CATALOG 2011

LAYERTEC®
OPTICAL COATINGS · OPTICS

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 or rare earth metal doped crystals such as Yb:KGW 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.

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 such as 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 figure 1).

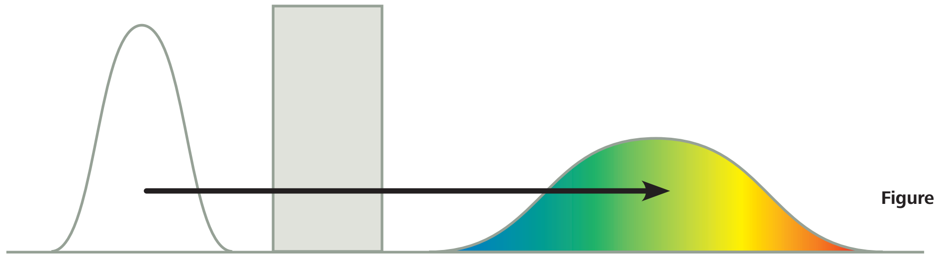

Figure 1: Broadening of a pulse by propagation through an optical medium (schematic drawing)

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. Also 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, also the phase relationship among the Fourier components of the pulse must be preserved in order to avoid broadening or distortion of the pulse.

A 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 61) 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 reflected 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 figure 2 explains this effect in terms of different optical path lengths of blue, green and red light in such a negative dispersion mirror.

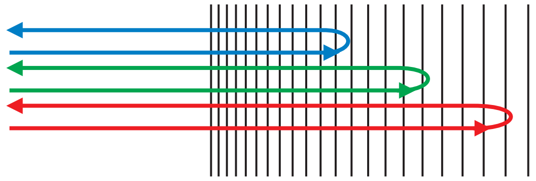

Figure 2: Optical path lengths of blue green and red light in a negative dispersion mirror (schematic drawing)

LAYERTEC offers femtosecond laser optics with different bandwidths. This catalog shows e.g. 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 ultra broadband components (bandwidth of one octave or more).

Each of these chapters shows low dispersion laser and turning mirrors, negative dispersion mirrors or mirror pairs, output couplers and beam splitters of the corresponding bandwidth. Moreover, we want to present silver mirrors for fs applications which are the components with the broadest low-GDD wavelength region available.

Please note that the GDD spectrum of a dielectric negative dispersion mirror is not a continuous 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. A considerable flattening of these oscillations can be achieved by using mirror pairs consisting of mirrors with slightly shifted GDD oscillations which compensate each other. These mirror pairs are especially designed for this compensation behaviour. Figure 3 shows a schematic drawing of such a mirror pair and the corresponding GDD spectra.

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 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 **G**roup **D**elay (GD) $\Phi'(\omega_0)$, the **G**roup **D**elay **D**ispersion (GDD) $\Phi''(\omega_0)$ 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:
Assuming the phase shift is linear in frequency (i. e. $GD \neq 0$, $GDD = 0$ 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 $GDD \neq 0$, two important effect are observed:

- The reflected pulse is temporarily broadened. This broadening effect depends only on the absolute value of the GDD. LAYERTEC offers "low GDD mirrors", i. e. mirrors with $|GDD| < 20\,fs^2$ 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 GDD, so that the momentary frequency may become higher (up-chirp, $GDD > 0$) or lower (down-chirp, $GDD < 0$). 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 20fs and below.

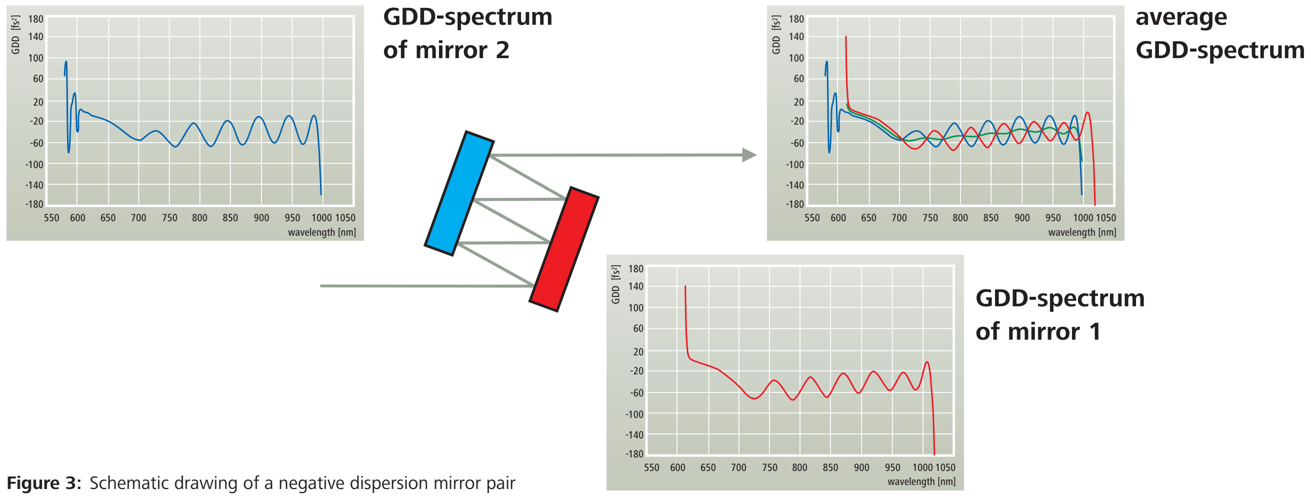

Figure 3: Schematic drawing of a negative dispersion mirror pair

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 82 – 83) 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 provides pulses of some hundred femtoseconds pulse length. For each wavelength components with different amounts of negative GDD are presented.

Besides these optics for the spectral range of the Ti:Sapphire ground wave and for the very promising Yb:YAG- and Yb:KGW-lasers we also offer 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 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.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

- 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 reflectivity of the mirrors (R > 99.99%)
- Spectral tolerance 1% of centre wavelength
- LIDT = 0.1 ... 0.3 J/cm² depending on the coating design
- In-house design calculation and GDD measurement capabilities
- Centre wavelength, GDD and TOD according to customer specification
- all components are supplied with measured GDD spectra

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STANDARD MIRRORS FOR FEMTOSECOND LASERS

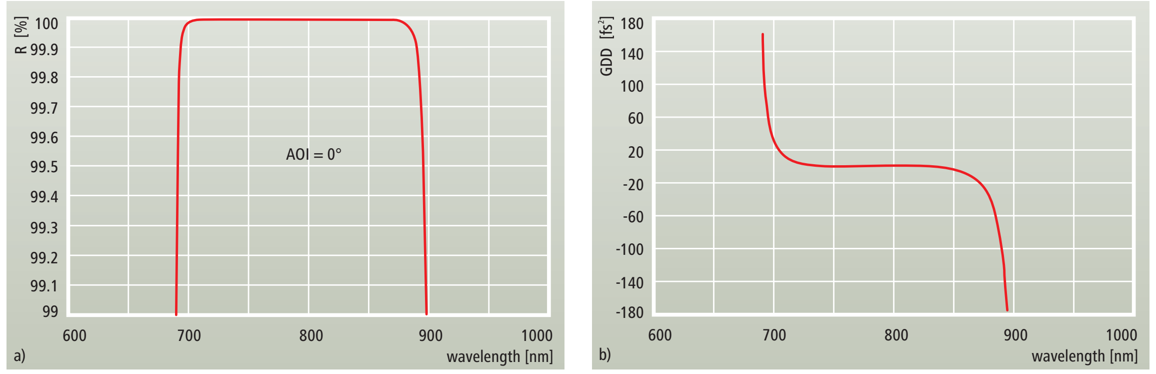

Figure 1: Reflectance (a) and GDD (b) spectra of a standard low dispersion femtosecond laser mirror

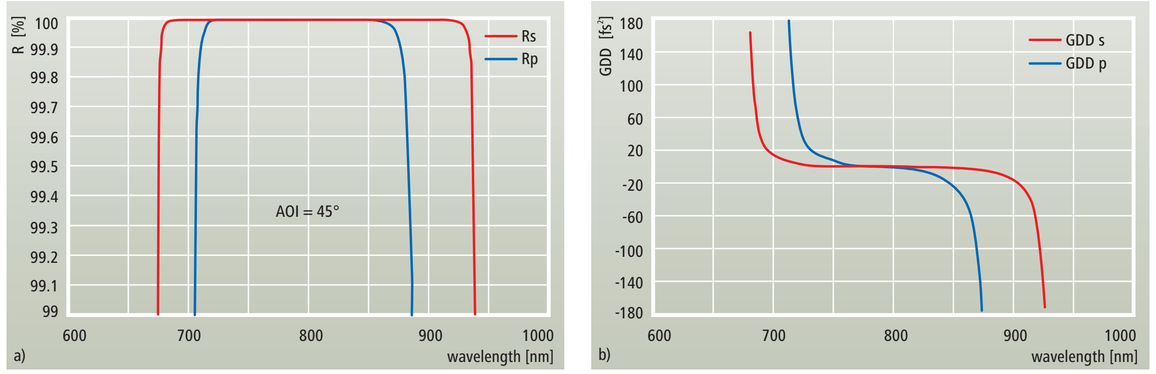

Figure 2: Reflectance (a) and GDD (b) spectra of a standard low dispersion turning mirror

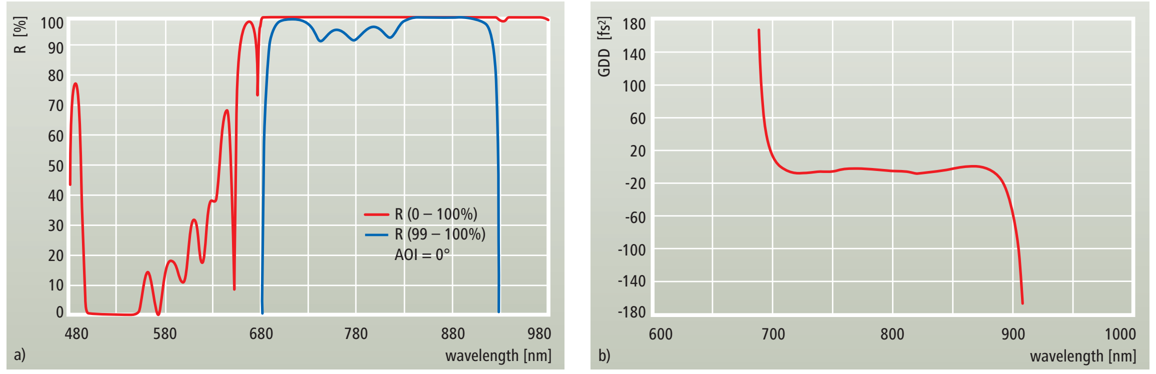

Figure 3: Reflectance (a) and GDD (b) spectra of a standard low dispersion pump laser mirror

All types of mirrors are also available with negative GDD (e.g. – 40fs²).
For high dispensive mirrors see page 64 – 65.

550 – 1100 nm

NEGATIVE DISPERSION MIRRORS

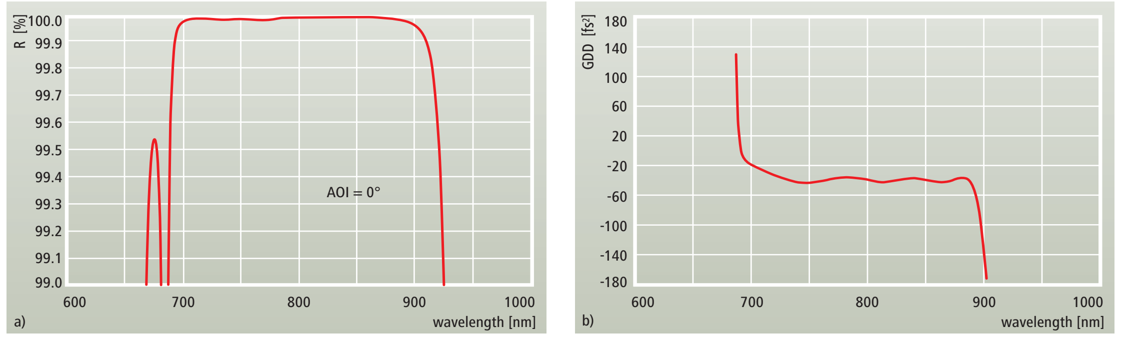

Figure 4: Reflectance (a) and GDD (b) spectrum of a standard negative dispersion mirror with GDD = –40 ± 10 fs²

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OUTPUT COUPLERS AND BEAM SPLITTERS

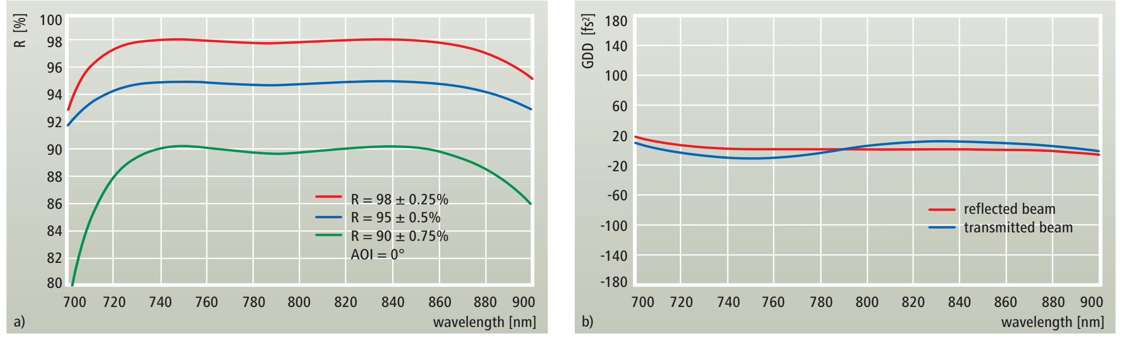

Figure 5: Reflectance (a) and GDD (b) spectra of several standard output couplers (the GDD spectra are calculated for R = 98%, but they are similar for all degrees of reflectivity)

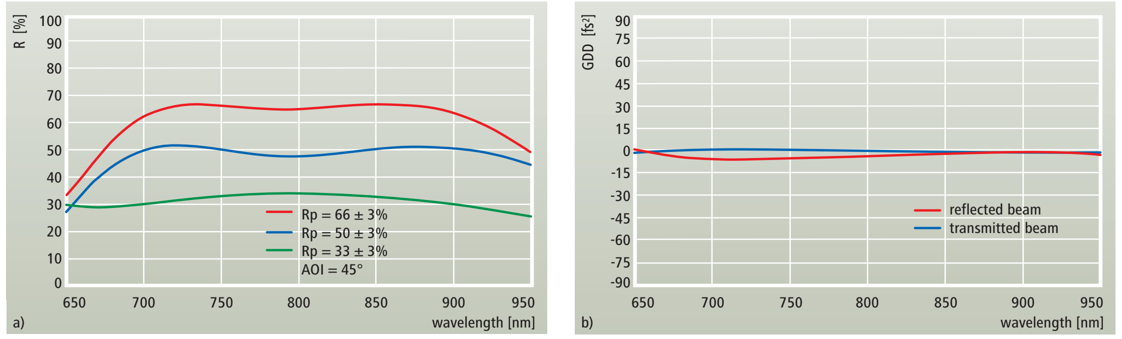

Figure 6: Reflectance (a) and GDD (b) spectra of several standard beam splitters for AOI = 45° and p-polarized light (the GDD spectra are calculated for R = 50%, but they are similar for all degrees of reflectivity)

- 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: Rs < 0.5%; p-pol: rear side uncoated, Rp < 0.6%

HIGH DISPERSIVE MIRRORS

Recent advances in design calculation and process control enable LAYERTEC to offer high dispersive 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 dispersive mirrors reduce the intra-cavity losses resulting in higher output power of the laser.

HIGH DISPERSIVE MIRROR PAIR FOR THE 600 nm RANGE

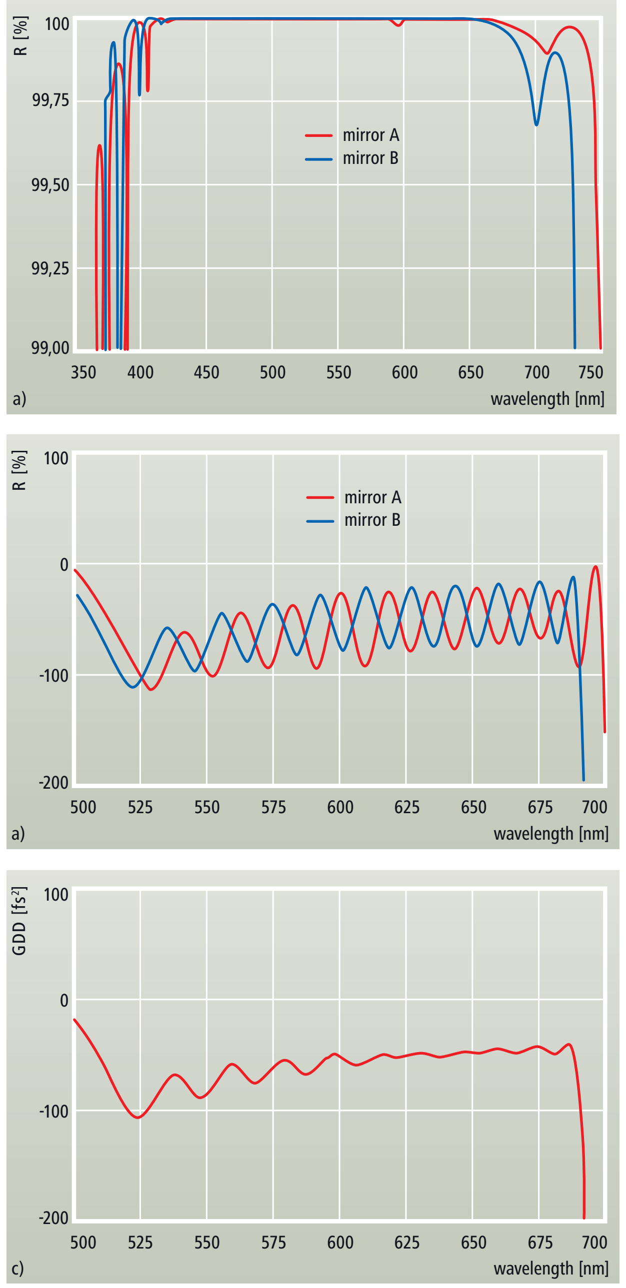

Figure 1: Reflectance (a), calculated (b) and measured average (c) GDD spectra of a high dispersive mirror pair with a bandwidth of 190 nm and a GDD of -100 … -50 fs² in the 600 nm range

HIGH DISPERSIVE MIRROR FOR THE 800 nm RANGE

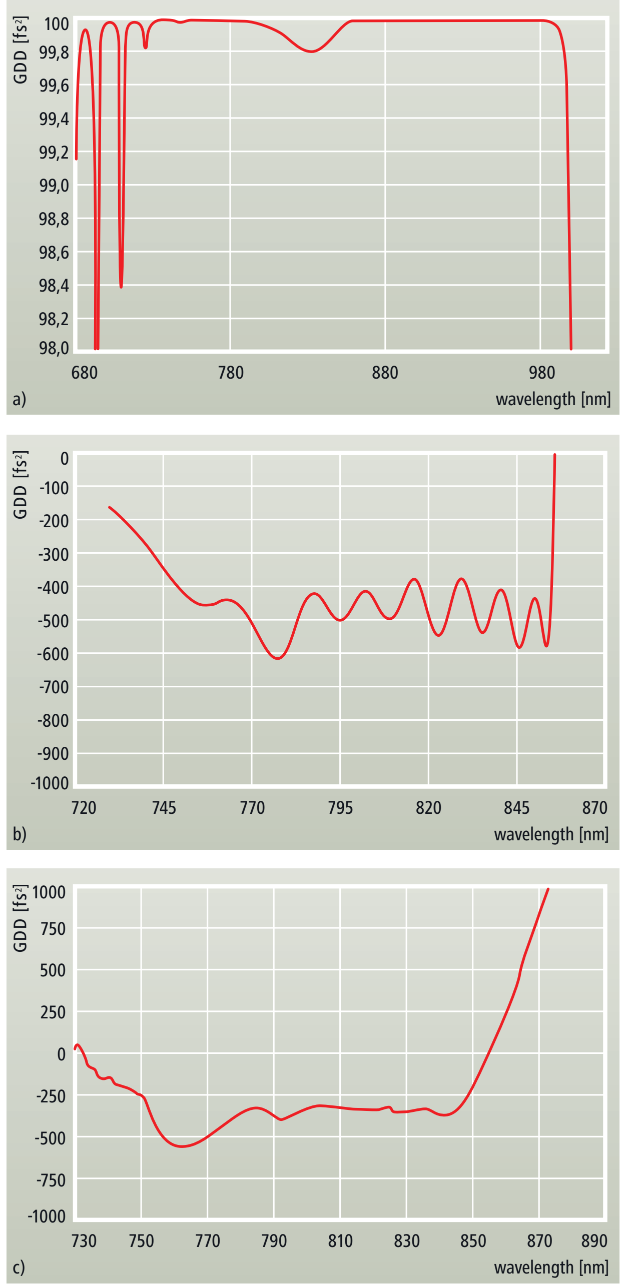

Figure 2: Reflectance (a), calculated (b) and measured (c) GDD spectra of a high dispersive mirror with a bandwidth of 120 nm and a GDD of -450 ± 100fs² in the 800 nm range

Measured and calculated GDD-curves match very well which proves the reliability of the coating process.

550 – 1100 nm

HIGH DISPERSIVE MIRROR PAIRS FOR THE Ti-SAPPHIRE LASER WAVELENGTH RANGE

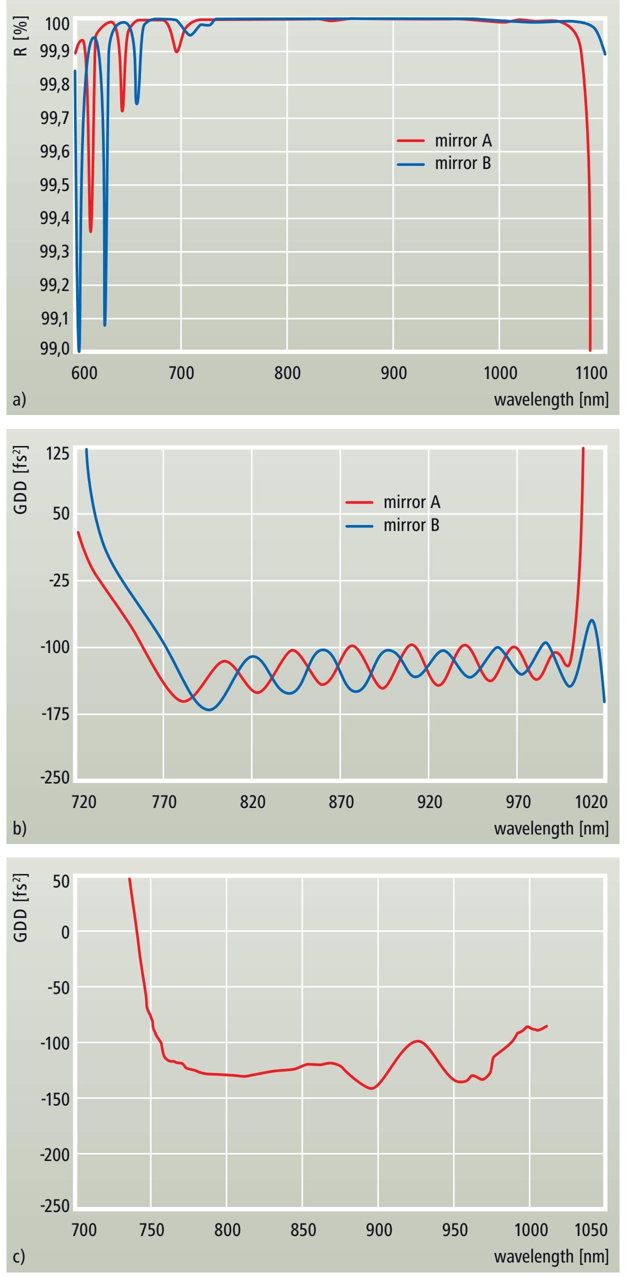

Figure 3: Reflectance (a), calculated (b) and measured average (c) GDD spectra of a high dispersive mirror pair with a bandwidth of 200 nm and an average GDD of -120 ± 40 fs² in the 800 nm range

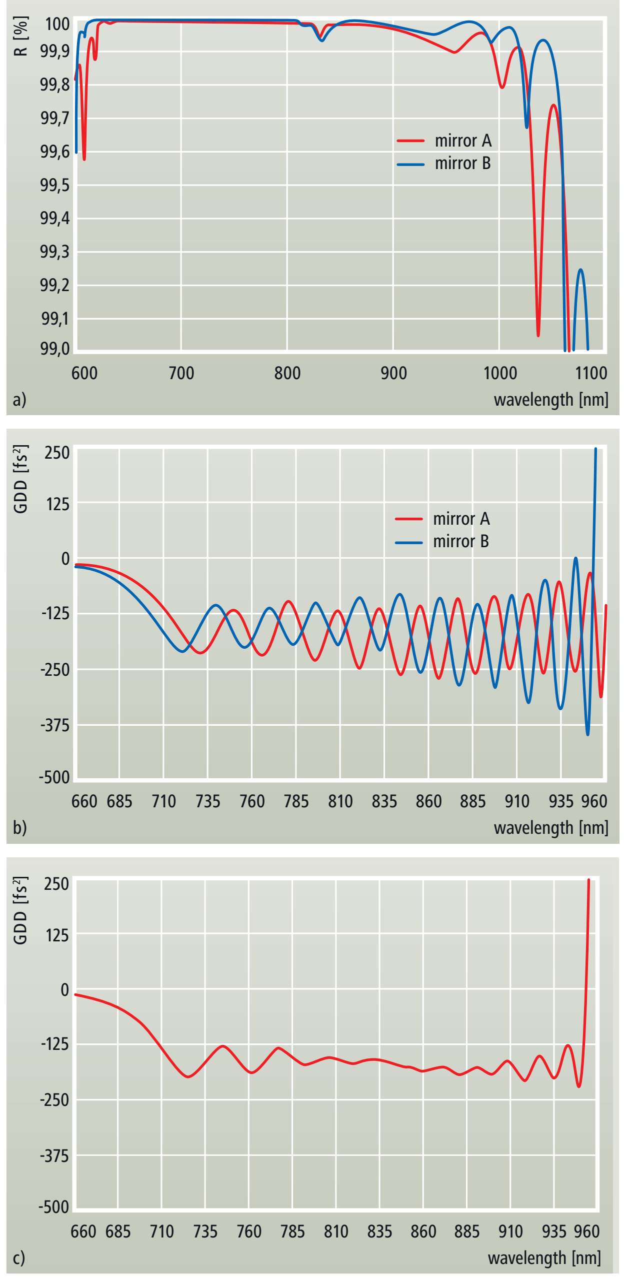

Figure 4: Reflectance (a), calculated (b) and measured average (c) GDD spectra of a high dispersive mirror pair with a bandwidth of 250 nm and an average GDD of -180 ± 40 fs² in the 800 nm range

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

Special features:

- GDD of high dispersive mirrors between -50 fs² and -500 fs²
- Very high reflectivity
- Measured LIDT 0.1 J/cm²
- Centre wavelength, bandwidth and GDD according to customer specification.
- Please note that bandwidth and GDD are closely connected. A high value of negative GDD results in a very narrow bandwidth.
- Spectral tolerance 1% of centre wavelength
- In-house design calculation and measurement capabilities (GDD 250 – 1700 nm, R-measurement by CRD 210 – 1700 nm)

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 and 650 – 950 nm
- Very high reflectivity of the mirrors (R > 99.8 % … R > 99.95 % depending on the design)
- Centre wavelength, bandwidth, GDD and TOD according to customer specification
- Spectral tolerance 1% of centre wavelength
- LIDT ≈ 0.1 J/cm²
- In-house design calculation and GDD measurement capabilities
- components are supplied with measured GDD spectra

NEGATIVE DISPERSION LASER MIRROR PAIR

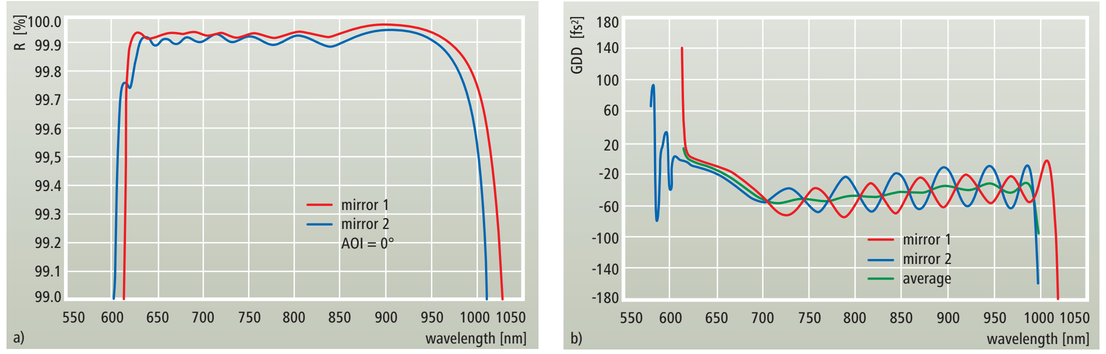

Figure 1: Reflectance (a) and GDD (b) spectra of a negative dispersion laser mirror pair

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 transmission around 500 nm) are also available.

NEGATIVE DISPERSION PUMP MIRROR PAIR

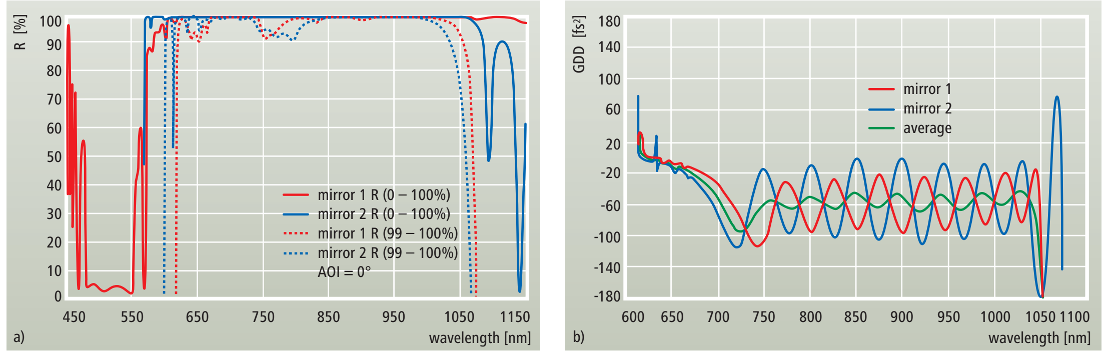

Figure 2: Reflectance (a) and GDD (b) spectra of a negative dispersion pump mirror pair

BROADBAND MIRROR PAIR WITH POSITVE AVERAGE GDD

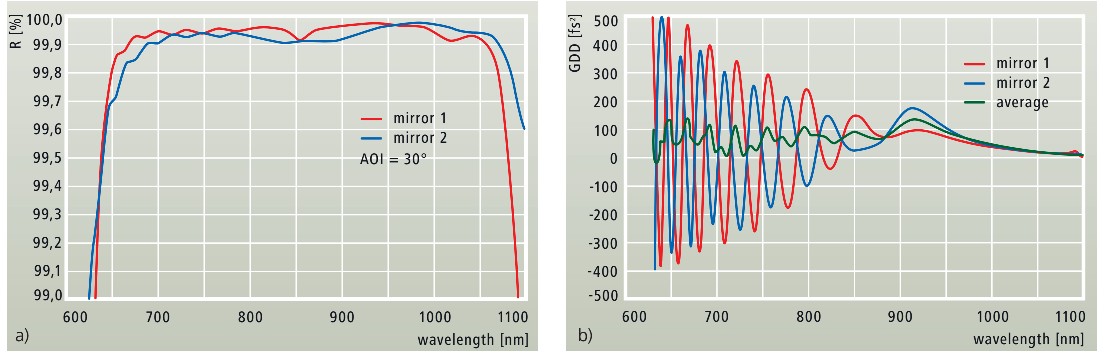

Figure 3: Reflectance (a) and GDD (b) spectra of a broadband mirror pair with positive average GDD for s-polarized light at AOI = 30°

550 – 1100 nm

BROADBAND NEGATIVE DISPERSION TURNING MIRRORS

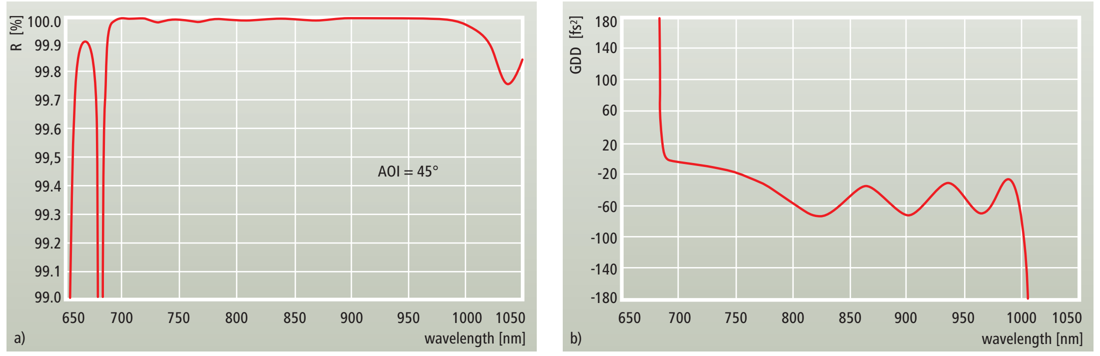

Figure 4: Reflectance (a) and GDD (b) spectrum of a broadband turning mirror for s-polarized light

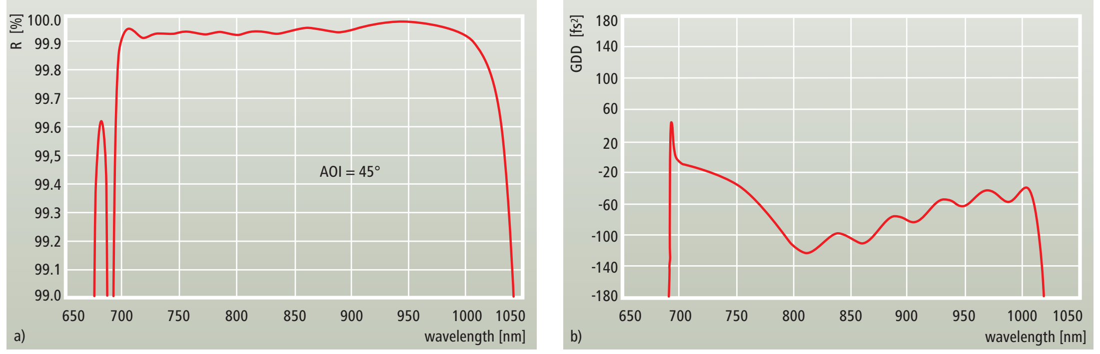

Figure 5: Reflectance (a) and GDD (b) spectrum of a broadband turning mirror for p-polarized light

BROADBAND OUTPUT COUPLERS

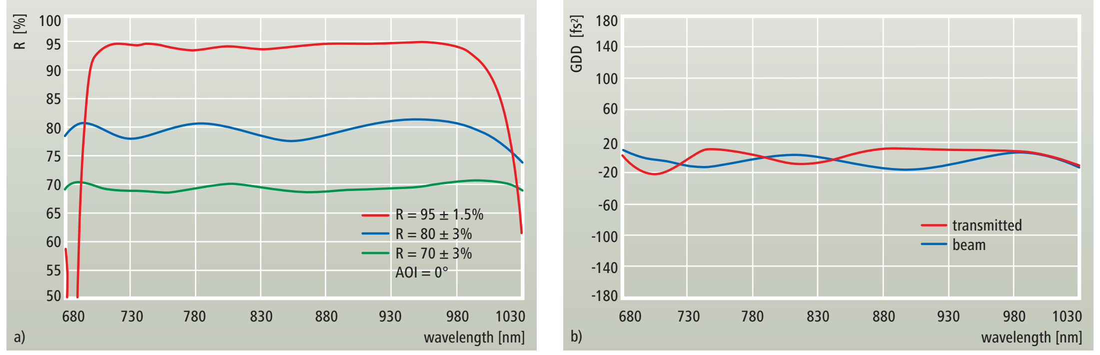

Figure 6: Reflectance (a) and GDD (b) spectra of several broadband output couplers. The GDD spectra are similar for all these components. Figure 6b shows the GDD spectra for the 80% output coupler.

BROADBAND BEAM SPLITTERS

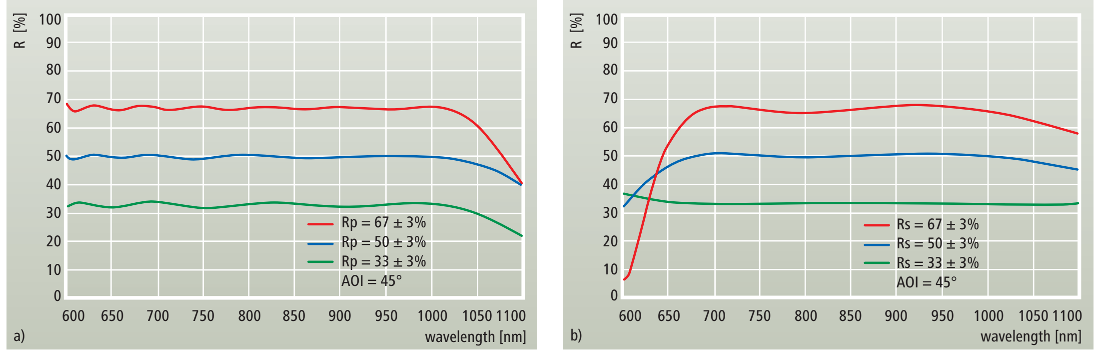

Figure 7: Reflectance spectra of several broadband beam splitters for p- (a) and s-polarization (b). The GDD values for reflected and transmitted light are in the range of ± 30 fs²

ULTRA BROADBAND FEMTOSECOND LASER OPTICS

- 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.
- Centre wavelength, bandwidth, GDD 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 GDD measurement capabilities
- components are supplied with measured GDD spectra

NEGATIVE DISPERSION LASER MIRROR PAIR

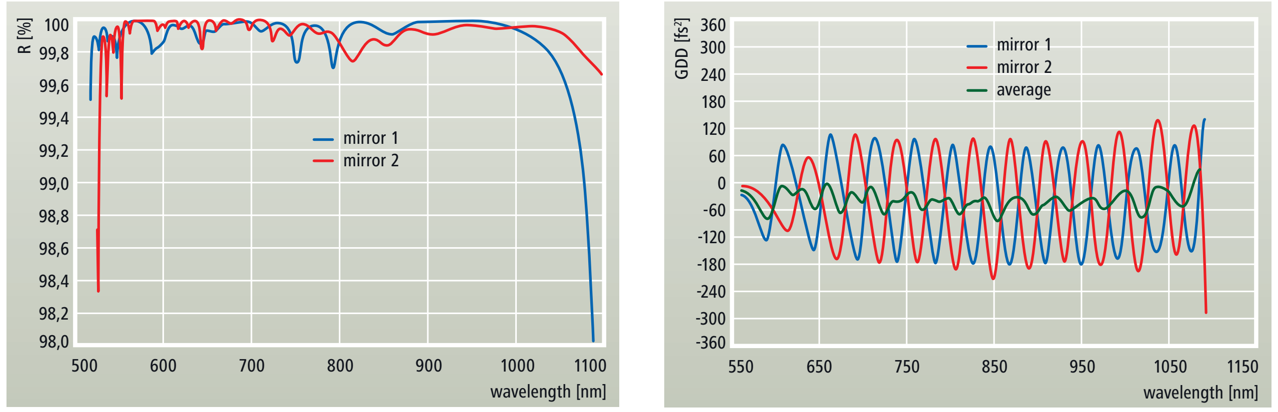

Figure 1: Reflectance (a) and GDD (b) spectra of an ultra broadband negative dispersion laser mirror pair; GDD-measurement see page 30

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

NEGATIVE DISPERSION PUMP MIRROR PAIR

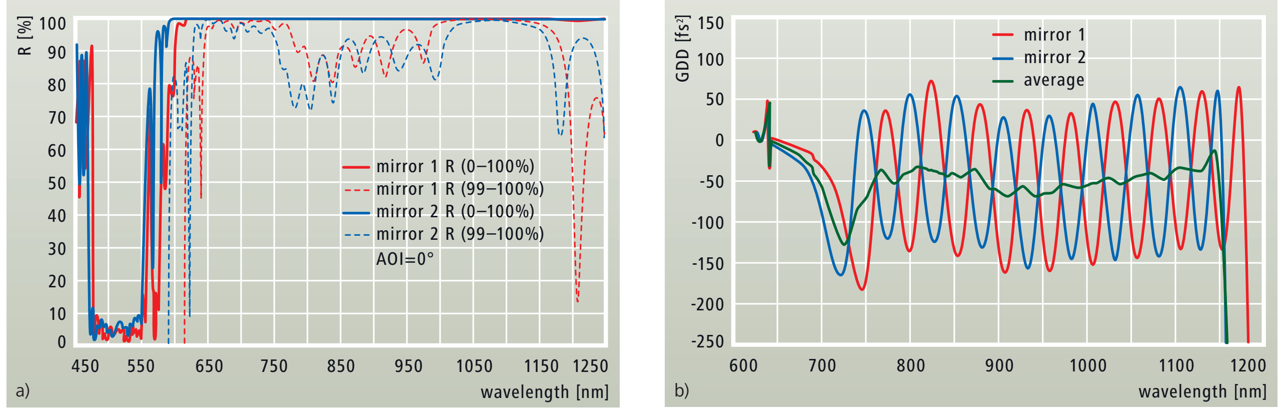

Figure 2: Reflectance (a) and GDD (b) spectra of an ultra broadband negative dispersion pump mirror pair

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

550 – 1100 nm

ULTRA BROADBAND NEGATIVE DISPERSION TURNING MIRROR PAIRS

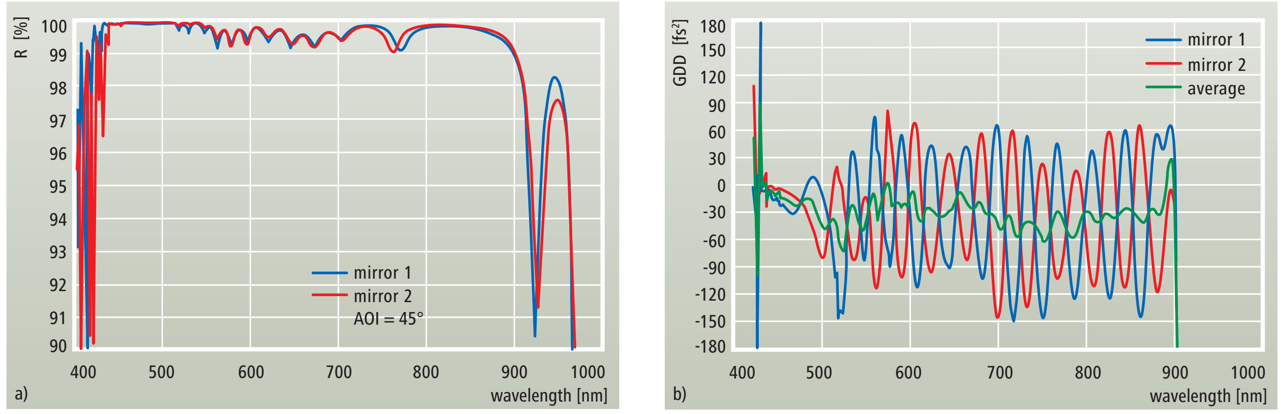

Figure 3: Reflectance (a) and GDD (b) spectra of an ultra broadband turning mirror pair for p-polarized light

ULTRA BROADBAND OUTPUT COUPLERS

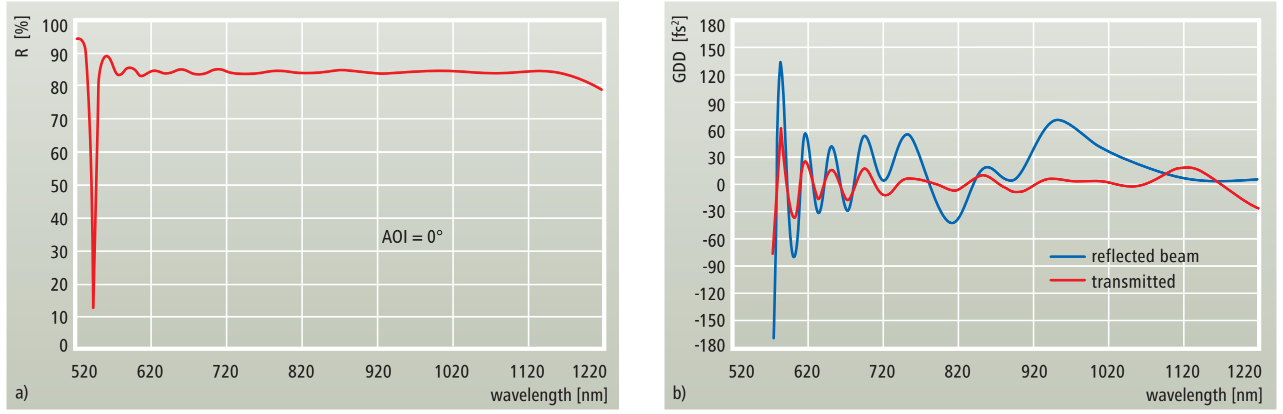

Figure 4: Reflectance (a) and GDD (b) spectra of an ultra broadband output coupler with R=85±3%

ULTRA BROADBAND BEAMSPLITTERS

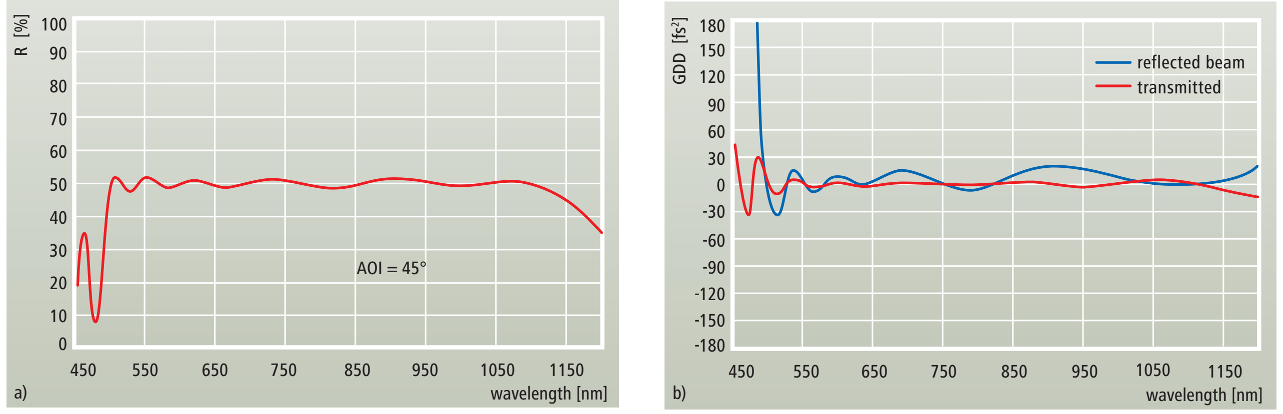

Figure 5: Reflectance (a) and GDD (b) spectra of an ultra broadband beamsplitter for p-polarized light with Rp=50±4%

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 fs³. Please note that without TOD optimization these oscillations are in the order of some thousands of fs³. Recently, broadband mirror pairs with low average TOD were developed (see fig. 4).

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MIRRORS OPTIMIZED FOR NEGATIVE OR POSITIVE THIRD ORDER DISPERSION

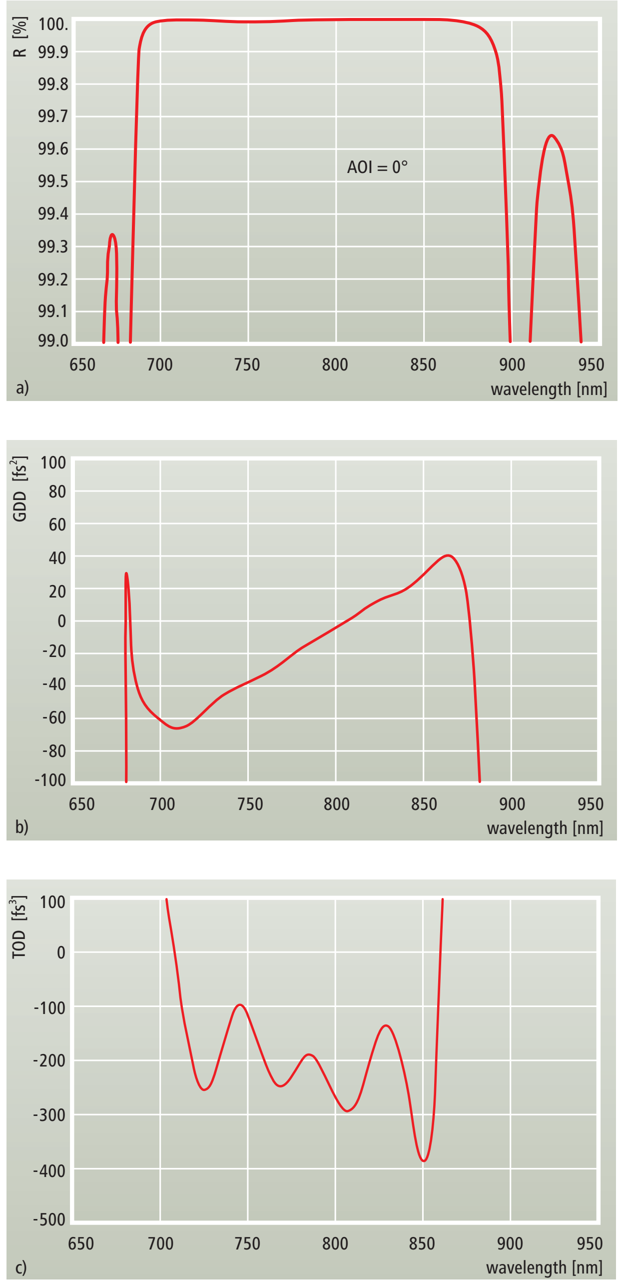

Figure 1: Reflectance (a), GDD(b) and TOD spectra (c) of a mirror optimized for nearly constant negative third order dispersion

- Centre wavelength and amount of TOD according to customer specifications

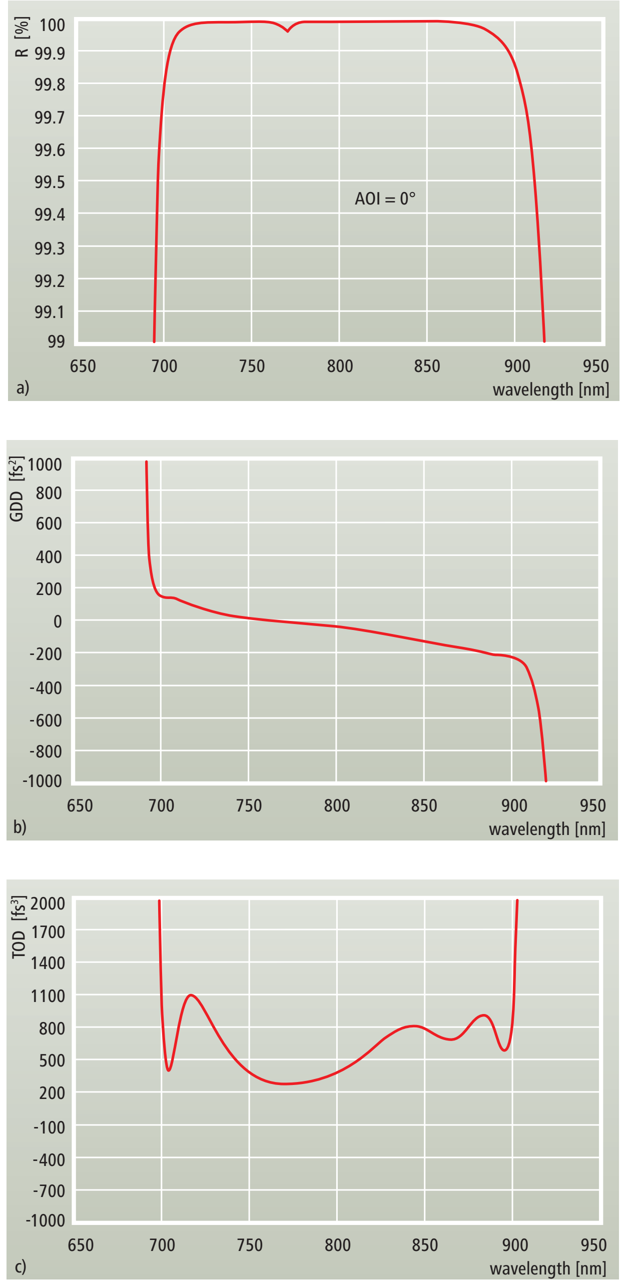

Figure 2: Reflectance (a), GDD(b) and TOD spectra (c) of a mirror optimized for nearly constant positive third order dispersion

- In the wavelength range of the Ti:Sapphire laser the bandwidth of single mirrors with optimized TOD is limited to about 150 nm

550 – 1100 nm

MIRROR PAIRS WITH OPTIMIZED THIRD ORDER DISPERSION

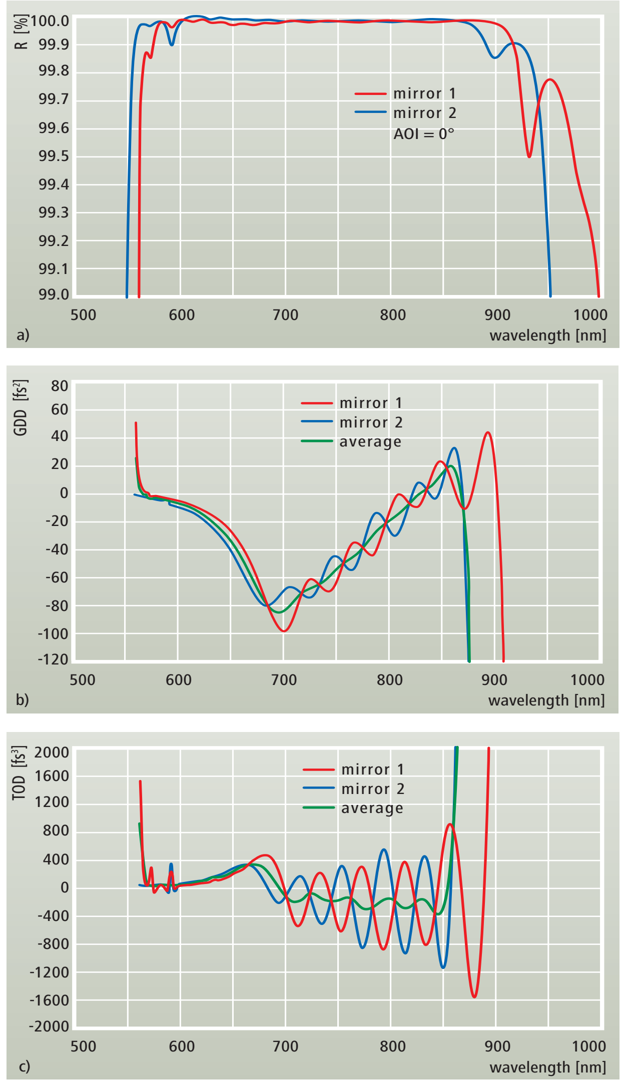

Figure 3: Reflectance (a), GDD(b) and TOD spectra (c) of a mirror pair optimized for nearly constant negative third order dispersion.

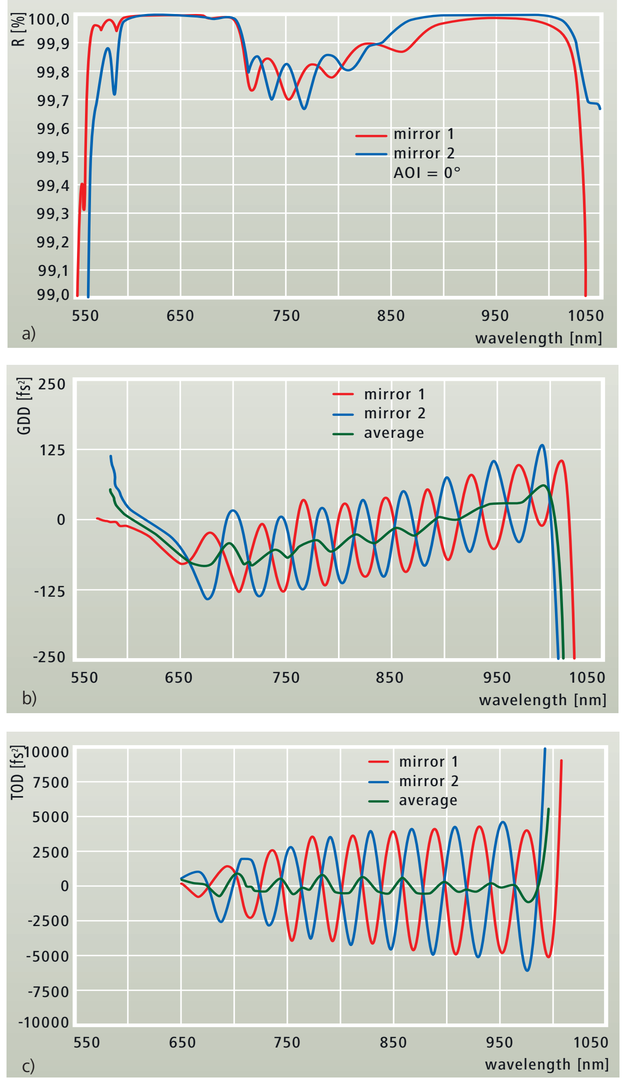

Figure 4: Reflectance (a), GDD(b) and TOD spectra (c) of a mirror pair optimized for broadband low third order dispersion.

Mirror pairs show very smooth GDD and TOD spectra, although the corresponding spectra of the single mirrors exhibit strong oscillations. Recently broadband low TOD mirror pairs (e.g. for a bandwidth of 400 nm, see fig. 4) were developed.

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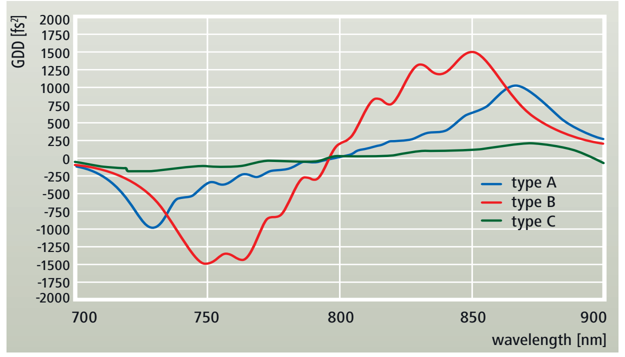
MIRRORS WITH DIFFERENT TOD VALUES



Increasing the GDD slope which means increasing the absolute TOD leads to a lower bandwidth and stronger GDD and TOD oscillations.

Figure 5: GGD spectra of three negative dispersive mirrors with different TOD values, i.e. different slope of the GDD curves

SILVER MIRRORS FOR FEMTOSECOND LASERS

SILVER MIRRORS OPTIMIZED FOR FEMTOSECOND APPLICATIONS

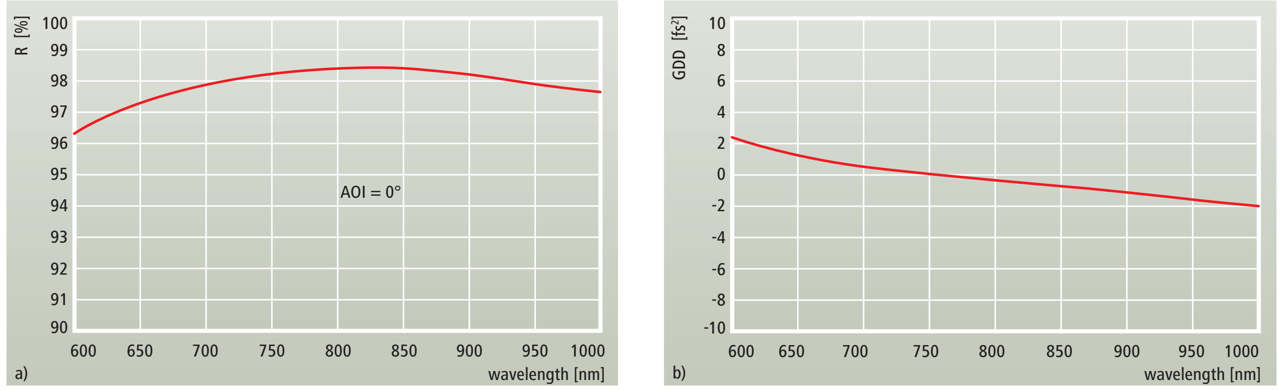


Figure 1: Reflectance (a) and GDD-spectrum (b) of a silver mirror optimized for use with fs-lasers in the wavelength range 600 – 1000 nm (AOI = 0°)

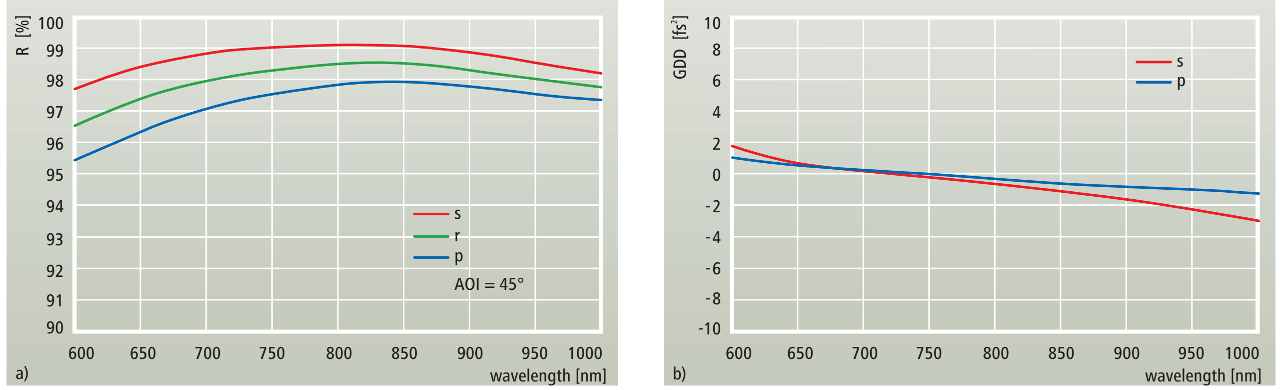


Figure 2: Reflectance (a) and GDD-spectra (b) of a silver mirror optimized for use with fs-lasers in the wavelength range 600 – 1000 nm (AOI = 45°)

Special features:

- High reflectance in the VIS and NIR
- Very broad reflectance band with GDD ~ 0 fs²
- Silver mirrors with defined transmission (e.g. 0.01%) show high LIDT-values (see table 1) and the same R and GDD values as shown in figures 1 and 2
- Extremely low straylight losses (TS ~ 3x10^{-5} in the VIS and NIR)
- Lifetimes of more than 10 years in normal atmosphere were demonstrated
- 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 – 200 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, 30 000 pulses, repetition rate 1 kHz, λ = 800 nm

Stock of standard components:

- Standard and fs-optimized protected silver on substrates with Ø = 12.7 mm, Ø = 25 mm and Ø = 50 mm:
  Plano,
  Plano/concave and plano/convex with a variety of radii between 10 mm and 10000 mm
- Other sizes, shapes, radii and coatings for other wavelengths ranges on request

550 – 1100 nm

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 GDD. The following figures show examples for silver mirrors with enhanced reflectivity at a specified wavelength (figures 3 and 4) and over the wavelength range of the Ti:Sapphire laser (figure 5). Also enhanced silver mirrors can be designed for a defined transmission (e.g. T = 0.01%).

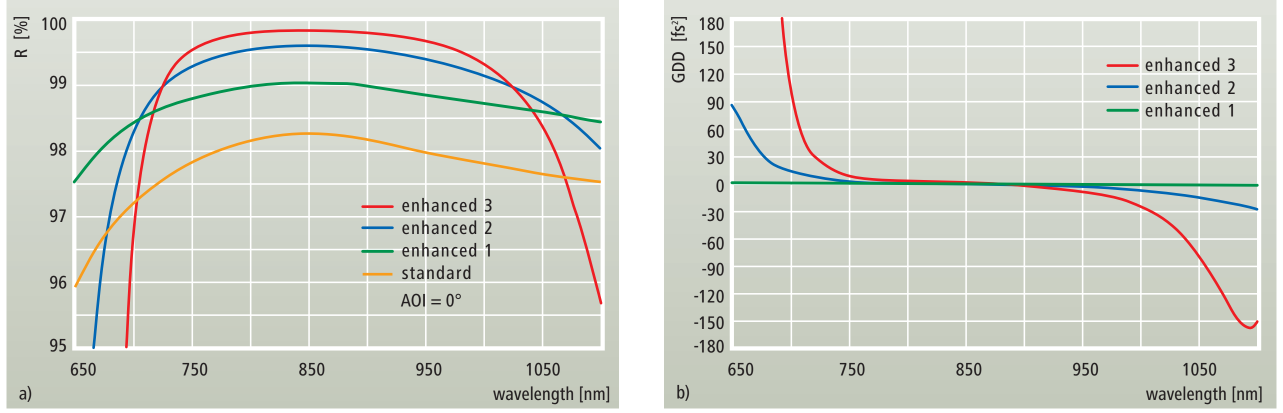


Figure 3: Reflectance (a) and GDD-spectra (b) of silver mirrors with different designs for enhanced reflectivity around 850 nm (AOI = 0°)

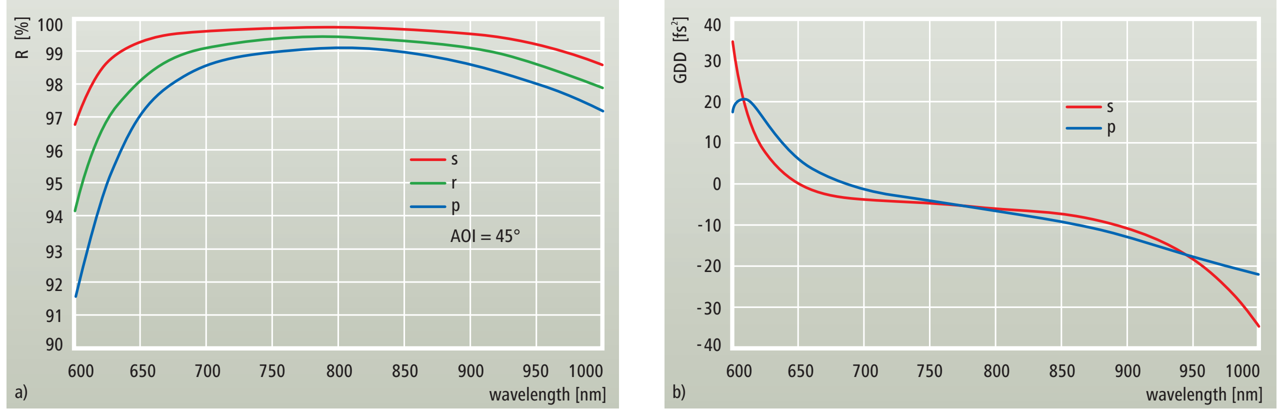


Figure 4: Reflectance (a) and GDD-spectra (b) of silver mirrors with enhanced reflectivity around 800 nm (AOI = 45°)

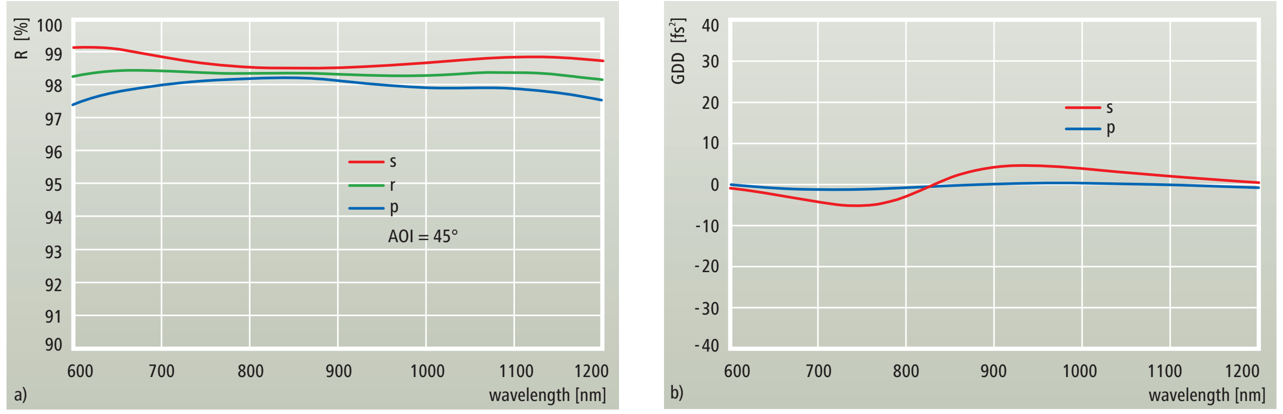


Figure 5: Reflectance (a) and GDD-spectra (b) of silver mirrors with enhanced reflectivity in the wavelength range 600 – 1200 nm (AOI = 45°)

HIGH POWER FEMTOSECOND LASER OPTICS

Coatings for femtosecond laser optics are usually optimized for special reflectance, transmittance and GDD 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 optics becomes more and more important. LAYERTEC has carried out detailed investigations of the LIDT of optics for fs and ps lasers.(*) As shown in the table on page 75 we found large differences in the LIDT values of standard, broadband and ultrabroadband optics and our high power mirrors. Standard low GDD mirrors (see page 62 figures 1 and 2) show a LIDT value of 0.3 J/cm^2 while negative GDD mirrors, broadband and ultrabroadband components (all other examples on page 64 – 69) 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 GDD components and the other optics mentioned above results from the different coating designs used. Especially the broadband and negative GDD designs result in low damage thresholds. Only the designs for standard low GDD 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 GDD < 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 GDD reflectance band with a reflectivity of up to 98.5% at normal incidence. Even silver mirrors with a defined transmission of 0.01% show higher damage thresholds than all dielectric ultra broadband components. For more information on silver mirrors see pages 72 –73.

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

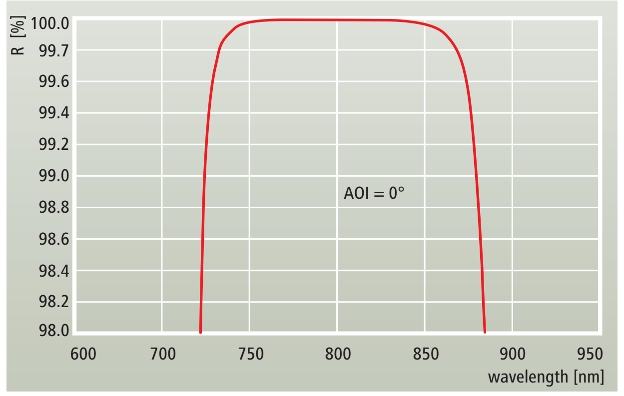


Figure 1: Reflectance spectrum of a high power fs laser mirror HR (0°, 800 nm) R > 99.9 %

550 – 1100 nm

OVERVIEW ABOUT LASER INDUCED DAMAGE THRESHOLDS OF FEMTOSECOND LASER OPTICS

Coating	reflectance at 800 nm	LIDT [J/cm²] *		
		50 fs	150 fs	1 ps
Bare gold	97.5%	0.33	0.33	
Fs-protected silver	**98.5%**	**0.38**	**0.38**	
Enhanced silver (800 nm)	99.7%		0.37	
Enhanced silver (600−1200 nm)	98.5%		0.24	
partially transparent silver (T(800 nm)=0.01%)	98.5%		0.22	
Negative dispersion mirrors	> 99.9%		~ 0.10	
Broadband low GDD mirrors	> 99.9%		~ 0.10	
Standard low GDD mirrors	> 99.9%		0.30	0.55
High power mirror type A	**> 99.9%**	**0.35**	**0.44**	**0.65**
High power mirror type B	**> 99.8%**		**0.75**	**1.04**
Single wavelength AR coating	< 0.2%			1.20 **
Broadband AR coating	< 0.5%			1.20 **

* Measurement conditions: 30000 pulses, repetition rate 1 kHz, λ=800 nm; 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

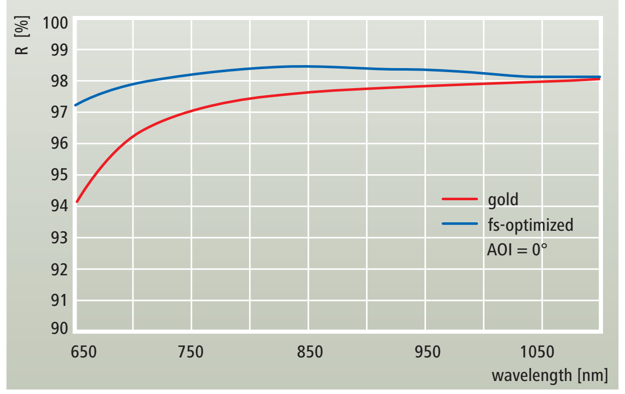


Figure 2: Reflectance spectra of bare gold and fs-optimized silver (optimized for high reflectance at 800 nm)

GDD OF HIGH POWER FEMTOSECOND LASER MIRRORS

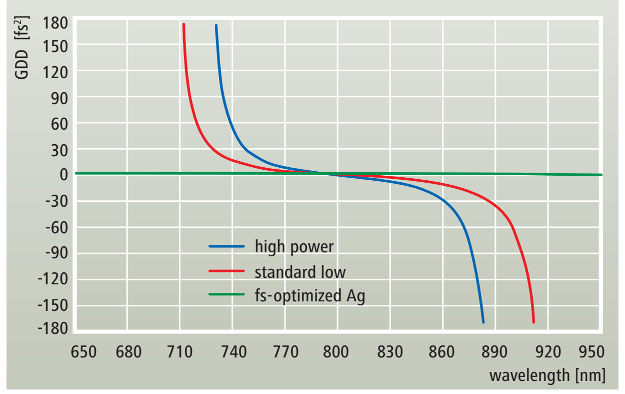


Figure 3: Group delay dispersion (GDD) of standard and high power dielectric mirrors and fs-protected silver mirrors

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 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.

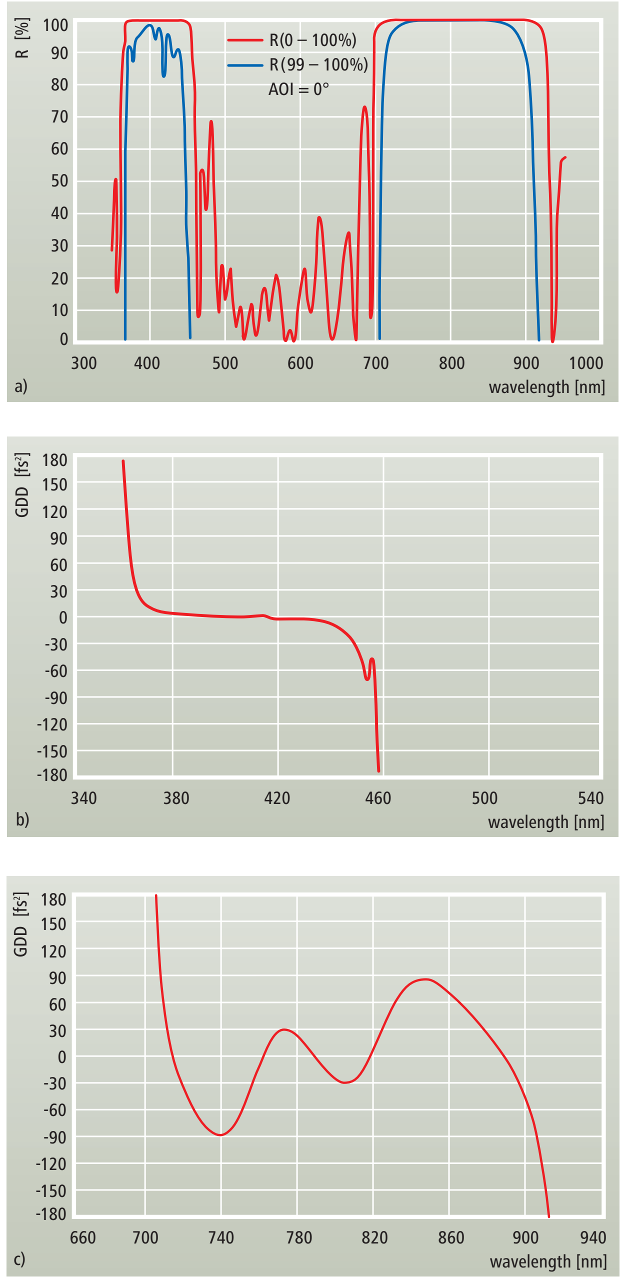


Figure 1: Reflectance- (a) and GDD-spectra (b, c) of a fs-optimized dual wavelength mirror for 400 nm + 800 nm

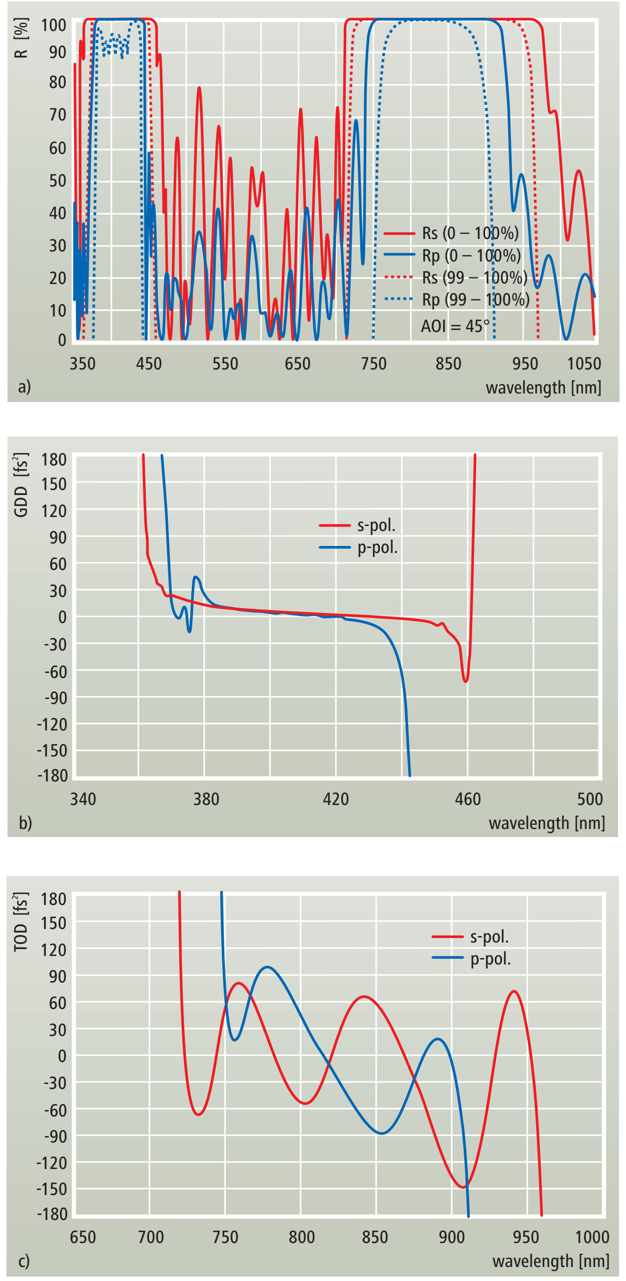


Figure 2: Reflectance- (a) and GDD-spectra (b, c) of a fs-optimized dual wavelength turning mirror for 400 nm + 800 nm

Special features:

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

300 – 600 nm

SEPARATORS FOR THE SECOND HARMONIC FROM THE GROUND WAVE

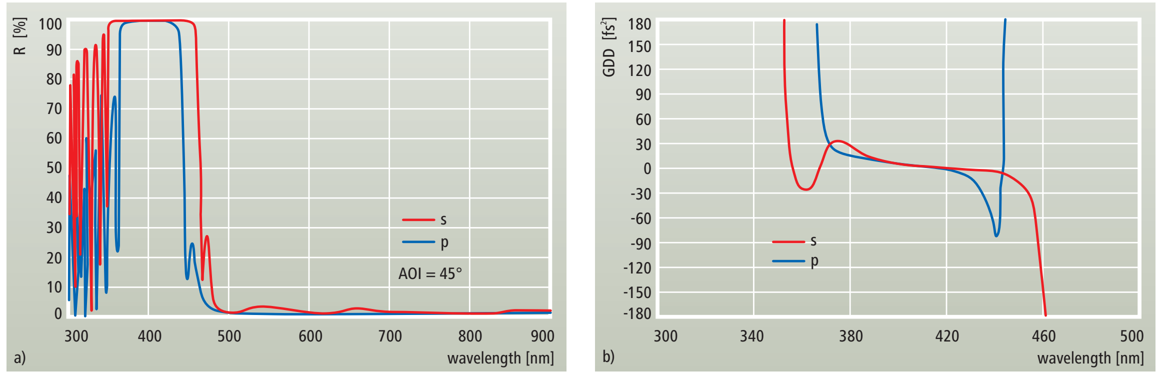


Figure 3: Reflectance- (a) and GDD-spectra (b) of a separator HR 400 nm + HT 800 nm (AOI = 45°)

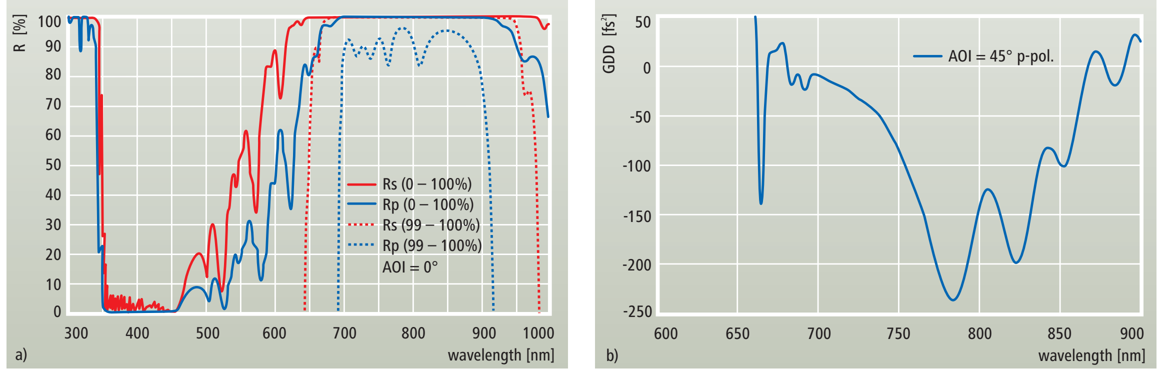


Figure 4: Reflectance- (a) and GDD-spectra (b) of a separator HR 800 nm (optimized for p-polarization) + HT 400 nm (AOI = 45°)

- Reflectivity R > 99.9% for s- and p-polarization in the reflection band
- Bandwidth of the 800 nm reflection band > 200 nm for p-polarization
- Transmission T > 95% for s- and p-polarization in the transmission band
- In principle, these components work for p- and s-polarization, but the performance can be optimized if the polarization is clearly specified
- All separators exhibit |GDD| < 20 fs² in the transmission band

NEGATIVE DISPERSION MIRROR PAIR FOR THE 400 nm SPECTRAL RANGE

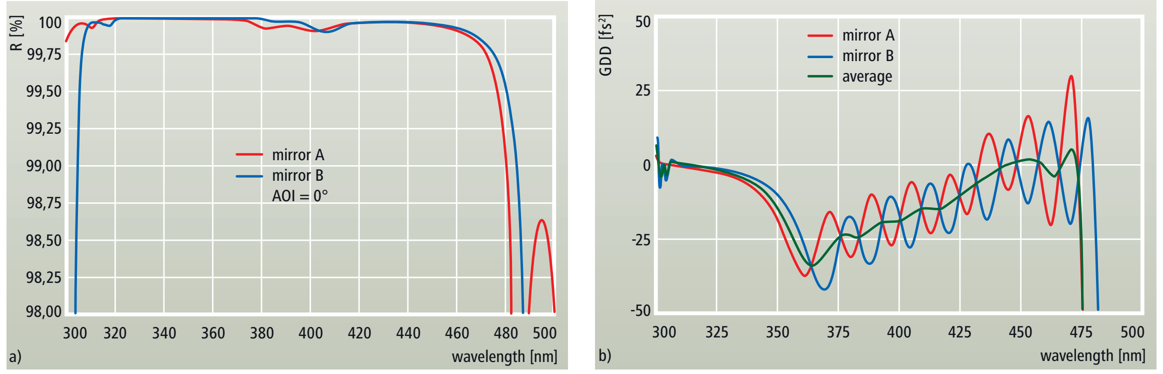


Figure 5: Reflectance- (a) and GDD-spectra (b) of a negative dispersion mirror pair for 350 nm – 480 nm with an average GDD varying from -30 fs² at 350 nm to 0 fs² at 480 nm (TOD optimized)

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

COMPONENTS FOR THE THIRD HARMONIC OF THE TI:SAPPHIRE LASER

The third harmonic of the Ti:Sapphire laser provides fs-pulses in the UV range (~250 – 330 nm). 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. For more information about optics for the third and the higher harmonics please see pages 80 – 81.

DUAL WAVELENTGH TURNING MIRRORS

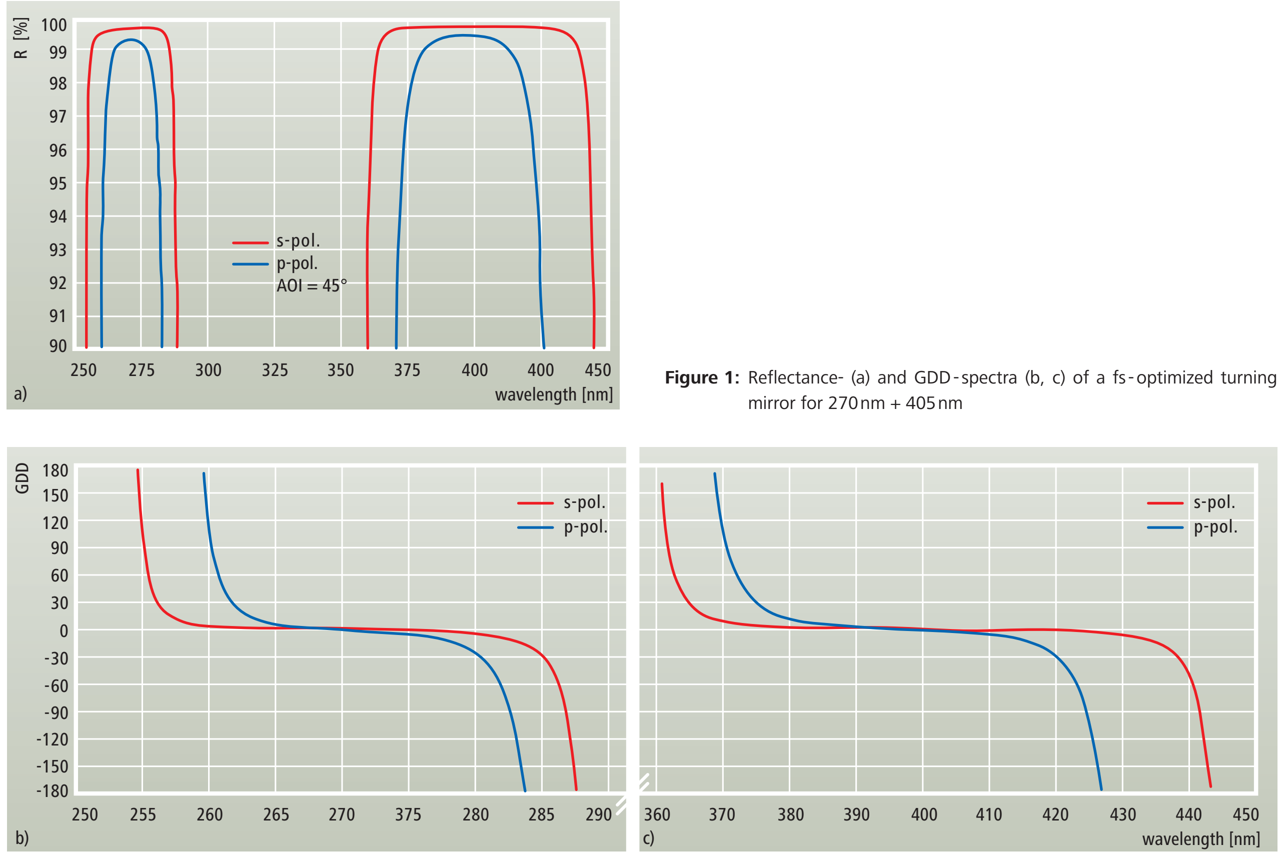


Figure 1: Reflectance- (a) and GDD-spectra (b, c) of a fs-optimized turning mirror for 270 nm + 405 nm

TRIPLE WAVELENTGH TURNING MIRRORS

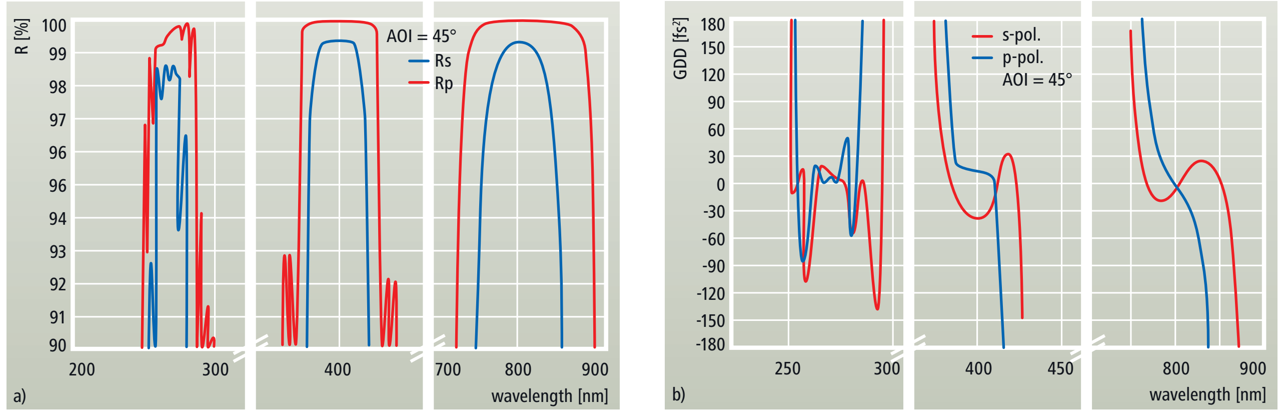


Figure 2: Reflectance- (a) and GDD-spectra (b) of a fs-optimized turning mirror for the 266 nm – 400 nm – 800 nm wavelength regions

Please note that this triple wavelength turning mirror exhibits |GDD| < 50 fs² in all three wavelength regions of interest.

250 – 400 nm

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

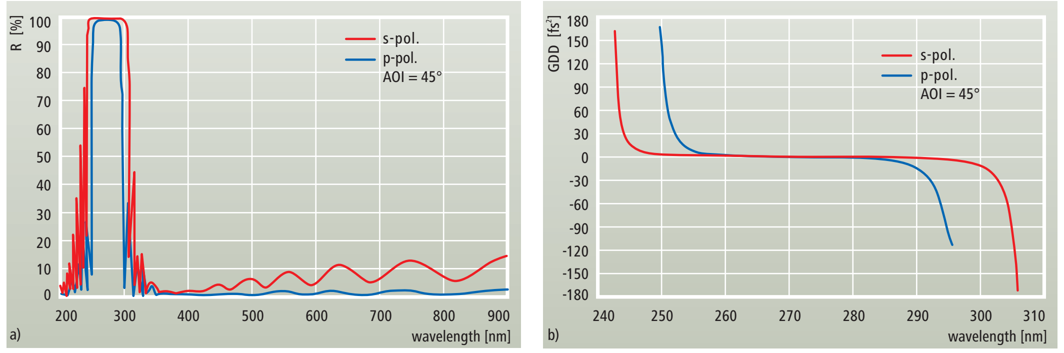


Figure 3: Reflectance- (a) and GDD-spectra (b) of a separator for HR 270 nm + HT 405 + 810 nm (45°)

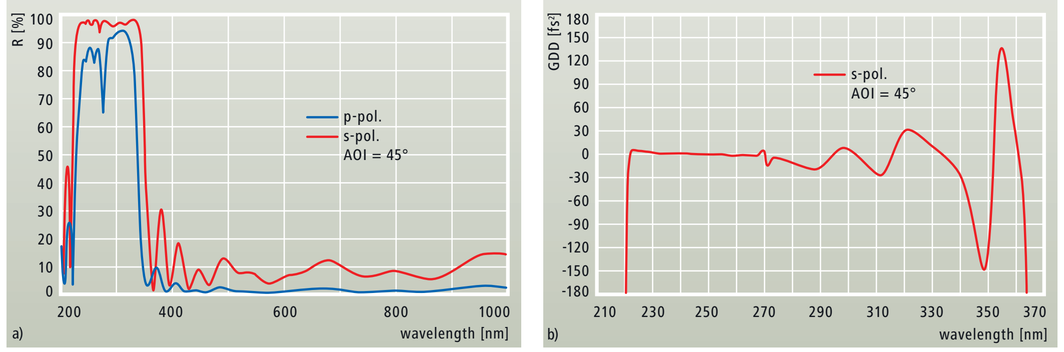


Figure 4: Reflectance (a) and GDD (b) spectra of a broadband separator with high reflectivity for s-polarized light throughout the wavelength range of the third harmonic of the Ti:Sapphire laser and high transmission for p-polarized light in the VIS and NIR: HRs (45°, 250 – 330 nm) > 95 % + Rp (45°, 440 – 1000 nm) < 3%

BROADBAND LOW DISPERSION MIRRORS

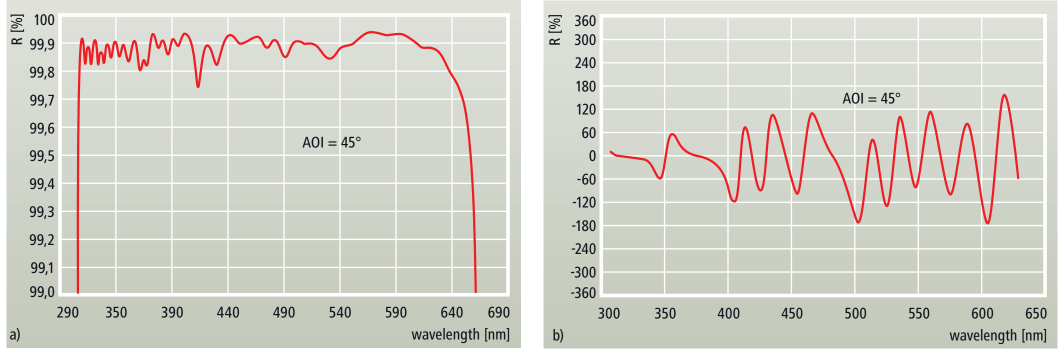


Figure 5: Reflectance- (a) and GDD-spectra (b) of a broadband negative dispersion mirror HRs (45°, 325 nm – 600 nm) with Rs > 99.7% and low GDD

NEGATIVE DISPERSION MIRROR PAIR

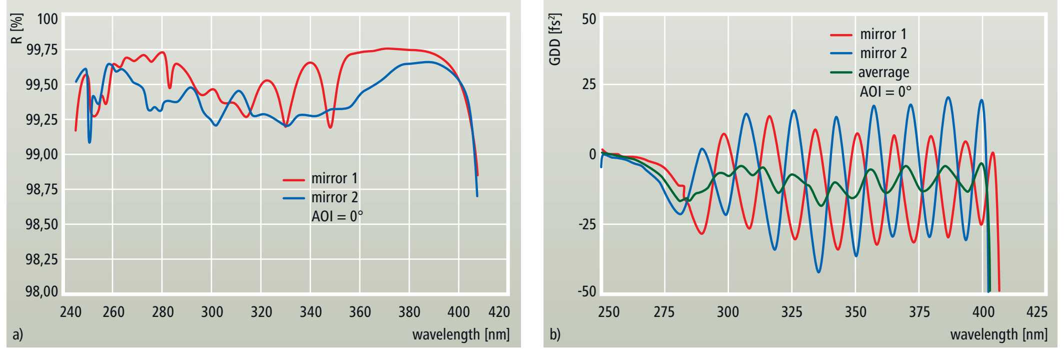


Figure 6: Reflectance- (a) and GDD-spectra (b) of a broadband negative dispersion mirror pair HR (0°, 275 nm – 400 nm) with R > 99% and an average GDD of ≈ -10 fs²

COMPONENTS FOR THE HIGHER HARMONICS OF THE Ti:SAPPHIRE LASER

The fourth and fifth harmonics of the Ti:Sapphire laser provide fs-pulses in the DUV/VUV 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 high reflectivity and low dispersion.

Standard components for the wavelength range 140 nm – 215 nm consist of fluoridic layer systems on CaF_2 substrates while components for longer wavelength can be made of oxides.

TURNING MIRRORS AND SEPARATORS FOR THE FOURTH HARMONIC

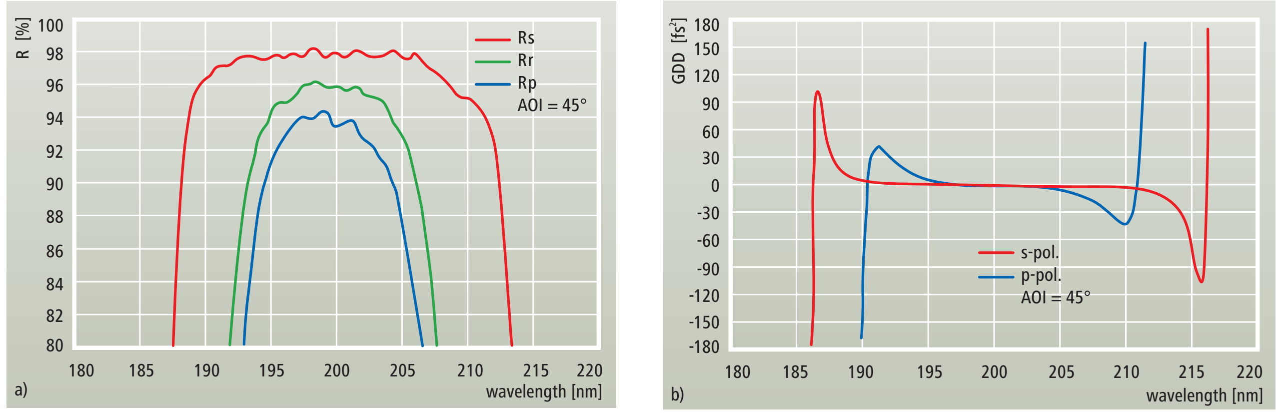


Figure 1: Reflectance (measured, a) and GDD-spectra (calculated, b) of a turning mirror for 200 nm (AOI = 45°)

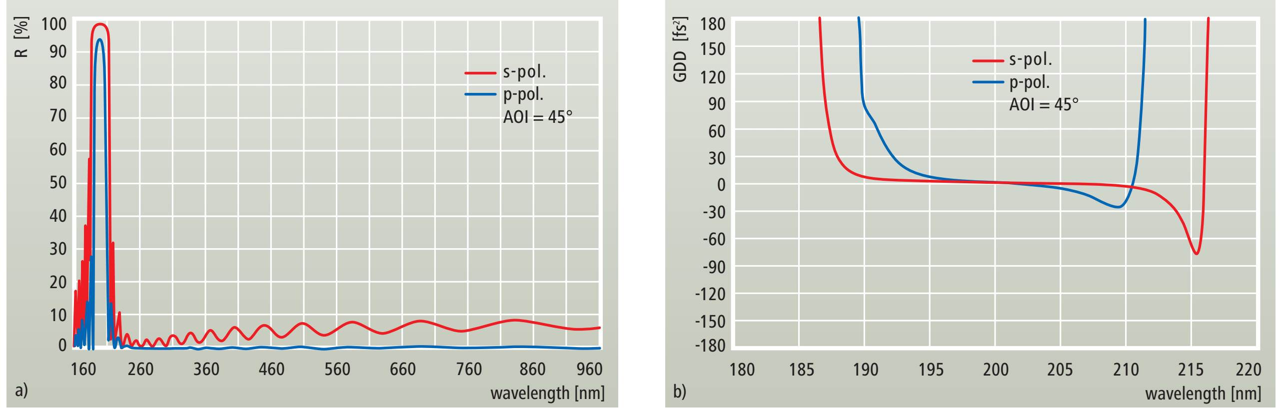


Figure 2: Reflectance (a) and GDD-spectra (b) of a separator for the fourth harmonic from the longer wavelength harmonics and the ground wavelength (AOI = 45°)

COMPONENTS FOR THE FIFTH HARMONIC

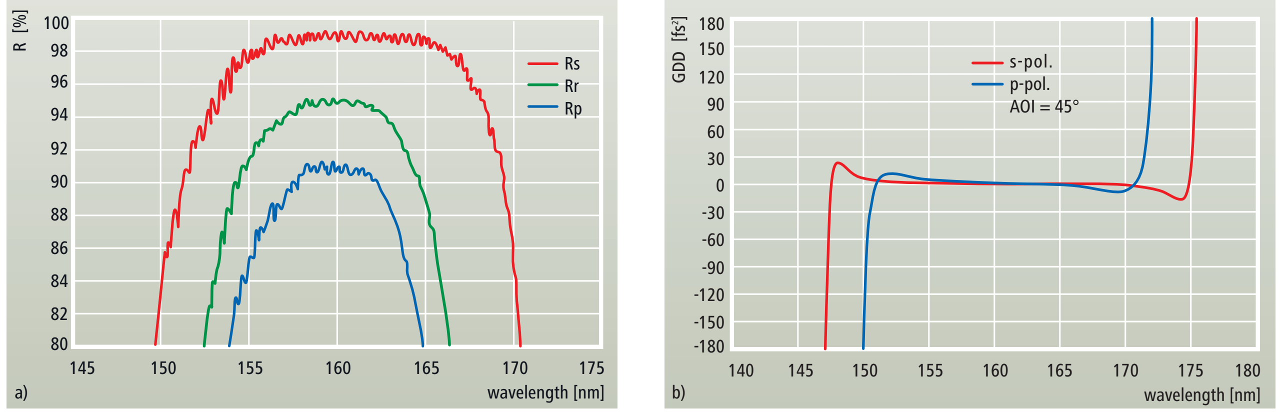


Figure 3: Reflectance (measured, a) and GDD-spectra (calculated, b) of a turning mirror for 160 nm (AOI = 45°)

140 – 250 nm

PROPERTIES OF FEMTOSECOND UV COATINGS

- Depending on the wavelength range of the ground wave the coatings described in the data sheets on the pages 78 – 81 can be used for the following centre wavelengths:
  - Third harmonic: 250 – 330 nm
  - Fourth harmonic: 180 – 250 nm
  - Fifth harmonic: 140 – 180 nm
- All coatings are optimized for broad reflection bands, high reflectivity and low GDD

Bandwidth of the high reflectance and low GDD range of standard components

Component	Wavelength range	P-polarization	S-polarization
		|GDD| < 20 fs²	|GDD| < 20 fs²
Turning mirror or separator 3rd harmonic	UV	30 nm (R > 99%)	50 nm (R > 99%)
Dual wavelength turning mirror	UV	15 nm (R > 99%)	26 nm (R > 99%)
	UV/VIS	34 nm (R > 99%)	72 nm (R > 99%)
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%)

BROADBAND REFLECTORS FOR THE 200 nm – 250 nm WAVELENGTH RANGE

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

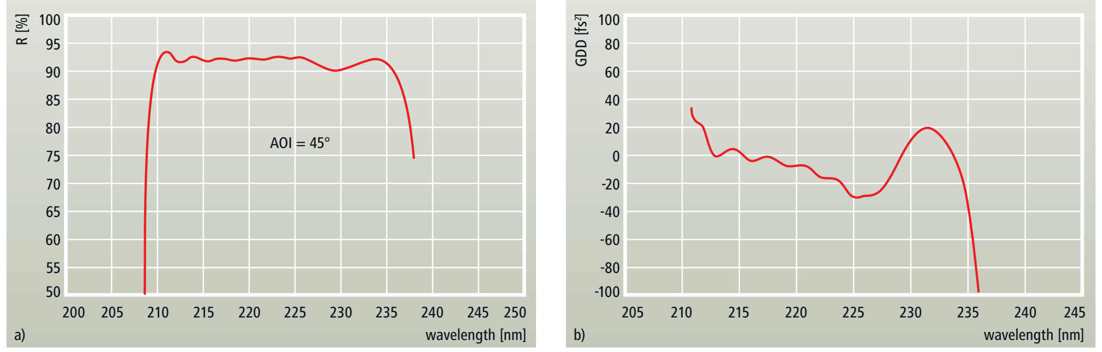


Figure 4: Reflectance (a) and GDD-spectra (b) of a broadband mirror HRs(45°, 210 – 235 nm) > 90%

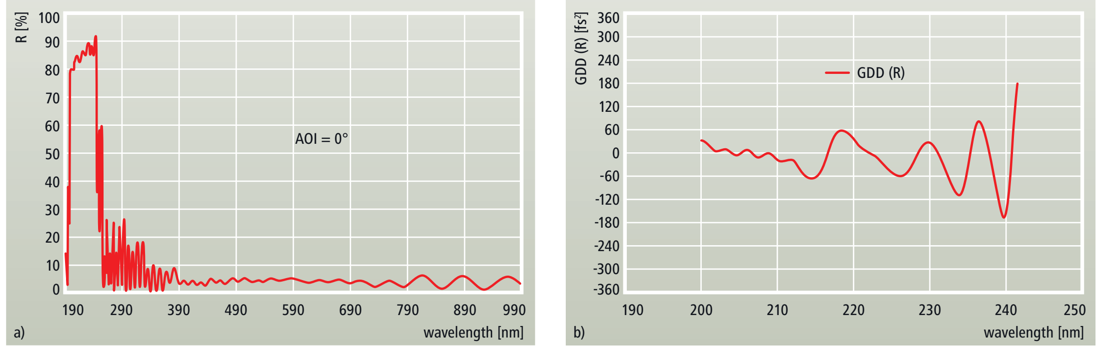


Figure 5: Reflectance (a) and GDD-spectra (b) of a broadband separator HR(0°, 200 – 245 nm) > 80% + R(0°, 300 – 1000 nm) < 10%

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 above. 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

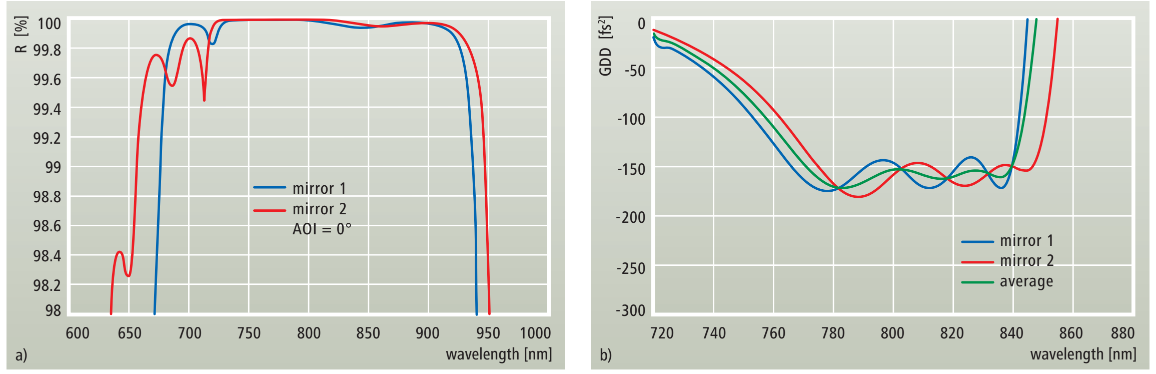
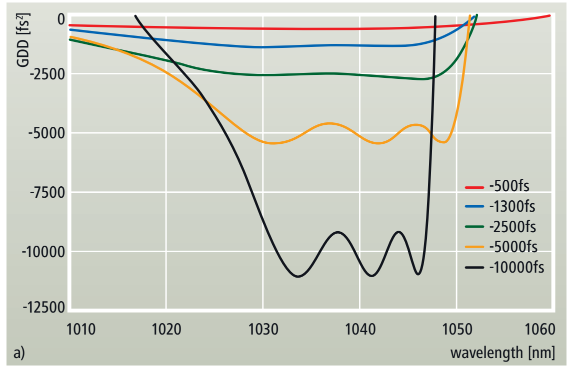


Figure 1: Reflectance (a) and GDD (b) spectra of a pair of GTI-mirrors for 780 – 840 nm (single mirrors: GDD = −160±20fs², mirror pair: GDD = −160±10fs²)

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

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



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

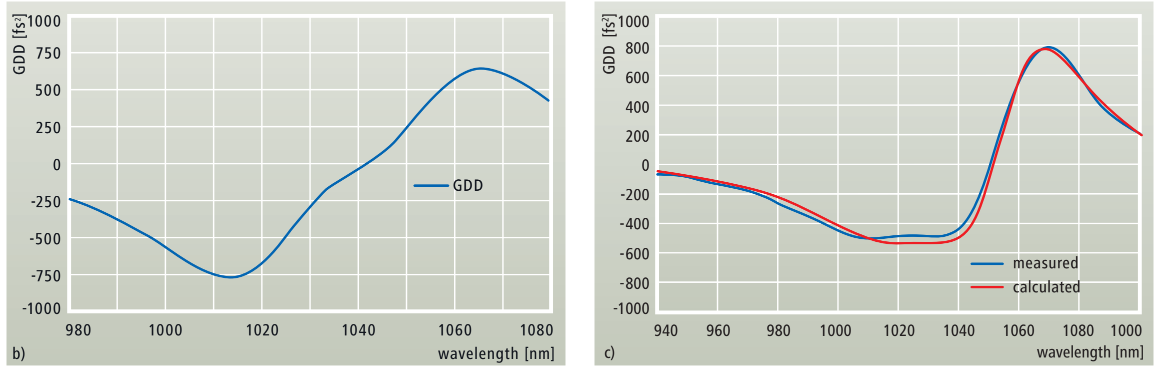


Figure 2: GDD spectra of GTI-mirrors for 1030nm with different GDD values (a), of a GTI-mirror with nearly constant TOD (b) and comparison of measured and calculated GDD spectra of a GTI mirror with GDD −500fs² (c)

Measured and calculated GDD-curves match very well which proves the reliability of the coating process.

600 – 1600 nm

GTI-MIRRORS FOR OTHER FEMTOSECOND LASERS

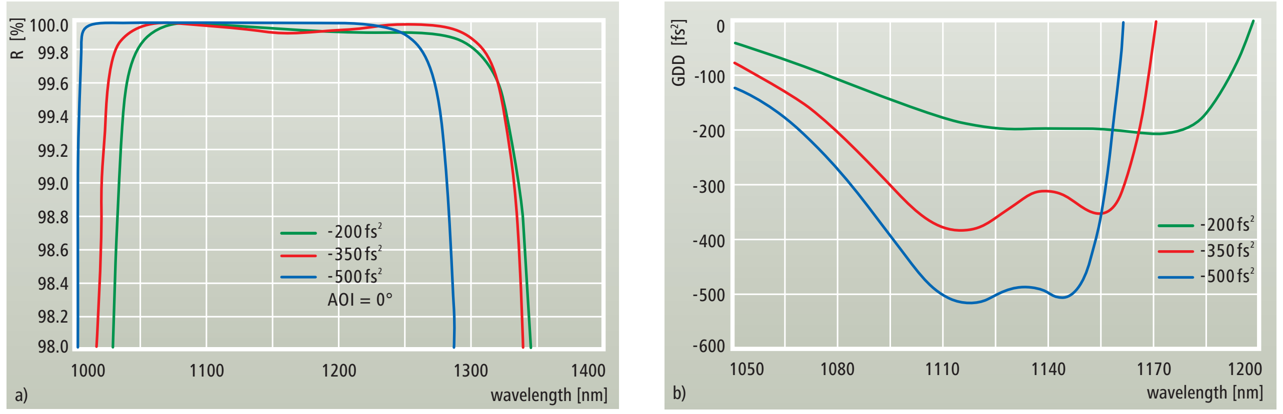


Figure 3: Reflectance (a) and GDD spectra (b) of GTI mirrors for 1130nm with different GDD values

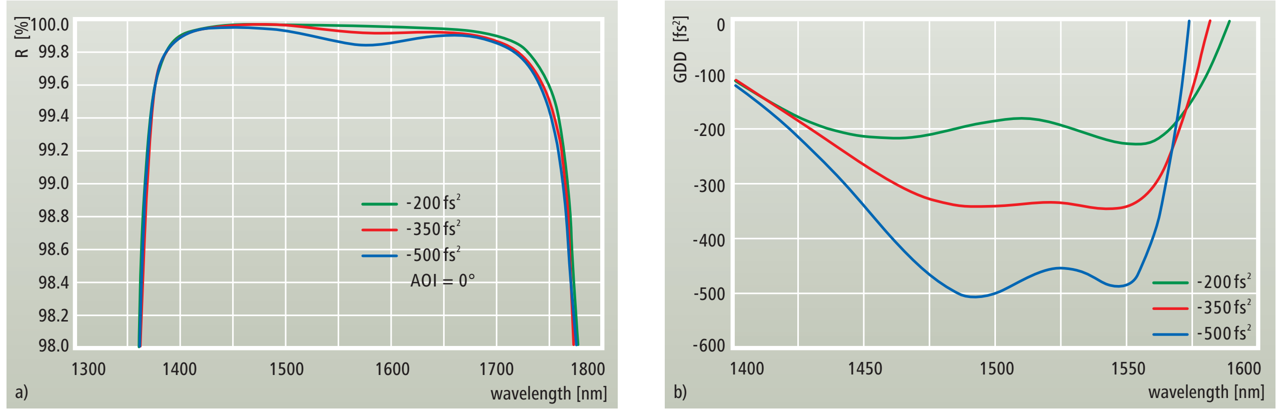


Figure 4: Reflectance (a) and GDD spectra (b) of GTI mirrors for 1500nm with different GDD values

Special features:

- GDD values according to customers specification
- Very high reflectivity
- Measured LIDT 0.1J/cm²
- Centre wavelength, bandwidth and GDD according to customer specification
  Please note that bandwidth and GDD are closely connected
  A high value of negative GDD results in a very narrow bandwidth
- Spectral tolerance 1% of centre wavelength
- In house design calculation and measurement capabilities (GDD 250−1700nm, R-measurement by CRD 210 – 1800nm)

OPTICS FOR FEMTOSECOND LASERS IN THE 1100 – 1600 nm 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 1100 nm and 1600 nm have been developed in the recent years, such as the Cr:Forsterite laser (1150 – 1350 nm) or the Er:Fibre laser (1550 nm). On these pages we present some examples of coatings such as negative dispersion mirrors and mirror pairs. For GTI mirrors please see page 83.

Special features:

- Very high reflectivity of the mirrors (R > 99.8 % … R > 99.99 % depending on the design)
- Centre wavelength, bandwidth, GDD and TOD according to customer specification
- Spectral tolerance 1% of centre wavelength
- LIDT ~0.1 J/cm²
- In-house design calculation and measurement capabilities (GDD 250 nm – 1700 nm, R 210 nm – 1700 nm)

NEGATIVE DISPERSION LASER AND PUMP MIRRORS

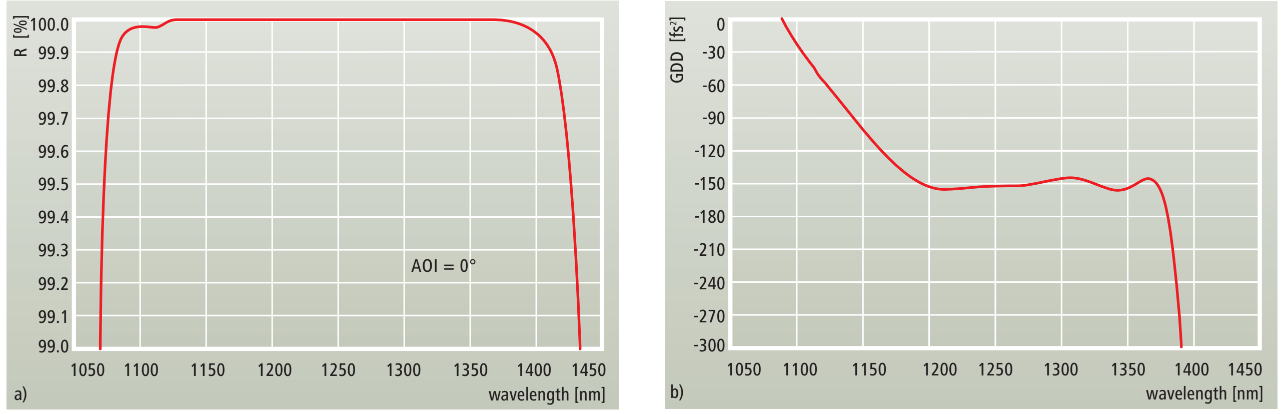


Figure 1: Reflectance (a) and GDD (b) spectrum of a negative dispersion laser mirror (GDD ~ −150 fs² for 1200 – 1370 nm)

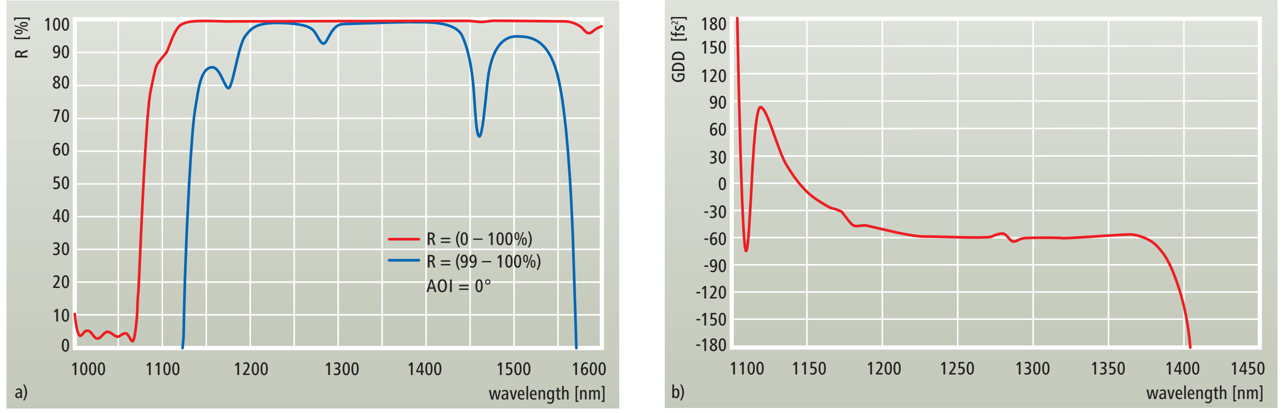


Figure 2: Reflectance (a) and GDD (b) spectrum of a negative dispersion pump mirror:
HR(0°, 1180 – 1380 nm) > 99.8% + R(0°, 1020 – 1070 nm) < 5%, GDD (1180 – 1380 nm) ~ −60 fs²

1100 – 1600 nm

BROADBAND NEGATIVE DISPERSION MIRROR PAIRS

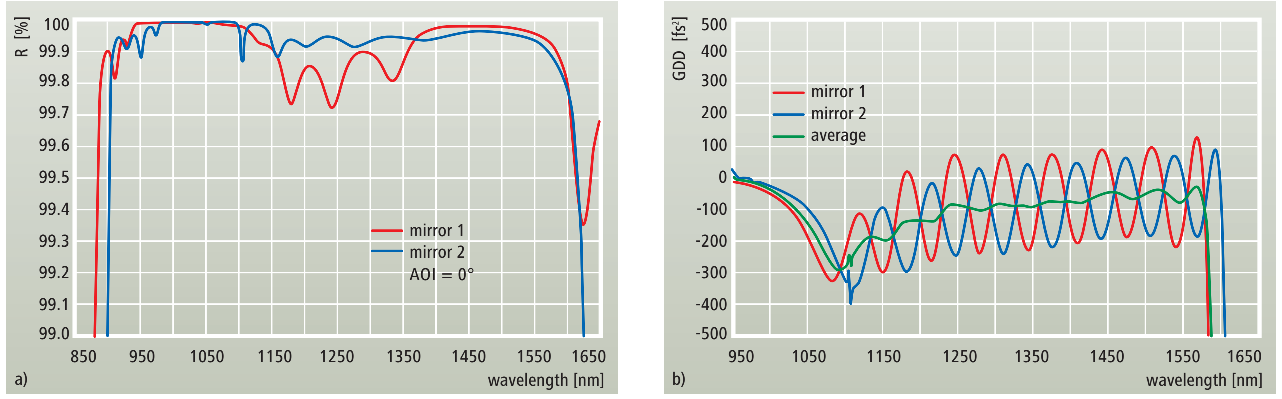


Figure 3: Reflectance (a) and GDD (b) spectra of a broadband negative dispersion mirror pair; single mirrors with R > 99.7 % (mirror 1) and R > 99.85 % (mirror 2)

Especially 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 transmission at the pump wavelength of the respective laser type) are also possible.

BROADBAND NEGATIVE DISPERSION TURNING MIRRORS

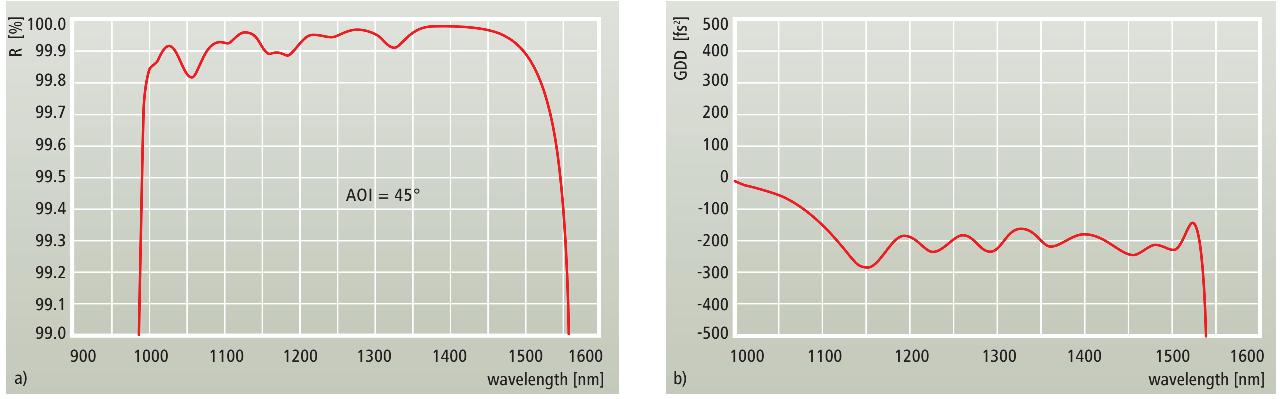


Figure 4: Reflectance (a) and GDD (b) spectrum of a broadband negative dispersion turning mirror for p-polarized light

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

SEPARATOR / COMBINER WITH NEGATIVE GDD

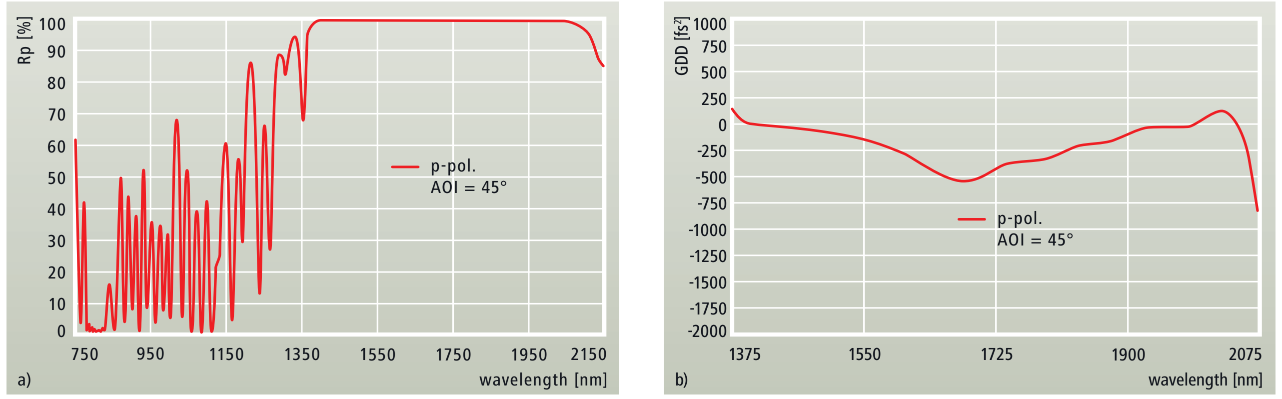
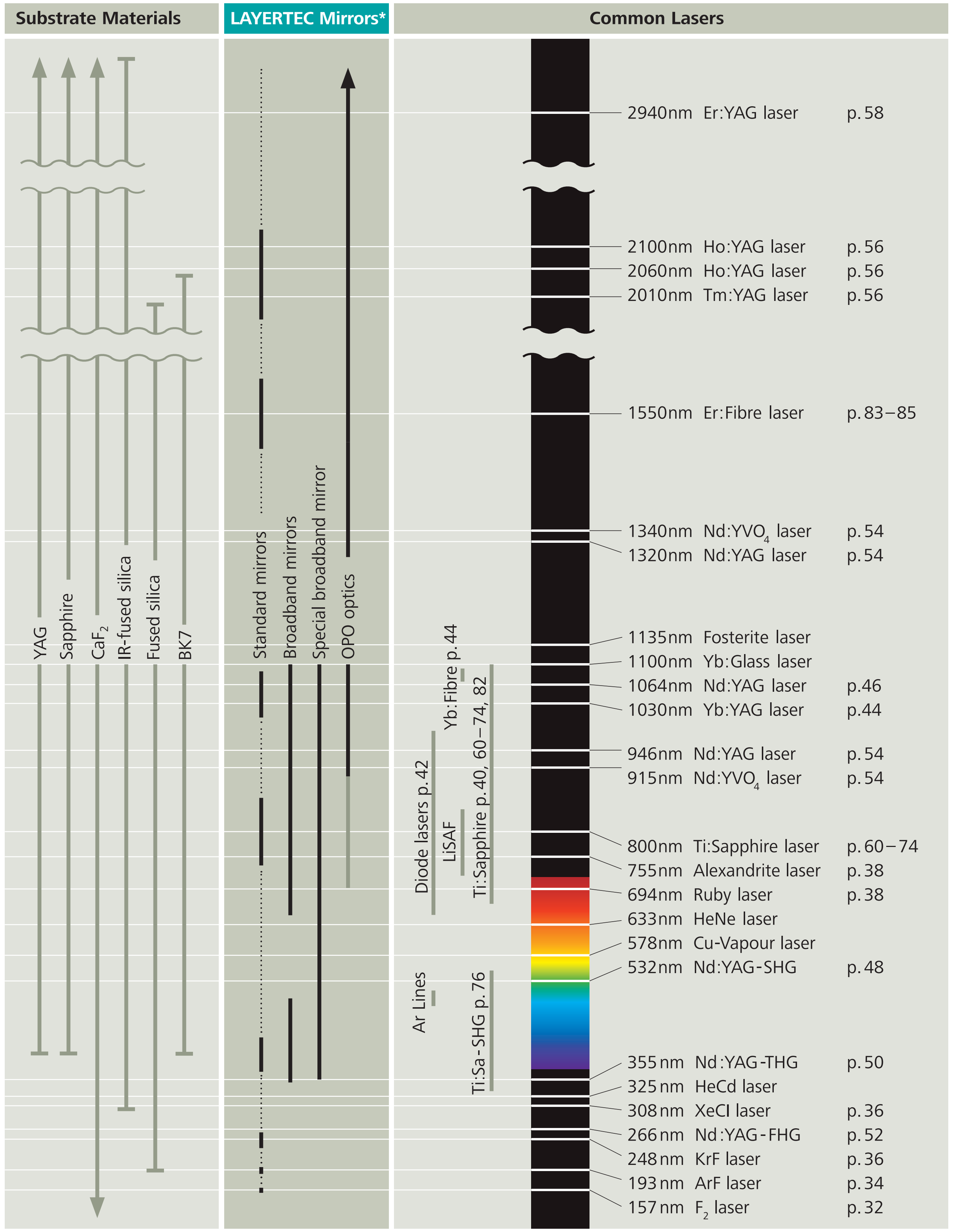


Figure 5: Reflectance (a) and GDD spectrum (b)

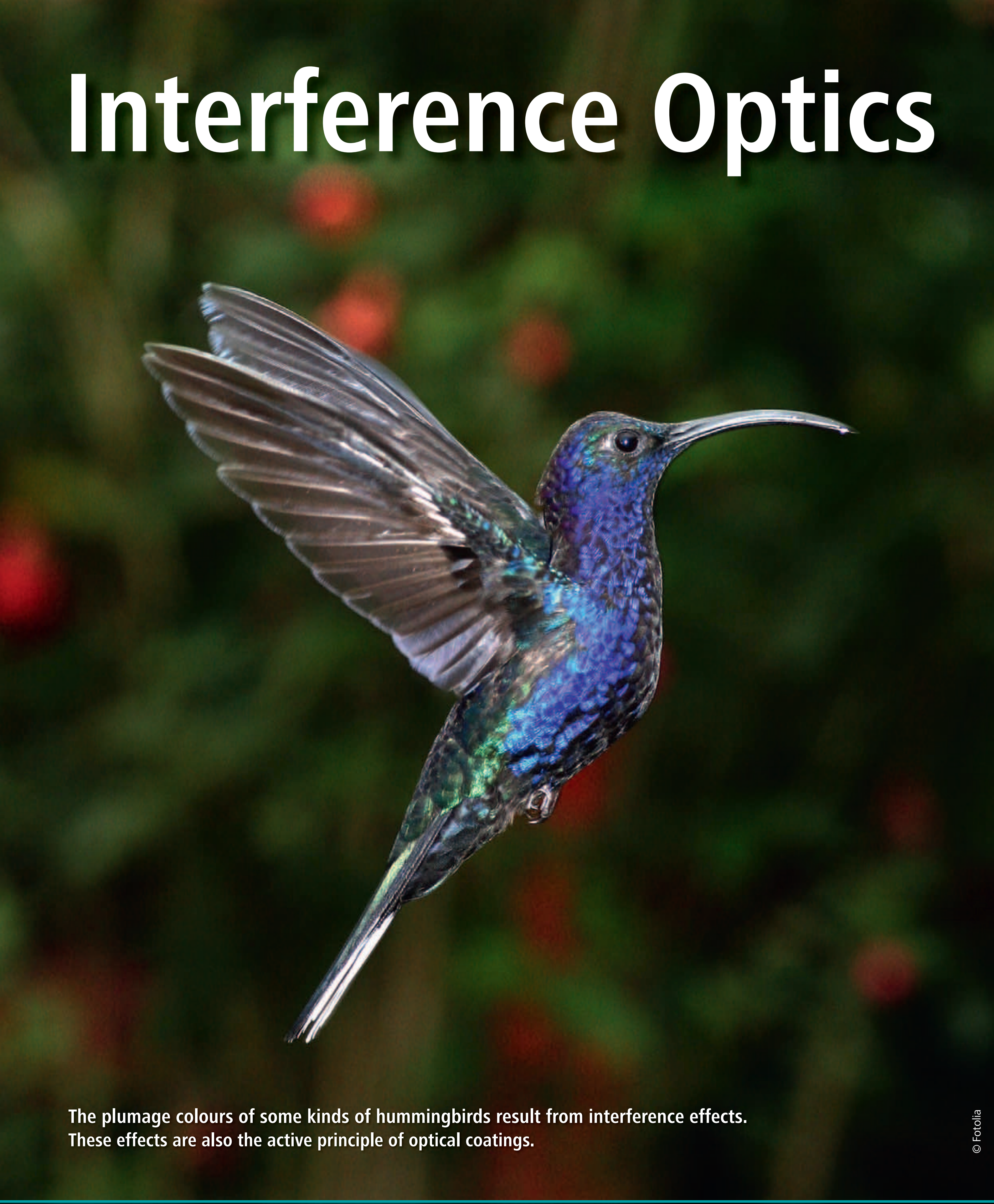
REGISTER

LAYERTEC MIRRORS



*Bandwidths of selected LAYERTEC mirrors

Interference Optics



The plumage colours of some kinds of hummingbirds result from interference effects.
These effects are also the active principle of optical coatings.

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