Double Gires–Tournois interferometer negative-dispersion mirrors for use in tunable mode-locked lasers

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We report the implementation and operation of novel superhigh-reflectivity negative-dispersion dielectric mirrors for use in tunable ultrafast laser systems. The mirror structure is divided into two distinct regions: an underlying superhigh-reflectivity dielectric quarter-wavelength stack and an overlying negative-dispersion section consisting of only a few layers and forming simple multiple Gires–Tournois interferometers. The example that we present was designed for operation from 800 to 900 nm and has a near-constant group-delay dispersion of -40 fs^2 and a peak reflectivity greater than 99.99%. We show a comparison of the predicted and the measured mirror performance and application of these mirrors in a mode-locked Ti:sapphire laser tunable from 805 to 915 nm.

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Recent development of dielectric mirrors with broad bandwidths and specifically designed dispersion signatures has resulted in technological advances in ultrafast lasers.[1,2] These optics are commonly referred to as chirped mirrors and, either alone or in conjunction with prisms, are used to control laser-resonator dispersion and achieve sub-10-fs pulses[3,4] and broad tunability.[5] Typically such structures consist of more than 40 dielectric layers for which accurate dispersion control, then, relies on extensive optimization of the design of each layer thickness and on production to subpercent accuracy. For commercial ultrafast lasers we believe that it is important instead to implement negative-dispersion mirror (NDM) designs, which are easily reproducible and error tolerant. The simplest of these is the Gires–Tournois interferometer (GTI) mirror.[6] In these structures negative group-delay dispersion (GDD) is obtained by resonant trapping of select wavelengths in a spacer layer between the upper-surface reflection and the underlying high reflector (HR). The near-zero dispersion of the HR stack is not sensitive to layer-thickness process errors, so only the final layer thickness is critical. Using GTI mirrors, we developed a compact 80-MHz repetition-rate, prismless ultrafast oscillator, the Vitesse, by using multiple reflections from NDM's to simultaneously fold the laser resonator to small dimensions while giving incremental dispersion compensation at each reflection.[7] For such configurations, where the laser output coupling is of the order of 10% and there are more than 30 intracavity reflections per round trip, it is important to keep the loss per reflection to less than 0.03%. Such super-HR's ($R > 99.97\%$) can be achieved by use of very low-scattering mirrors deposited by means of ion-beam sputtering onto superpolished substrates, with <0.5-nm rms roughness.[8,9] However, GTI mirrors give a negative GDD that is appropriate for mode locking a laser over only a relatively narrow wavelength range. In this Letter we introduce a novel design for the fabrication of NDM's that meet the design requirements of super-HR with largely constant negative GDD over more than 100 nm.

To our knowledge this is the first implementation of a NDM design that incorporates the simplicity and intrinsically high reflectivity of GTI mirrors, while approaching the broadband negative GDD performance of chirped mirrors. The underlying high reflector is largely untouched, but the single GTI layer is extended to include a larger number of top layers and create multiple, double, or triple GTI structures that have more-constant negative dispersion. A typical structure optimized for a -40-fs^2 GDD for wavelengths from 800 to 900 nm is shown in Fig. 1. This dual Gires–Tournois interferometer (D-GTI) NDM design was obtained by use of a starting condition of a sequence of 40 quarter-wave optical thickness (QWOT) layers, for which layers 3 and 7 were initially chosen to have a half-wave optical thickness. Section 1, the underlying HR structure, was left untouched, and the ideal thickness of each of the seven top layers in Section 2, the D-GTI structure, was obtained by a numerical optimization that targeted just the desired

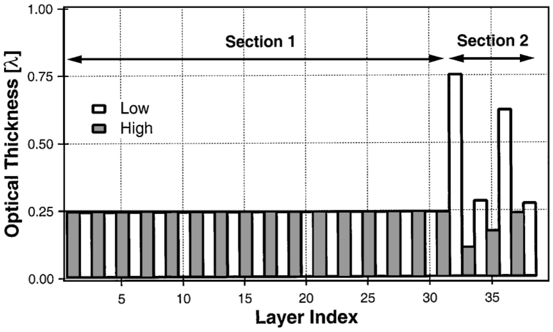

Fig. 1. Optical thickness at 820 nm as a function of layer index for a -40-fs^2 D-GTI NDM. There are alternating layers of high–low refractive index: Section 1, standard QWOT high-reflector structure; Section 2, D-GTI dispersion-control layers.

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GDD. This preserves the super-HR and no optimization of reflectivity is required.

Figure 2 shows the calculated reflectivity (R) and the GDD versus wavelength of the D-GTI NDM design in Fig. 1 and a high-reflector–pump-laser transmission optic (HR/HT) quarter-wave stack. The HR/HT is the other common coating used in a mode-locked laser, a simple quarter-wave stack with the last layer optimized for high transmission of an appropriate pump wavelength. Although the HR/HT quarter-wave stack shows a near-zero dispersion, the D-GTI NDM is very close to $-40\ \mathrm{fs}^2$ from 800 to 900 nm. To demonstrate the robustness of the design we performed a number of coating simulations, assuming a 0.5% random thickness variation for each layer. The predicted fabrication variation is less than $\pm 5\ \mathrm{fs}^2$ for wavelengths from 740 to 890 nm and less than $\pm 10\ \mathrm{fs}^2$ from 890 to 920 nm. Often the NDM bandwidth can be expanded further at the expense of the mirror fabrication tolerance. For example, it is possible to extend the operational bandwidth of the design in Fig. 1 by as much as 10 nm at the expense of significantly higher sensitivity to the (top seven) D-GTI layer thicknesses. The bandwidth and reflectivity performance of the structure as a whole is set primarily by the refractive-index ratio of the high–low-refractive-index pairs used in the QWOT structure. For a given material set there is a design trade-off between the desired operating bandwidth and the value of negative GDD that is required.

To demonstrate laser operation of this NDM design we fabricated the structure shown in Fig. 1. In the coating, we opted for a two-step process. The initial coating sequence yielded Section 1 plus an eighth-wave layer for efficient super-HR and pump-laser transmission structures. Some substrates were removed for use as simple HR/HT elements, and we followed this with deposition of the remainder of the structure to form the complete NDM devices shown in Fig. 1. All layers were deposited by use of only standard industry process-control capabilities. The authors of Ref. 10 independently arrived at a similar theoretical design in which three distinct GTI sections were placed on top of a QWOT-like stack for dispersion control. In their design the authors chose to perform additional optimization of the QWOT stack and consequently were not able to take advantage of the two-step coating process for the fabrication of HR/HT and NDM optics.

Measurements of the D-GTI NDM GDD were performed by use of white-light interferometry.[11] In this technique the test mirrors are placed in one arm of a Michelson interferometer, and an interferogram is recorded while the length of one of the arms is varied. A He–Ne laser traverses the same interferometer and is used to record and monitor the actual path-length difference. Applying a Fourier transform to the recorded interferogram yields the spectral phase as a function of frequency. Two identical NDM's are placed in the sample arm of the interferometer, for a total of four reflections, and the measured data are compared with the predicted performance. We obtained the measured GDD shown in Fig. 2 by averaging 100 data sets, followed by a twofold numerical differentiation to obtain the GDD values and by a twentyfold binomial smoothing of the final result. The standard deviation of the measured GDD is less than $\pm 5\ \mathrm{fs}^2$, and the calculated and the measured GDD are in good agreement. The reflectivity of the D-GTI NDM was measured at 820 nm by Rigrod intracavity laser loss analysis[12] as $R > 99.998\%\ (+0.002\%/-0.004\%)$, in agreement with the expected super-HR.

The NDM's were evaluated in a Kerr-lens mode-locked tunable mode-locked Ti:sapphire laser. The pump laser was a Coherent Verdi 532-nm source set to a fixed output power of 3.85 W. The Ti:sapphire laser resonator had an 80-MHz symmetric z configuration, with a 5-mm gain crystal, and a 2-mm-thick birefringent filter could be rotated for wavelength selection (Fig. 3). Four plano NDM mirrors with 4 reflections per optic were used for dispersion compensation and folding of the resonator to obtain 32 NDM reflections per round trip. In addition, the end mirror and one curved mirror were chosen to be NDM's for additional dispersion compensation. The Kerr-lens mode locking was assisted by an intracavity slit and initiated by a rapid mechanical scan of the end high reflector. After optimization of the laser, mode-locked operation and continuous tuning were achieved from 805 to 915 nm by rotation of the birefringent filter with no additional

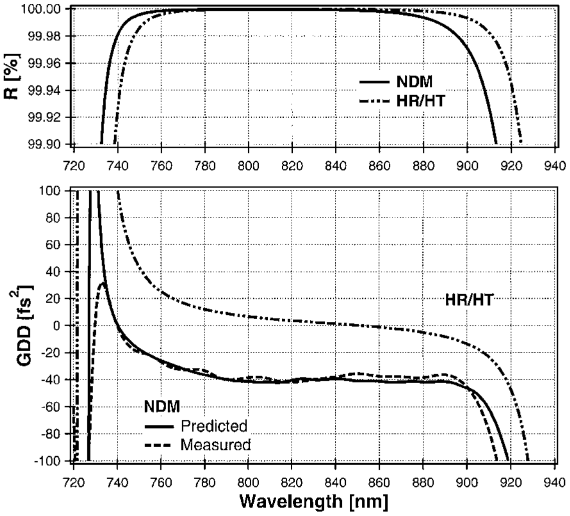

Fig. 2. Calculated reflectivity R and GDD versus wavelength of the HR/HT and the D-GTI NDM's.

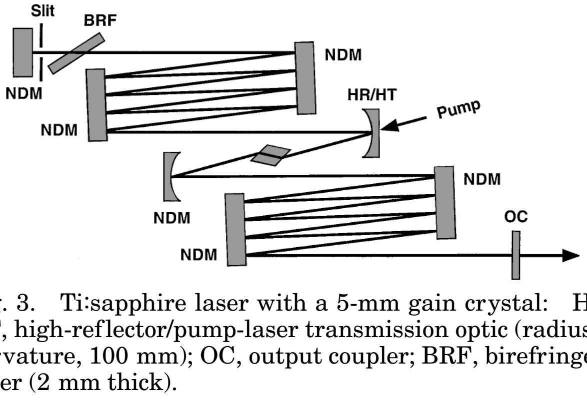

Fig. 3. Ti:sapphire laser with a 5-mm gain crystal: HR/HT, high-reflector/pump-laser transmission optic (radius of curvature, 100 mm); OC, output coupler; BRF, birefringent filter (2 mm thick).

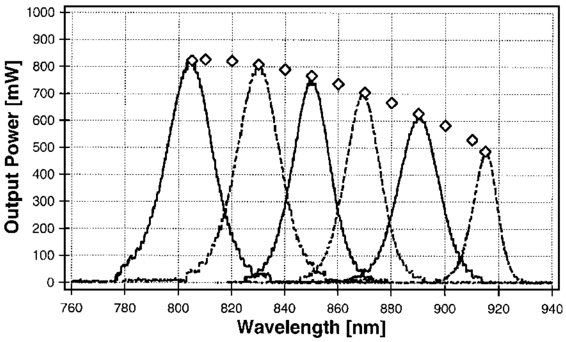

Fig. 4. Select mode-locked laser spectra for the laser shown in Fig. 3. Continuous wavelength tuning from 805 to 915 nm was obtained by rotation of the birefringent filter.

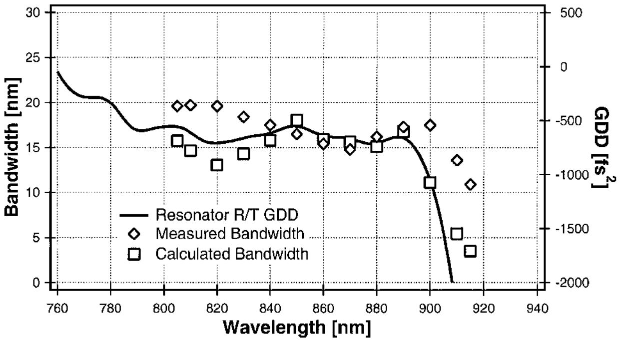

Fig. 5. Calculated resonator round-trip (R/T) GDD with measured and calculated laser bandwidth as a function of wavelength.

resonator adjustment. This tuning range was chosen because it is of particular interest in green fluorescent protein multiple-photon microscopy, in which one can use this range for differential imaging with a single compact laser to obtain access to both the wtGFP (760–820 nm) and the eGFP (910–970-nm) bands.

Select representative spectra in the tuning band scaled to the appropriate laser output power are shown in Fig. 4. The bandwidth is fairly constant, 17.0 ± 2.5 nm for operation from 805 to 900 nm, and undergoes a bandwidth reduction at longer wavelengths, consistent with the change in resonator dispersion. We calculate the resonator GDD by summing the NDM, HR/HT, and material dispersion and use this GDD with the intracavity laser energy to calculate the pulse width, using

$$\tau = 3.53|D|/\phi W,$$

where D is the round-trip cavity GDD in femtoseconds squared, W is the pulse energy, and ϕ is $10^{-6}\ \mathrm{W}^{-1}$.[13] We obtain the bandwidth from the pulse length τ by assuming transform-limited sech^2 pulses in the Kerr-lens mode-locked process. Given the experimental uncertainty in the exact cavity GDD total, the calculated bandwidth is in reasonable agreement with the measurement. Typical pulse durations directly from the laser were measured to be ~70 fs. The tuning range was limited in part by the transmission of the output coupler and could be extended by another 10 nm by a change in the intracavity power. Ultimately, however, the tuning range is limited by the shape of the overall resonator dispersion shown in Fig. 5.

In conclusion, we have demonstrated a novel design for the fabrication of negative GDD super-HR's for use in tunable mode-locked lasers. The structure is based on a resonant multiple-GTI structure that is a few layers thick and introduces a largely constant negative GDD to a standard super-HR structure. These NDM's are suitable for fabrication in commercial deposition chambers and standard industry process control. Good agreement between the theoretically predicted and the measured values of GDD was demonstrated, and dispersion-compensating NDM performance in an ultrafast laser system was demonstrated.

To date, several different structures have been designed to cover various portions of the Ti:sapphire tuning range. Structures that have a slightly positive GDD slope to better match the negative GDD slope contribution from transmissive intracavity optical components are possible. Structures with more than two GTI structures have also been explored, as they can provide somewhat larger negative GDD performance at similar bandwidths. However, our simulations have indicated that these structures are more susceptible to fabrication errors. In general, D-GTI structures can be fabricated for operation at other wavelengths that are suitable for use with dielectric mirror technologies.

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