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

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

LAYE RTEC 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.
Please note that the GDD spectrum of a dielectric negative dispersion mirror 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 chosen types of negative dispersion mirrors exhibit oscillations. 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 already capabilities for design calculation and also for GDD-measurements in the wavelength range from 250 – 1700 nm.

**References:**
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.

All types of mirrors are also available with negative GDD (e.g. - 40 fs²). For high dispersion mirrors see page 76.

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

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

• 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, $45^\circ$) $\approx 0.6 \%$.

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

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

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

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

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

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
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 fs$^2$. 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.

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

**STANDARD FEMTOSECOND LASER OPTICS**

**NEGATIVE DISPERSION MIRRORS AOI = 0°**

**HIGH DISPERSION MIRRORS AOI = 0°**

**HIGH DISPERSION MIRROR PAIRS AOI = 0°**

**Figure 1:** Reflectance and GDD spectra of a standard negative dispersion mirror with GDD $\approx -40 \pm 10$ fs$^2$

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

**Figure 2:** Reflectance and GDD spectra of a high dispersion mirror with a bandwidth of 120 nm and a GDD of $-450 \pm 100$ fs$^2$ in the 800 nm range

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

**Figure 3:** Reflectance and GDD spectra of a high dispersion mirror pair with a bandwidth of 200 nm and an average GDD of $-120 \pm 40$ fs$^2$ per bounce in the 800 nm range

- a) Reflectance vs. wavelength
- b) Calculated GDD vs. wavelength
- c) Measured GDD vs. wavelength
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 fs³. Please note that without TOD optimization these oscillations are on the order of some thousands of fs³.

**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

**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

**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)
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 ±1 % of center wavelength.
- In-house design calculation and GDD measurement capabilities.
- GDD measurement reports are included in the delivery.

**MIRROR PAIRS FOR AOI = 0°**

![Figure 1](image1)

**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](image2)

**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](image3)

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

**LIDT - INFO**

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

Measurements were performed at Laser Zentrum Hannover
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 Rs to achieve “zero” GDD for Rs and Tp, 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 ~ 15 % for the p-polarized component. As an AR coating for the p-polarization LAYERTEC suggests the use of the design from fig. 3a.
200 – 300 nm BANDWIDTH

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 ± 1 % of center wavelength.
- In-house design calculation and measurement capabilities (GDD 250 – 1700 nm, reflectance measurement by CRD 220 – 1800 nm).

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

**Figure 4**: Reflectance and GDD spectra of a high dispersion mirror pair with a bandwidth of 250 nm and an average GDD of -180 fs$^2$ ± 40 fs$^2$ per bounce in the 800 nm range
a) Reflectance vs. wavelength
b) Calculated GDD vs. wavelength
c) Measured average GDD vs. wavelength

**Figure 5**: Reflectance, GDD and TOD spectra of a mirror pair optimized for broadband low third order dispersion
a) Reflectance vs. wavelength
b) GDD vs. wavelength
c) TOD vs. wavelength

**LIDT - INFO**
\[ \approx 0.1 \text{ J/cm}^2, \ 800 \text{ nm}, \ 150 \text{ fs} \]
Measurements were performed at Laser Zentrum Hannover
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 ± 1 % of center wavelength.
- In-house design calculation and GDD measurement capabilities.
- GDD measurement reports are included in the delivery.

NEGATIVE DISPERSION LASER MIRROR PAIRS FOR AOI = 0°

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

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

NEGATIVE DISPERSION PUMP MIRROR PAIRS FOR AOI = 0°

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

LIDT - INFO

≈ 0.1 J/cm², 800 nm, 150 fs,

Measurements were performed at Laser Zentrum Hannover
**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 Ø =12.7 mm, Ø = 25 mm and Ø = 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

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

* 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, λ = 800 nm
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°)
- 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°)
- 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°)
- 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 materials 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 fs².

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
   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
OVERVIEW ABOUT LASER INDUCED DAMAGE THRESHOLDS OF FEMTOSECOND LASER OPTICS

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

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.
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.

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

**Figure 1:** Reflectance and GDD spectra of a fs-optimized dual wavelength mirror for 400 nm + 800 nm at $\text{AOI} = 0^\circ$

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

**Figure 2:** Reflectance and GDD spectra of a fs-optimized dual wavelength turning mirror for 400 nm + 800 nm at $\text{AOI} = 45^\circ$

- a) Reflectance vs. wavelength
- b, c) GDD vs. wavelength
FEMTOSECOND LASER OPTICS
SELECTED SPECIAL COMPONENTS
METALLIC COATINGS FOR LASER AND ASTRONOMICAL APPLICATIONS

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

- 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.

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

- Bandwidth of the 800 nm reflectance band > 200 nm for p-polarization.
- All separators exhibit |GDD| < 20 fs² in the transmittance band.

- 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°

TRIPLE WAVELENGTH TURNING MIRRORS FOR AOI = 45°

BROADBAND LOW DISPERSION 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

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 $|\text{GDD}| < 50 \text{ fs}^2$ in all three wavelength regions of interest.

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
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.

NEGATIVE DISPERSION MIRROR PAIR FOR AOI = 0°

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

Figure 6: Reflectance and GDD spectra of a broadband negative dispersion mirror pair HR (0°, 275 – 400 nm) > 99 % with an average GDD of \( \approx -10 \text{ fs}^2 \) per bounce
a) Reflectance vs. wavelength
b) GDD vs. wavelength
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<sub>2</sub> 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.
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.

<table>
<thead>
<tr>
<th>Component</th>
<th>Wavelength range</th>
<th>P-polarization</th>
<th>S-polarization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turning mirror or separator 3rd harmonic</td>
<td>250 nm – 330 nm</td>
<td>30 nm (R &gt; 99 %)</td>
<td>50 nm (R &gt; 99 %)</td>
</tr>
<tr>
<td>Dual wavelength turning mirror</td>
<td>250 nm – 330 nm</td>
<td>15 nm (R &gt; 99 %)</td>
<td>26 nm (R &gt; 99 %)</td>
</tr>
<tr>
<td></td>
<td>370 nm – 500 nm</td>
<td>34 nm (R &gt; 99 %)</td>
<td>72 nm (R &gt; 99 %)</td>
</tr>
<tr>
<td>Turning mirror or separator 4th harmonic</td>
<td>180 nm – 250 nm</td>
<td>5 nm (R &gt; 93 %)</td>
<td>15 nm (R &gt; 97 %)</td>
</tr>
<tr>
<td>Turning mirror or separator 5th harmonic</td>
<td>140 nm – 180 nm</td>
<td>4 nm (R &gt; 90 %)</td>
<td>12 nm (R &gt; 97 %)</td>
</tr>
<tr>
<td>Turning mirror or separator 6th harmonic</td>
<td>125 nm – 140 nm</td>
<td>8 nm (R &gt; 85 % unpolarized)</td>
<td></td>
</tr>
</tbody>
</table>

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 ± 1 % of center wavelength.
- In-house design calculation and measurement capabilities (GDD 250 – 1700 nm, reflectance measurement by CRD 210 – 1800 nm).

LIDT - INFO
≈ 0.1 J / cm², 800 nm, 150 fs,
Measurements were performed at Laser Zentrum Hannover

<table>
<thead>
<tr>
<th>GDD [fs²]</th>
<th>Reflectance [%] measured by CRD</th>
</tr>
</thead>
<tbody>
<tr>
<td>-500</td>
<td>99.99</td>
</tr>
<tr>
<td>-1300</td>
<td>99.98</td>
</tr>
<tr>
<td>-2500</td>
<td>99.97</td>
</tr>
<tr>
<td>-5000</td>
<td>99.95</td>
</tr>
<tr>
<td>-10000</td>
<td>99.95</td>
</tr>
</tbody>
</table>
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.

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.
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**

≈ 0.1 J / cm² (estimated)

**GTI MIRRORS FOR AOI = 0°**

**Figure 1:** Reflectance and GDD spectra of a negative dispersion laser mirror (GDD = -150 fs² 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) ≈ - 60 fs²
- a) Reflectance vs. wavelength
- b) GDD vs. wavelength

**Figure 3:** Reflectance and GDD spectra of GTI mirrors for 1500 nm with different GDD values
- a) Reflectance vs. wavelength
- b) GDD vs. wavelength
BROADBAND NEGATIVE DISPERSION
MIRROR PAIRS FOR AOI = 0°

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.

1100 – 1600 nm

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.