPTIMIZED FOR POSITIVE THIRD ORDER DISPERSION

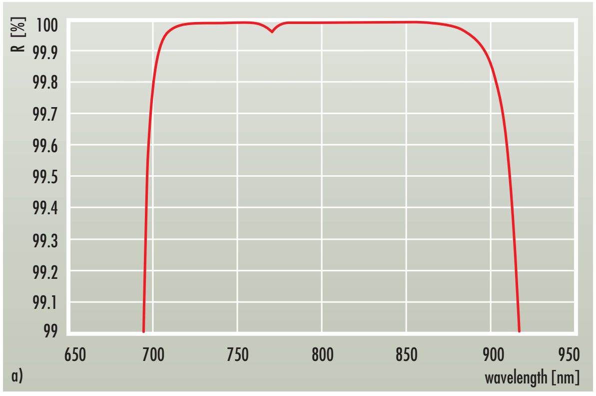
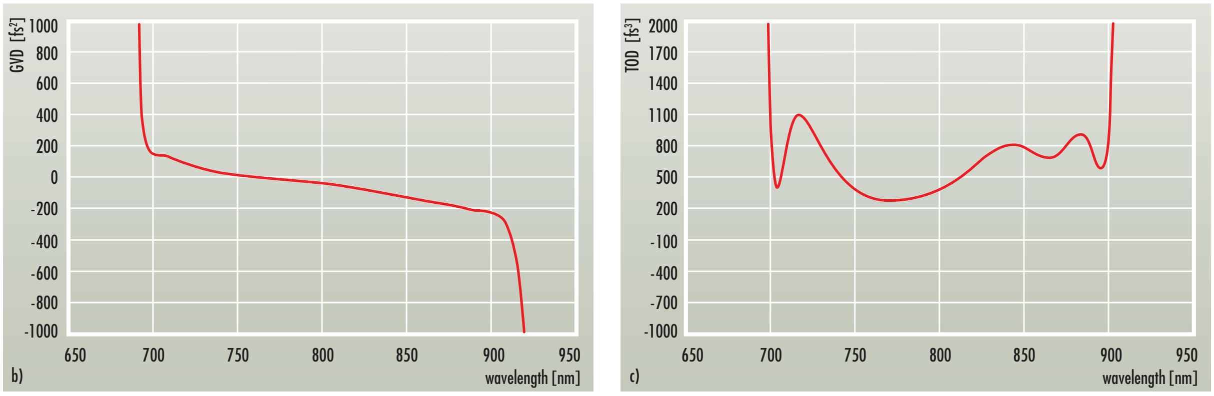


Figure 2: Reflectance (a), GVD (b) and TOD spectra (c) of a mirror optimized for nearly constant positive third order dispersion



OPTIMIZED SILVER MIRRORS FOR USE AS LOW TOD COMPONENTS

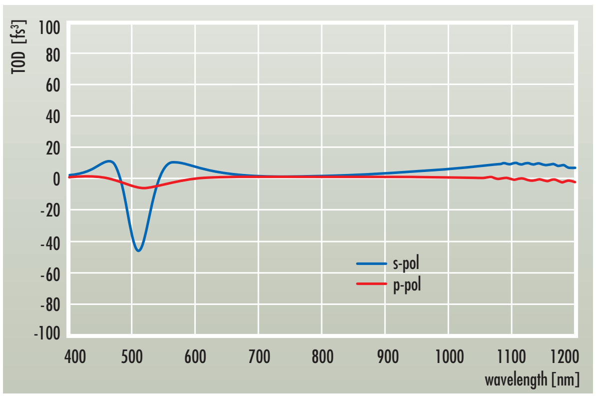


Figure 3:
TOD spectra of a fs-optimized silver mirror (turning mirror for 600–1000nm)

For the reflectivity and GVD of fs-optimized silver mirrors please see pages 40–41.

Coatings for femtosecond laser optics are usually optimized for special reflectance, transmittance and GVD spectra. The laser induced damage threshold (LIDT) of such coatings is less important for the majority of the applications. Nevertheless, high power fs laser are under investigation and the output power of fs lasers has increased enormously over the recent years (see. Ref.[1)] and the references therein). Thus, the LIDT of fs laser optitics becomes more and more important. LAYERTEC has carried out detailed investigations on the LIDT of optics for fs and ps lasers.* As shown in the table on page 45 we found large differences in the LIDT values of standard, broadband and ultrabroadband optics and our high power mirrors. Standard low GVD mirrors (see p. 34 figures 1 and 2) show a LIDT value of 0.3 J/cm^2 while negative GVD mirrors, broadband and ultrabroadband components (all other examples on p. 34 – 39) have an LIDT of about 0.1 J/cm^2.

Our investigations proved that the LIDT of femtosecond laser optics depends on the coating materials and on the coating designs. The difference in the LIDT values of standard low GVD components and the other optics mentioned above results from the different coating designs used. These designs are mainly optimized for GVD, spectral bandwidth and reflectance. Especially the broadband and negative GVD designs result in low damage thresholds. Only the designs for standard low GVD components reached higher LIDT values. In all of these cases materials with a high contrast of the refractive indices were chosen in order to achieve large bandwidths. Higher LIDT values can be achieved using other coating materials. However, mirrors made of these materials have only a bandwidth of about 80 nm because of the lower contrast of the refractive indices. Nevertheless, this bandwidth is enough for pulse lengths as low as 150 fs. All high power designs are optimized for GVD < 20 fs^2.

We distinguish the different high power designs because of different material combinations and designs which need different efforts with respect to the preparation of the coatings and which differ also with respect to the mechanical properties, e. g. the stress in the layers. The spectral bandwidth of these coatings is nearly the same. An example is shown in figure 1.

It was also found that LAYERTECs optimized silver mirrors have LIDT values which are higher than that of standard components in the fs range. Silver mirrors are advantageous because of their extremely broad zero GVD reflectance band with a reflectivity of up to 98.5 % at normal incidence. For more information on silver mirrors see pages 60 – 61.

1) E. Innerhofer, T. Südmeyer, F. Brunner, R. Häring, A. Aschwanden and R. Paschotta, C. Hönninger and M. Kumkar, U. Keller, "60 W average output power in 810 fs pulses from a thin-disk Yb:YAG laser", OPTICS LETTERS Vol. 28, No. 5, p. 367–369

* In cooperation with the Laser Zentrum Hannover and the Friedrich-Schiller-Universität Jena. Most of this work was done within the framework of the German joined project PRIMUS which was supported by the Bundesministerium für Forschung und Technologie.

DIELECTRIC HIGH POWER MIRRORS

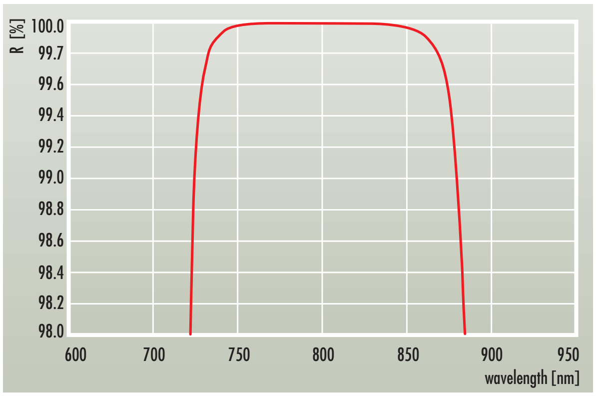


Figure 1: Reflectance spectrum of a high power fs laser mirror HR (0°, 800 nm) R > 99.9 %

OVERVIEW ABOUT LASER INDUCED DAMAGE THRESHOLDS OF FEMTOSECOND LASER OPTICS

Coating	Reflectance at 800nm	LIDT [J/cm²]* 50fs	150fs	1ps
Bare gold	97.5%	0.33	0.33	
fs-protected silver	**98.2%**	**0.38**	**0.38**	
Enhanced silver (800nm)	99.7%		0.37	
Enhanced silver (600–1200nm)	98.5%		0.24	
Negative dispersion mirrors	>99.9%		~0.1	
Broadband low GVD mirrors	>99.9%		~0.1	
Standard low GVD	>99.9%		0.3	0.55
High power mirror type A	**>99.9%**	**0.35**	**0.75**	**1.04**
High power mirror type B	**>99.8%**		**0.44**	**0.65**
Single wavelength AR coating	<0.2%			1.2**
Broadband AR coating	<0.5%			1.2**

* Measurement conditions: 30000 pulses, repetition rate 1kHz, l=800nm; measurements were performed at Laser Zentrum Hannover and Friedrich-Schiller-Universität Jena according to ISO 11254

** Self focussing effects may destroy the substrate while the AR coating is still stable

METALLIC HIGH POWER MIRRORS

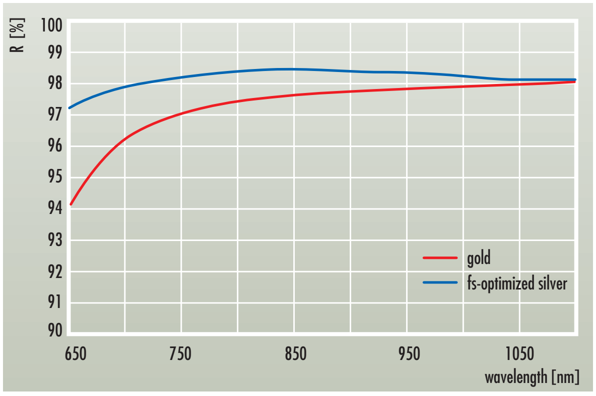


Figure 2: Reflectance spectra of bare gold and fs-optimized silver (optimized for high reflectance at 800nm)

GVD OF HIGH POWER FEMTOSECOND LASER MIRRORS

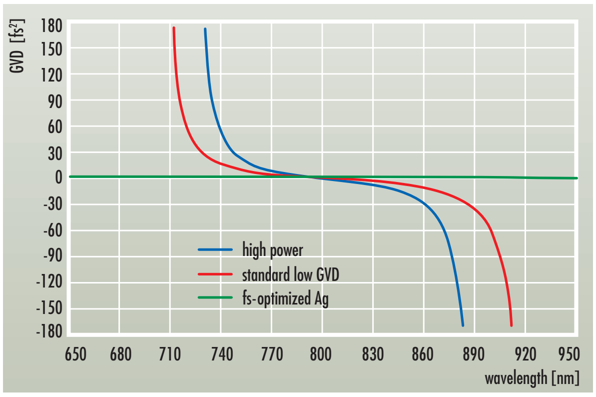


Figure 3: Group velocity dispersion (GVD) of standard and high power dielectric mirrors and fs-protected silver mirrors

COMPONENTS FOR THE SECOND HARMONIC OF fs-LASERS

DUAL WAVELENGTH MIRRORS

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

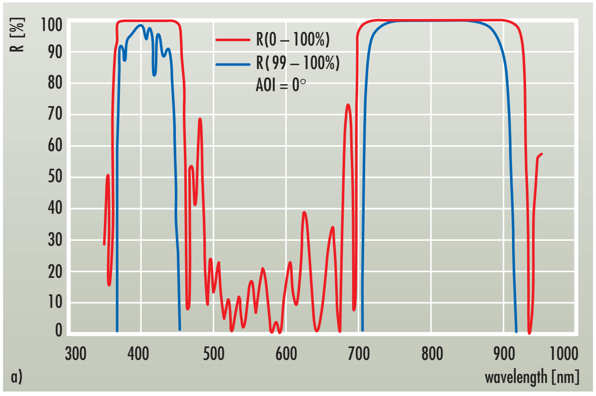
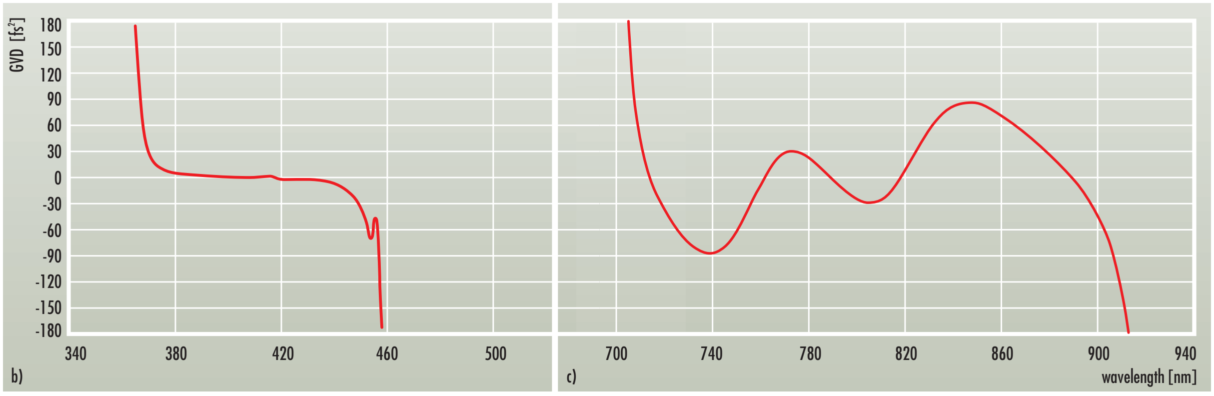


Figure 1: Reflectance- (a) and GVD-spectra (b, c) of a fs-optimized mirror for 400 nm + 800 nm



LOW DISPERSION MIRRORS FOR THE 400 nm SPECTRAL RANGE

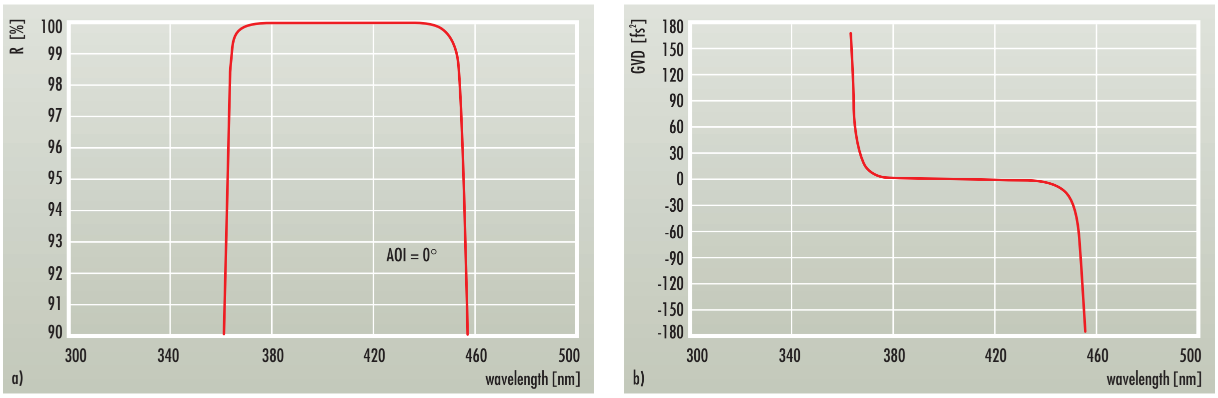


Figure 2: Reflectance (a) and GVD spectrum (b) of a low dispersion mirror for 375 nm – 450 nm

Special features:

- Very high reflectivity (R>99.9%)
- Centre wavelength and bandwidth according to customer specifications
- Spectral tolerance 1% of centre wavelength

SEPARATORS FOR THE SECOND HARMONIC FROM THE GROUND WAVE

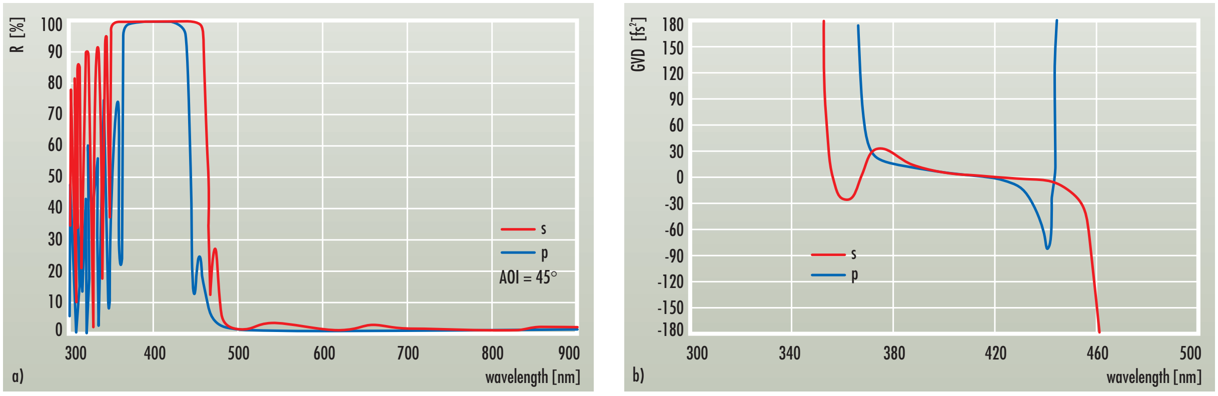


Figure 3: Reflectance- (a) and GVD-spectra (b) of a separator HR 400nm + HT 800nm (AOI=45°)

- High transmittance around 800nm: T>95% for s- and p-polarization
- GVD around 800nm: |GVD|>20fs² in transmission

NEGATIVE DISPERSION MIRROR FOR THE 400nm SPECTRAL RANGE

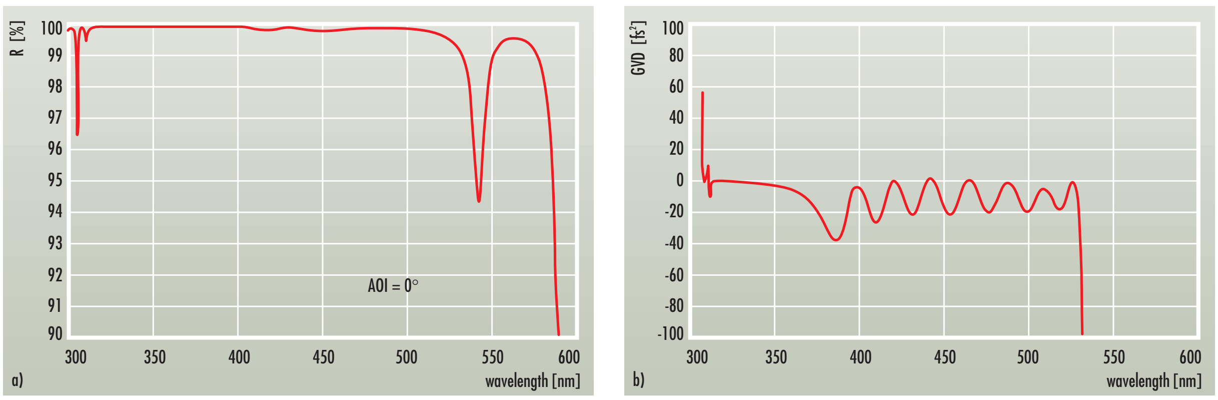


Figure 4: Reflectance (a) and GVD-spectra (b) of a negative dispersion mirror for 375nm – 450nm with GVD ≈ -15fs²

- OEM and prototype production according to customers specifications
- In house design calculation capabilities

Ernst-Abbe-Weg 1, D-99441 Mellingen, Germany, e-mail: info@layertec.de
Phone 49 (0)3 64 53 / 7 44-0, Fax 49 (0)3 64 53 / 7 44-40, www.layertec.de

COMPONENTS FOR HIGHER HARMONICS OF THE Ti:SAPPHIRE LASER

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

DUAL WAVELENTGH TURNING MIRRORS

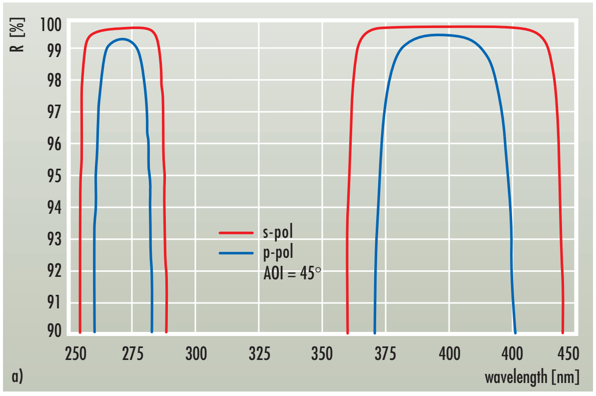
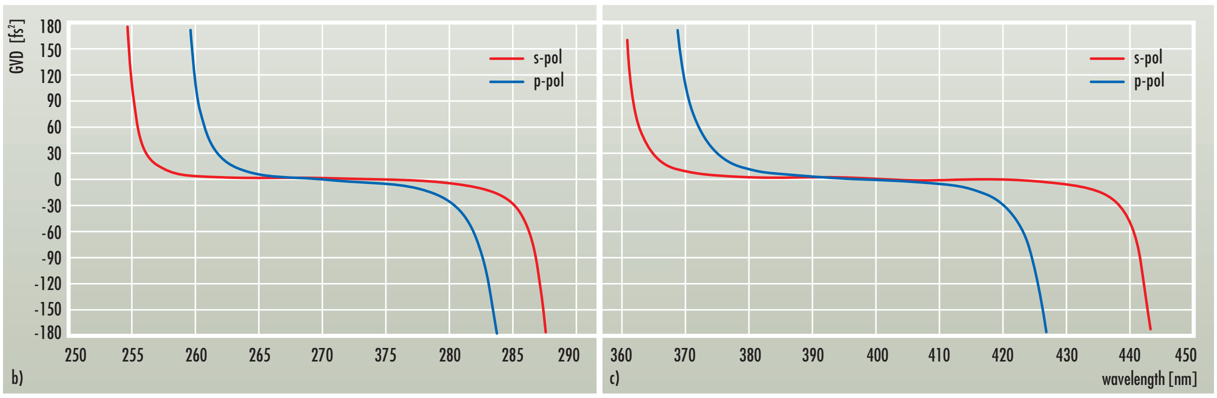


Figure 1: Reflectance- (a) and GVD-spectra (b, c) of a fs-optimized turning mirror for 270nm + 405nm



SEPARATORS FOR THE THIRD HARMONIC FROM THE SECOND HARMONIC AND THE GROUND WAVE

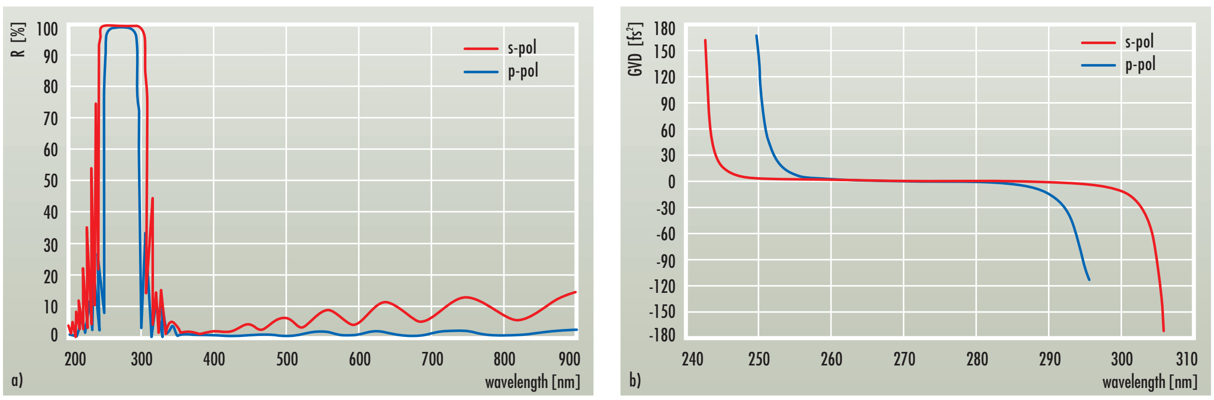


Figure 2: Reflectance- (a) and GVD-spectra (b) of a separator HR 270nm + HT 405 + 810nm (45°)

COMPONENTS FOR HIGHER HARMONICS OF THE Ti:SAPPHIRE LASER

TURNING MIRROR FOR THE FOURTH HARMONIC

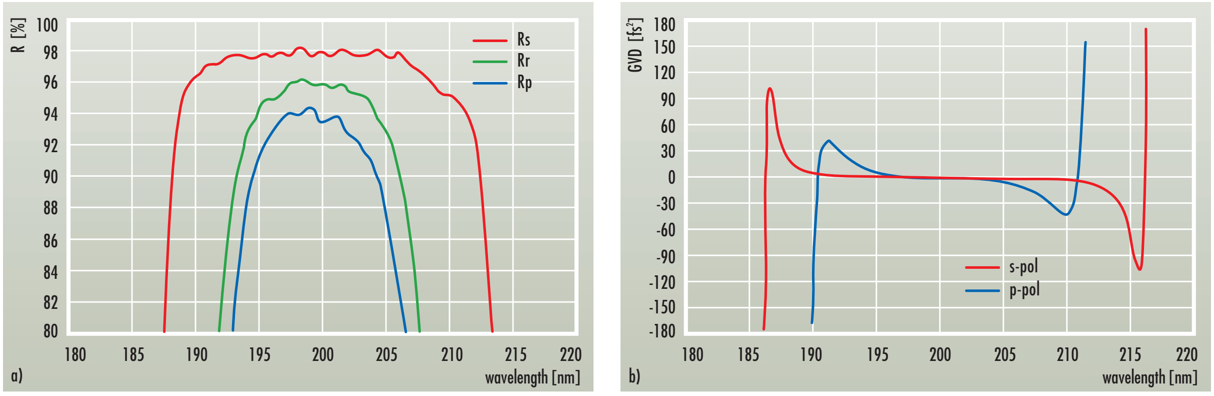


Figure 3: Reflectance (measured, a) and GVD-spectra (calculated, b) of a turning mirror for 200nm (AOI = 45°)

PROPERTIES OF FEMTOSECOND UV COATINGS

- Depending on the wavelength range of the ground wave the coatings described in this data sheet can be used for the following centre wavelengths:
  - Third harmonic: 250 – 310 nm
  - Fourth harmonic: 180 – 230 nm
  - Fifth harmonic: 150 – 180 nm
- Bandwidths of the coatings are given in the table below
- Coatings are optimized for broad reflectance bands, high reflectivity and low GVD
- Different substrate and coating materials depending on the wavelength range; components for 220nm and below consist of fluoridic layer systems on CaF_2-substrates

Bandwidth of the high reflectance and low GVD range

Component	Wavelength range	P-polarization R > 99%, $\lvert GVD \rvert$ < 20 fs²	S-polarization R > 99.5%, $\lvert GVD \rvert$ < 20 fs²
Turning mirror 3rd harmonic	UV	30 nm	50 nm
Separator 3rd harmonic	UV	30 nm	50 nm
Dual wavelength turning mirror	UV	15 nm	26 nm
	UV / VIS	34 nm	72 nm
Turning mirror 4th harmonic	UV	5 nm (R > 93 %)	15 nm (R > 97 %)
Turning mirror 5th harmonic	UV	4 nm (R > 90 %)	12 nm (R > 97 %)

GIRES-TOURNOIS-INTERFEROMETER (GTI) MIRRORS

Gires-Tournois-Interferometer mirrors are used for pulse compression in femtosecond lasers such as Yb:YAG- or Yb:KGW-lasers. LAYERTEC offers GTI mirrors also for the Ti:Sapphire wavelength range and for wavelengths up to 1600nm. Compared to prism compressors GTI mirrors reduce the intra cavity losses resulting in higher output power of the laser.

GTI-MIRRORS FOR THE Ti:SAPPHIRE WAVELENGTH RANGE

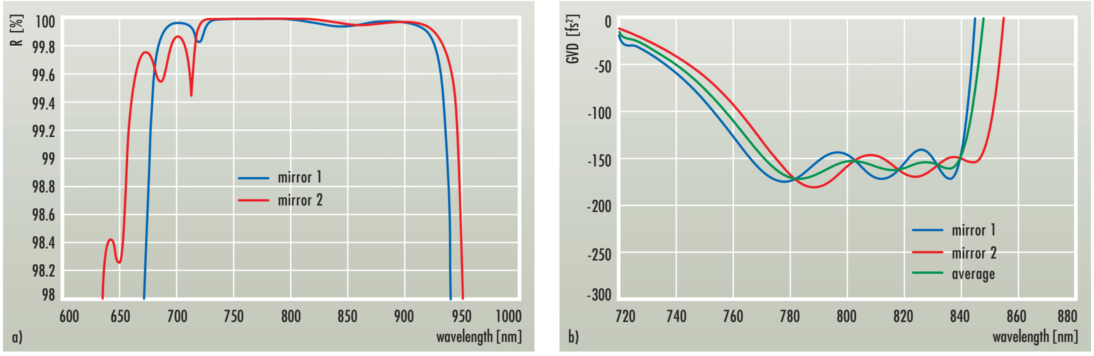
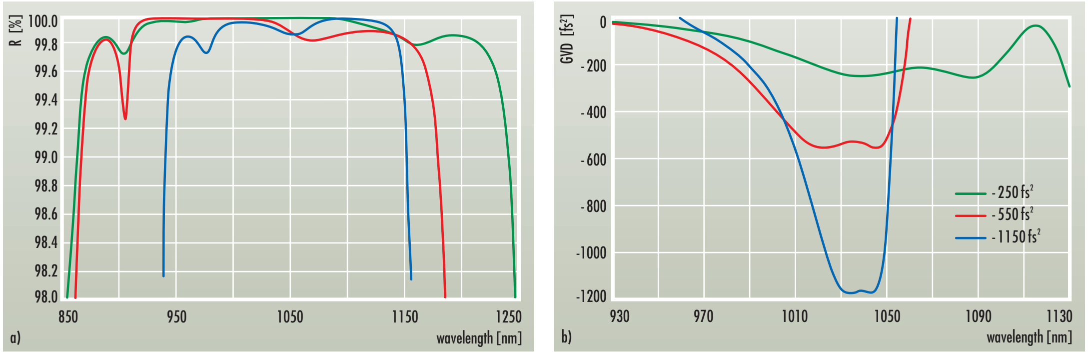


Figure 1: Reflectance (a) and GVD (b) spectra of a pair of GTI-mirrors for 780 – 840nm (single mirrors: GVD= -160 ± 20fs², mirror pair: GVD = -160 ± 10fs²)

The mirror pair shows a very smooth average GVD spectrum, although the single mirrors exhibit considerable GVD oscillations.

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



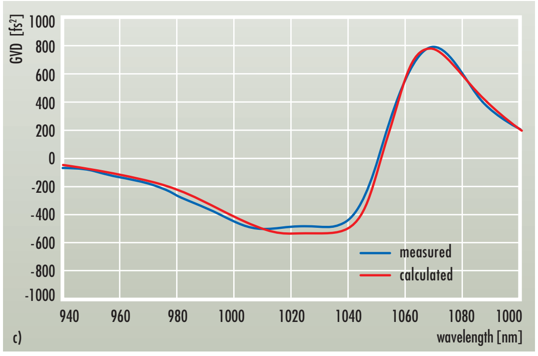


Figure 2: Reflectance (a) and GVD spectra (b) of GTI-mirrors for 1030nm with different GVD values, comparison of measured and calculated GVD spectra of a GTI mirror with GVD≈ -500fs² (c)

Measured and calculated GVD-curves match very well which proofes the reliability of the coating process.

GTI-MIRRORS FOR OTHER FEMTOSECOND LASERS

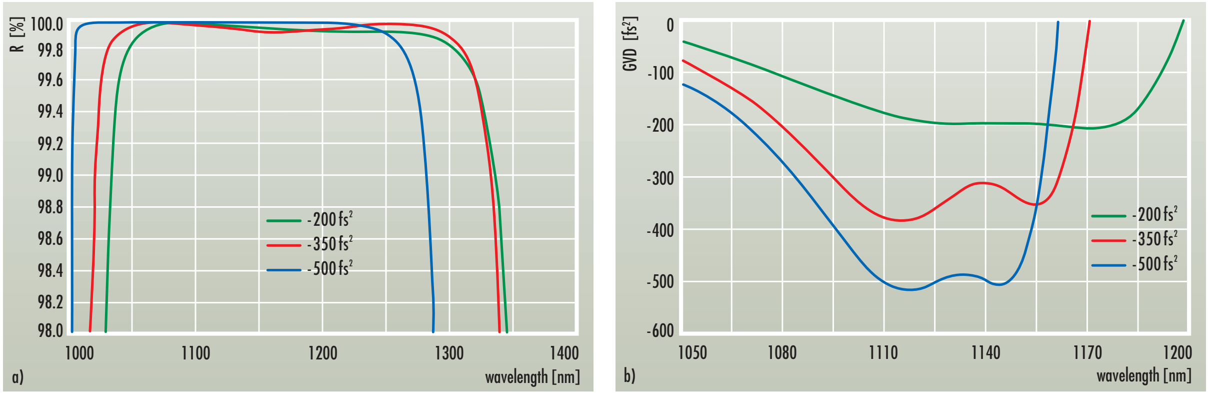


Figure 3: Reflectance (a) and GVD spectra (b) of GTI mirrors for 1130nm with different GVD values

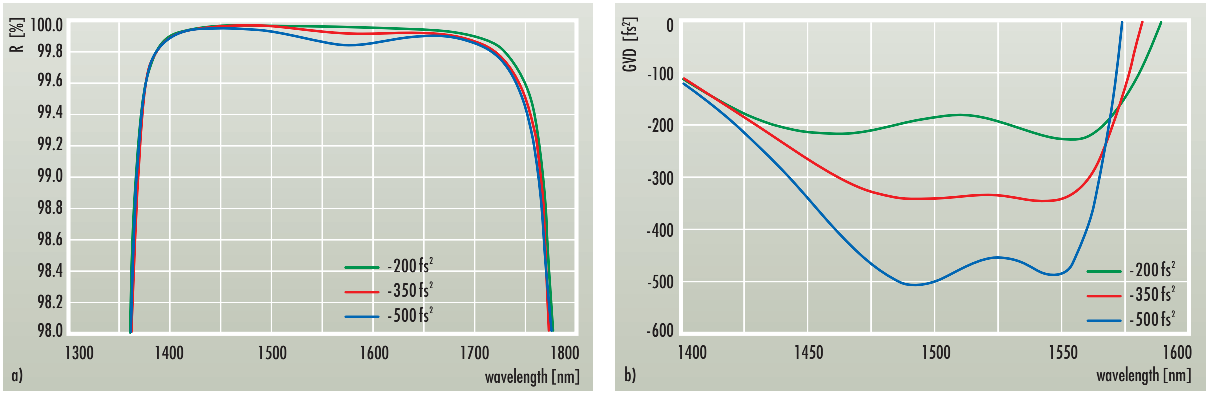


Figure 4: Reflectance (a) and GVD spectra (b) of GTI mirrors for 1500nm with different GVD values

OEM-production:

- Very high reflectivity (R > 99.8 %)
- GVD between -200fs² and -1200fs²
- LIDT » 0.1J/cm²
- Centre wavelength, bandwidth and GVD according to customer specification
  Please note that bandwidth and GVD are closely connected. A high value of negative GVD results in a very narrow bandwidth.
- Spectral tolerance 1% of centre wavelength
  GTI-mirrors with a GVD up to 500fs² are designed for a bandwidth of Δλ > 20nm and will meet the specification even if the centre wavelength is 1% apart from the design wavelength. At higher GVD-values it is favourable to design the laser so that the GTI-mirror can be tilted by ±20° to adjust the mirror for its best performance.
- In house design calculation and measurement capabilities (630–1100nm).

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

Although Ti:Sapphire lasers are at present the most important femtosecond lasers many applications require femtosecond pulses at considerably longer wavelengths. Several lasers emitting light between 1100nm and 1600nm have been developed in the past years, such as the Cr:Forsterite laser (1150–1350nm) or the Er:fibre laser (1550nm). On these pages we present some examples of coatings – negative dispersion mirrors and mirror pairs, cavity and turning mirrors – which are intented to show our capabilities also for femtosecond laser optics in this spectral region.

Special features:

- Very high reflectivity of the mirrors (R > 99.8 % … R > 99.95 % depending on the design)
- OEM-production:
  Centre wavelength, bandwidth, GVD and TOD according to customer specification
- Spectral tolerance 1% of centre wavelength
- LIDT ~0.1J/cm²
- In house design calculation capabilities

NEGATIVE DISPERSION LASER AND PUMP MIRRORS

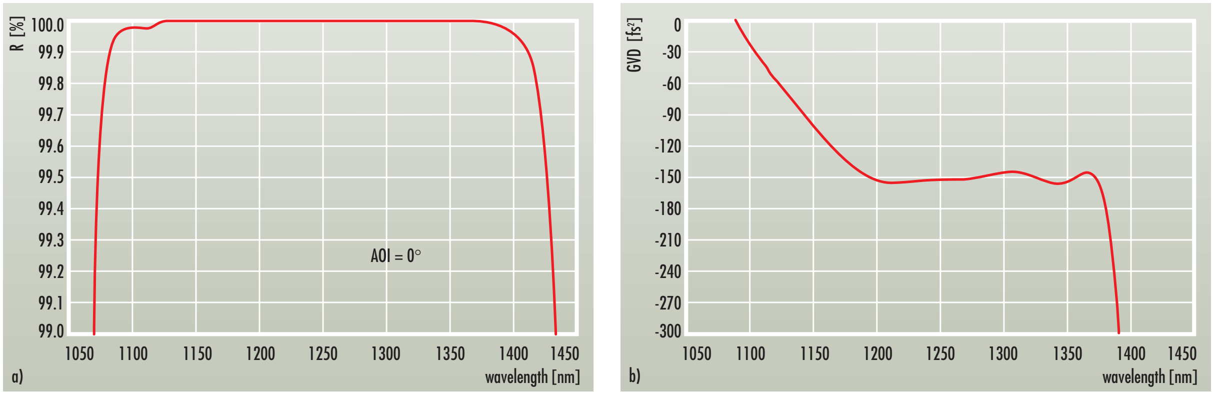


Figure 1: Reflectance (a) and GVD (b) spectrum of a negative dispersion laser mirror (GVD~ -150fs² for 1200–1370nm)

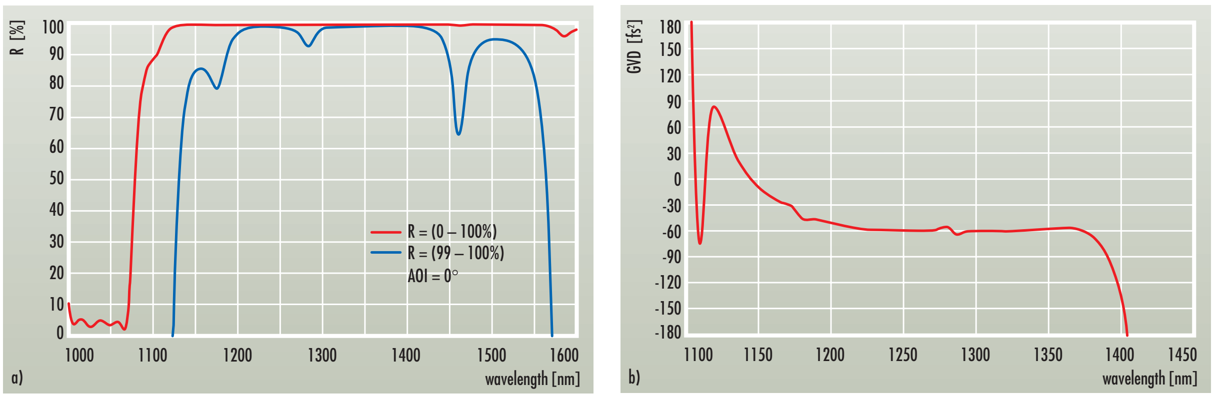


Figure 2: Reflectance (a) and GVD (b) spectrum of a negative dispersion pump mirror: R(1020–1070nm) < 5 % + R(1180–1380) > 99.8 % + GVD(1180–1380nm) ~ -60fs²

BROADBAND NEGATIVE DISPERSION MIRROR PAIRS

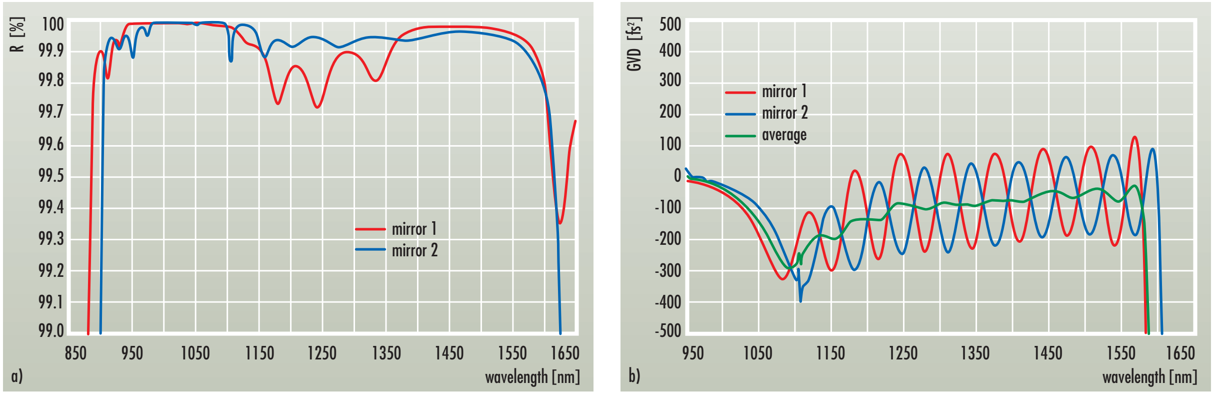


Figure 3: Reflectance (a) and GVD (b) spectra of a broadband negative dispersion mirror pair; single mirrors with R > 99.7 % (mirror 1) or R > 99.85 % (mirror 2)

Especially designed mirror pairs show a very smooth average GVD spectrum, although the single broadband mirrors exhibit strong GVD oscillations. Pump mirror pairs (i. e. mirror pairs with one mirror showing high transmission around 1050nm) are also possible.

BROADBAND NEGATIVE DISPERSION TURNING MIRRORS

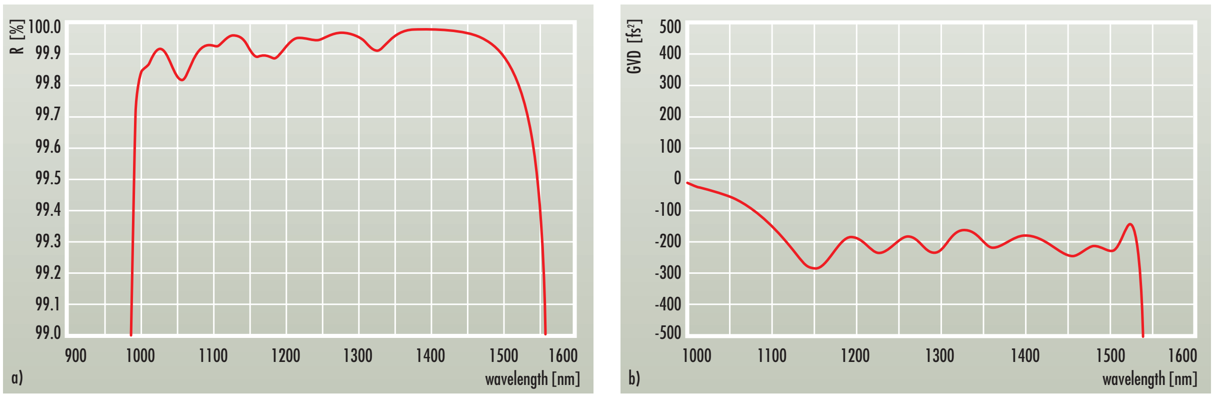


Figure 4: Reflectance (a) and GVD (b) spectrum of a broadband negative dispersion turning mirror for p-polarized light

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