High-dispersive mirrors for high power applications

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Abstract: We report on the development and manufacturing of two different types of high-dispersive mirrors (HDM). One of them provides a record value for the group delay dispersion (GDD) of $-4000\,\text{fs}^2$ and covers the wavelength range of 1027-1033 nm, whereas the other one provides $-3000\,\text{fs}^2$ over the wavelength range of 1020-1040 nm. Both of the fabricated mirrors exhibit a reflectance of >99.9% and are well suited for intracavity applications. Mirrors of the second type have been successfully employed in a Kerr-lens mode-locked Yb:YAG thin-disk oscillator for the generation of 200-fs pulses with multi-10-W average power.

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1. Introduction

In the last decades, ultrafast high-energy oscillators and amplifiers have become ubiquitous in research labs as well as in a number of industrial applications [1–3]. Recently, the pulse energy of femtosecond diode-pumped thin-disk oscillators has increased significantly to levels above 10 µJ at MHz-repetition rates and pulse durations have been reduced below 200
fs [4–7]. Such high energy lasers open new horizons in the femtosecond and attosecond science [8]. Dispersive mirrors (DM) [9–26] constitute key components of these systems, with their performance significantly affecting that of the laser.

Capitalizing on recent advances in dispersive multilayer mirror technology [9–26], here we report on a new generation of a low-loss and alignment-insensitive high-dispersive mirrors (HDM). In contrast to previously reported HDMs [21,22] used in Yb:YAG disk oscillators and Ti:Sapphire oscillators and amplifiers, the new HDM provides higher values of GDD in the wavelength range from 1020 to 1040 nm, permitting scaling of sub-picosecond Yb:YAG disk oscillators [6, 27–29] to higher pulse energies and average powers.

High-power oscillators are not the only application of HDMs that can benefit from optics with high dispersion, low losses and negligible thermal effects. Enhancement cavity technology [30] relies on such optics as well. Due to the high reflectivity of HDM (99.97%) one can use such mirrors in enhancement cavities requiring total losses to be suppressed to the level of 0.1-0.2% per roundtrip.

As a first application, we apply this novel HDM for power-scalable Kerr-lens mode-locking of an Yb:YAG thin-disk laser. We obtained 200-fs pulses at 17 W average power and 270-fs pulses at 45 W at 40 MHz repetition rate by using the prototypical HDM described in this paper for dispersion control inside of the cavity.

2. Design and production

The total group delay (GD) introduced in the HDM structure is a result of two combined effects: a penetration effect [9] and a resonance effect or the so called Gires-Tournois interferometer dispersive mirrors [13–15]. Our HDMs are designed to provide ~3000 fs^2 and ~4000 fs^2 of GDD in the wavelength ranges centered at 1030 nm. The delay related to penetration effect is ~30%. The resonance effect provides of ~70% of GDD. The combination of penetration and resonance effects allows to enhance the GDD by factor of ~2 without increasing the total physical thickness of the structure. Manufacturing HDMs is highly challenging due to the high sensitivity of the mirror’s performance to deviations in layer thicknesses from their design value. Such a sensitivity to deposition errors has so far been the limiting factor of their use in Yb:YAG disk oscillators. Despite these challenges, HDMs could be demonstrated to compensate a significant amount of GDD in systems operating at the micro joule level [22, 26]. In order to design HDMs, a novel robust synthesis technique [31,32] was applied. First we designed HDMs (called HDM1) with group delay dispersion (GDD) of ~4000 fs^2 in the wavelength region from 1025 nm to 1035 nm and theoretical reflectance of 99.97% (Fig. 1) for an 11 MHz Yb:YAG thin-disk oscillator. Commercially available OptiLayer software [33–35] has been used to design the HDMs. HDM1 permitted the stable operation of the laser up to intracavity pulse energies of 50-60 µJ and durations of ~1 ps at a repetition rate of 11 MHz [36]. The measured GDD of the HDM1 design is shown in Fig. 1 together with the theoretical GDD and the corridor of GDD errors. For the HDM1, the GDD measurements are in a good agreement with the theoretical GDD. Figure 1 reveals that the actual layer thickness accuracy during this deposition may be estimated as better than 0.5 nm, since most of the measured GDD data lie within the 68.3% corridor of errors. High thickness accuracy during deposition allowed us to fabricate HDM designs in a highly reproducible and reliable way. During the experiments with Yb:YAG oscillator, we found out that the emission bandwidth of Yb:YAG gain media may be truncated by the spectral bandwidth of HDM1. Another problem was connected with a high sensitivity of HDM1 to deposition errors that caused not unsatisfactory production yield of the HDM1 design. To overcome these issues, we had to improve the design of the mirror. To this end, we reduced slightly the nominal value of GDD in order to obtain more robust and broader design. The advanced HDM (named HDM2) works in the wavelength range of 1020–1040 nm, and has a nominal GDD of ~3000 fs^2 and average theoretical reflectance of 99.985% (in the absence of scattering losses), see Fig. 2.
Fig. 1. The theoretical reflectance (magenta) and GDD (blue) of HDM1. The measured point of reflectance (black cross) was obtained by using a loss-meter (Novawave) based on the ring-down technique. The measurement of GDD (red crosses) has been performed with a white light interferometer [38].

Fig. 2. The theoretical reflectance (magenta) and GDD (blue) of HDM2. The measured point of reflectance (black cross) was obtained by using loss-meter (Novawave) based on the ring-down technique. The measurement of GDD (red crosses) has been performed with a white light interferometer.

To proof manufacturability of designs we performed an error yield analysis. It allows us to estimate how many designs with random deviations from target layer thicknesses will still fulfill our requirements. The error yield analysis is a statistical procedure, therefore the yield estimations may change for different runs with the same parameters. In order to have more stable results, we performed 1000 tests (corresponding to 1000 independent coating runs). The results of error yield analysis of HDM1 and HDM2 are summarized in Table 1. For example, in case of 0.3% relative errors for HDM1 from 1000 virtual coating runs only 163 runs (corresponding to 16.3%) will fulfill requirements. In case of HDM2 - 237 coating runs (corresponding to 23.7%) will be successful. Similar behavior is observed for the absolute errors and larger relative errors (0.5%). Therefore HDM1 demonstrates smaller production yield for both absolute and relative errors. In order to experimentally demonstrate manufacturability of the HDM, we have produced designs discussed above. The HDMs consist of layers with thicknesses in the range from 15 nm to 800 nm. Time-controlled deposition is one of the most suitable layer thickness control techniques available for production of dispersive mirrors. In accordance with the error yield analysis, in order to realize designed HDMs, accuracy of the layer thicknesses better than 0.5 nm is required. The desired precision can be reached with a state-of-the-art magnetron sputtering machine (Helios, Leybold Optics GmbH, Alzenau, Germany), which is currently one of the most precise plants available for production of dispersive optics [20–26, 32].
Table 1. The Theoretically Calculated Error Yield Analysis of HDM1 and HDM2

| The level of errors | Relative errors | Absolute errors | Requirements | Bandwidth |
|---------------------|-----------------|-----------------|--------------|-----------|
|                     | 0.3%            | 0.5%            | 0.3nm        | 0.5nm     |
| HDM1                | 16.3%           | 5.7%            | 44.5%        | 21.6%     | R>99.95%, GDD=4000fs² (±300fs²) | 1027–1033 nm |
| HDM2                | 23.7%           | 10.9%           | 98.6%        | 89.9%     | R>99.95%, GDD=3000fs² (±300fs²) | 1025–1035 nm |

The GDD values measured with white-light interferometer [38] are indicated by red crosses in Figs. 1-2. The measured values for HDM2 lie much closer to the calculated curve (see Fig. 2) in comparison to HDM1 (see Fig. 1). The difference between theoretical and measured GDD can be explained by higher sensitivity of the HDM1 design to errors in layer thicknesses and has been predicted by the error yield analysis. Both measurements are in a good agreement with the conclusion obtained from the error yield analysis.

3. Pulse analysis, applications, and perspectives

Modern high-energy thin-disk femtosecond oscillators mostly utilize two main perspective gain medias Yb:YAG and Yb:Lu₂O₃. The latter has an emission bandwidth of approximately 12 nm FWHM centered at 1034 nm. For oscillators operated at a negative cavity GDD, the maximum pulse energy that is achievable in the regime of stable operation is predicted to be given by [39]: $E \sim \beta A_{\text{eff}} / \gamma$, where $\beta$ is the net GDD, $A_{\text{eff}}$ is the average mode area, $E$ is the energy of pulse and $\gamma$ is the net self-phase modulation coefficient. According to this formula the achievable pulse energy increases linearly with the magnitude of negative group-delay dispersion. To test the utility of the design, we simulated the propagation of a chirp-free Gaussian pulse of 200-fs pulse duration with spectrum as the one shown in Fig. 3 (upper inset) through a hypothetical delay line consisting of the designed mirrors with the target GDD removed.

![Fig. 3. Pulse transmission analysis of HDM2. Intensity profiles of a bandwidth-limited Gaussian pulse (blue lines) and its replica, propagated through a hypothetical delay line made up of 10 bounces off the designed HDM2 with their nominal GDD and TOD removed (red lines) on a linear scale. Inset (below) the same intensity profile on a logarithmic scale. The amplitude of the pulse transmitted through the delay line is not normalized but can be directly compared to that of the input pulse, the temporal shift is artificial for better visibility. The theoretical spectrum is shown on the upper inset.](image)

We summed up two spectral dispersion curves: one which represents the material that must be compensated for (+3000 fs²), and another one with an opposite sign, which represents the designed dispersion of the mirror. This procedure takes into account all higher order dispersions, which are unavoidable for the DM. The GDD fluctuations accumulated over 10
bounces, affect negligibly the contrast of the pulse (see pulse in logarithmic scale, on Fig. 3), leaving its shape and duration almost unchanged. The main practical limitations for scaling of output power appeared to be the thermal effect and damage threshold of intracavity elements, including HDM. We have compared temperature changes on the surface of available mirrors at 47 W in a continuous wave operation of the laser. The output coupler has reflectivity of 94.5%, thus the intracavity power is by factor of 18 larger than the output power of the oscillator. We have measured temperature of mirrors around beam spot with thermal camera. Both HDM1 and HDM2 demonstrate relatively low temperature: maxima 311 K and 314 K, respectively. In case we switch power off, the temperature is drop to 298 K for whole surface of the mirror. The high-reflectance mirror (quarter-wave stack) made from the same alternating materials as HDM has maximum temperature of 312 K. The temperatures of all available mirrors have changed in the range from 311 K to 350 K.

HDM2 mirrors were successfully implemented in Kerr-lens mode-locked Yb:YAG thin-disk oscillator [7]. It delivers 270-fs 1.1-µJ pulses at an average power of 45 W and a repetition rate of 40 MHz with an optical-to-optical efficiency of 25% (see Fig. 4).

![Fig. 4. Autocorrelation measurement and spectrum at 45W output power and 14% output coupler transmission. Time-bandwidth product is 0.36 (ideal 0.315).](image)

4. Conclusions and discussion

For the first time, we demonstrate HDMs with GDDs as high as −3000 fs$^2$ and −4000 fs$^2$ at a central wavelength of 1030 nm ±5nm. The measured reflectance are >99.91% and >99.97% for HDM1 and HDM2, respectively. The novel robust synthesis technique was applied to the design of a high-dispersive mirror. The HDM2 were successfully implemented in an Yb:YAG disk oscillator with 270-fs pulses at an average power of 45 W and a repetition rate of 40 MHz. Beyond high-power oscillators the unique combination of high dispersion, low losses and negligible thermal effects are also expected to benefit enhancement cavity technology as well.

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