Newly designed multilayer thin film mirror for dispersion compensation in Ti:sapphire femtosecond lasers

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There are two different effects to generate group delay dispersion by multilayer thin film mirrors: chirper effect and Gires-Tournois effect. Both effects are employed to introduce desired dispersion in the designed mirror. Thus the designed mirror provides large dispersion throughout broad waveband. Such mirror can be used for dispersion compensation in Ti:sapphire femtosecond lasers. Most group delay dispersion of a 5-mm Ti:sapphire crystal can be compensated perfectly with only four bounces of the designed mirror.

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Nowadays, the performance of the ultrashort pulse laser systems is determined by the efficient control of dispersion[1,2]. The shortest pulses achieved directly from laser oscillators are limited by the bandwidth over which adequate control of the frequency-dependent group delay dispersion (GDD) can be accomplished[3,4]. The difficulty in meeting the requirements for shorter and shorter pulses lies in the fact that precise control of the group delay over broad waveband is required.

Multilayer thin film mirrors[5−10] are employed to compensate the dispersion of materials used in femtosecond (fs) lasers for generating gain such as Ti:sapphire, Cr:LiSAF and Cr:LiCAF, which enables the intracavity dispersion being controlled. They can exhibit high reflectivity over a large bandwidth and precise control of the frequency-dependent group delay within the tuning range, allowing the fs mode-locked operation. In addition, they can be designed to be transparent at the pump wavelength(s) to replace standard dichroic mirror coatings in these fs laser cavities. Multilayer thin film mirrors have played and will continue to play an important role in ultrashort pulse laser systems.

Gires-Tournois interferometer (GTI) is the simplest structure possible to achieve desired dispersion. It consists of one partial reflector, a cavity, and a 100% reflector. Such interferometers have to be obtained by thin-film techniques[11], so they are usually known as Gires-Tournois (G-T) mirrors. G-T mirrors can supply large dispersion, but they are not able to maintain linearity of group delay throughout the broad reflection band. Another thin film realization is chirped mirror. Chirped mirrors can exhibit a broad high-reflectance range, but cannot introduce comparable levels of GDD.

In this paper, newly designed thin film mirror has been reported. They can provide large dispersion throughout the whole reflectivity range.

It is well known that achievable thin film design obtained by computer optimization is strongly depend on the predesign structure. With proper predesign structures, converge to designs with desired performance can be obtained after limited iterations while with improper predesign structures, it is difficult to find a useful design. In this paper, the predesign employed both two G-T cavities and chirped layer thickness. As shown in Fig. 1, a chirped mirror design with simple linear chirp may exhibit strong oscillations, which is just because longer wavelengths have to pass the front section of the mirror and then slight reflections in the front section interfere with the strong reflection from the back[6]. To reduce such undesired oscillations, several methods[6,7,12,13] have proposed for the calculation of starting structures. In this paper, the chirped layer thickness relies on the superimposing a quasi-periodic modulation on a linear variation of the optical thickness of the layers. The chirped layer thickness is given by

$$t(x) = t_0(x) + A(x)\sin\left[2\pi\frac{x}{\Lambda(x)}\right],$$

where

$$t_0(x) = \frac{1}{4}\left(\frac{\lambda_{\min} - \lambda_{\max}}{d}x + \lambda_{\max}\right),$$

$$\Lambda(x) = 5t_0(x),$$

$$A(x) = \frac{50}{d}x + 12.5, \tag{1}$$

$\lambda_{\max}$ and $\lambda_{\min}$ are the maximum and minimum wavelengths of the mirror, respectively, x means the distance

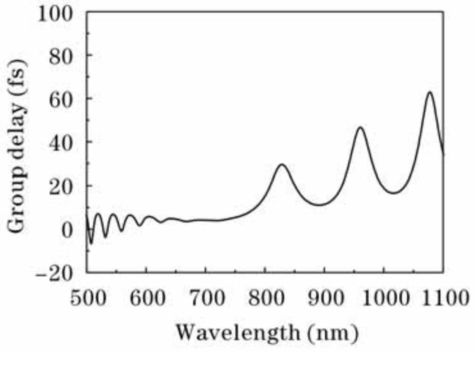

Fig. 1. Group delay of chirped mirror.

of the respective layer from the substrate, d is the total layer thickness of the coating and fulfills $d \geq \pi c^2 \left|\text{GDD}\right| (1/\lambda_{\min} - 1/\lambda_{\max})$.

The computer optimization is processed by TFCalc software[14] with above predesign structure. The design targets are given by continuous high reflectivity ($R > 99.5\%$) from 750 to 850 nm, continuous high transmittance ($T = 95\%$) from 510 to 550 nm, large GDD of -58 fs^2 at central wavelength of 800 nm and TOD of -39 fs^3 from 750 to 850 nm, which correspond to the dispersion compensation of a fs laser with a 5-mm Ti:sapphire crystal.

Figure 2 shows the optimized structure. It is composed of 40 alternating high and low refractive index layers, in which high and low refractive index materials are Ta_2O_5 and SiO_2, respectively. The refractive indices of Ta_2O_5 and SiO_2 are 2.098 and 1.480 at 800 nm, respectively. The substrate is BK7 glass.

Figure 3 gives the calculated reflectivity of the structure shown in Fig. 2. Continuous high reflectivity is obtained from 750 to 850 nm. Compared with previous design[15,16], this design also exhibits near-constant low reflectivity from 510 to 550 nm, which is easy to enable the transparency at the pump wavelength of 532 nm.

Figure 4 gives the calculated GDD of the structure shown in Fig. 2. It is seen that the designed mirror can exhibit a near-constant GDD of -58 fs^2 from 750 to 850 nm. Furthermore, the slope coefficient of GDD versus wavelength is positive; hence the third-order dispersion (TOD) is negative, which can partially compensate the negative TOD of Ti:sapphire crystal.

As above mentioned, there are two alternative effects to obtain dispersion in a multilayer structure: the chirped effect and the G-T effect. The maximum achievable negative GDD of chirped mirror is limited by the maximum group delay difference that can be obtained between the extremes of the reflectivity range. If the designed mirror is chirped mirror, the maximum achievable group delay difference can be calculated[5,6] to be 14.05 fs. However, as shown in Fig. 5, the maximum difference is 17.2 fs, which is larger than the maximum difference obtained only by chirped effect. So the designed mirror is thought to employ another effect. Figure 6 shows the optical field inside our designed mirror at the three wavelengths of the reflection band. It is testified that the designed mirror has employed both of the above effects. First of all, as in chirped mirrors, the longer wavelength light (850 nm) penetrates deeper into the designed multilayer structure, which results in the various optical delays of various wavelengths. Secondly, the 800- and 850-nm lights undergo some resonance, as shown in Figs. 6 and 7, which indicate that the designed mirror also employs G-T effect.

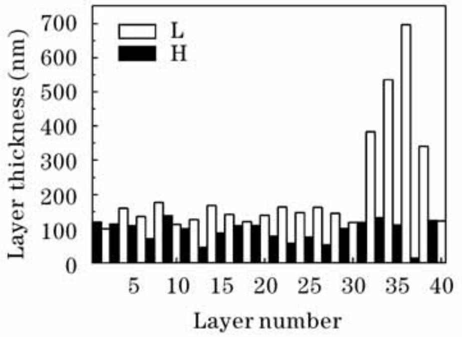

Fig. 2. Physical thickness of the designed mirror.

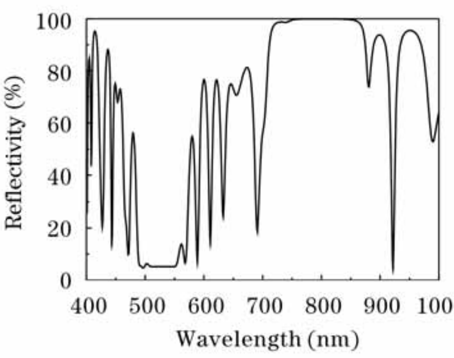

Fig. 3. The reflectivity of the designed mirror.

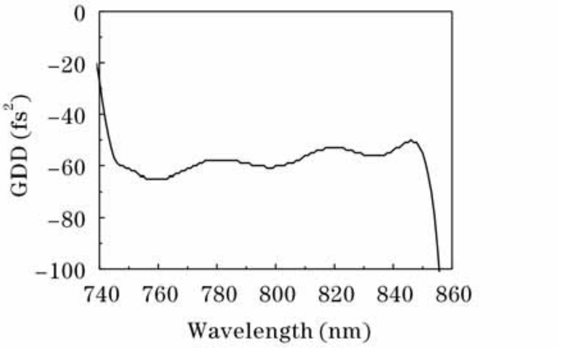

Fig. 4. GDD of the designed mirror.

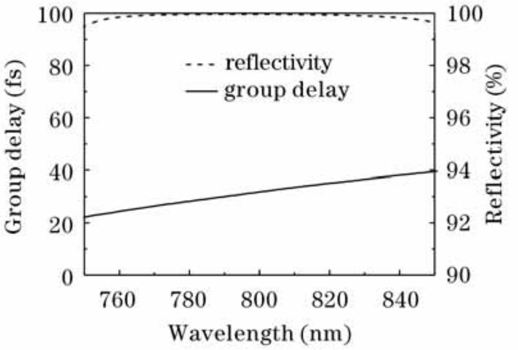

Fig. 5. Group delay of the designed mirror.

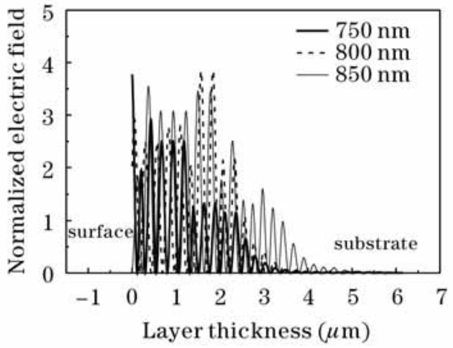

Fig. 6. Magnitude of the optical electric field inside the structure at different wavelengths.

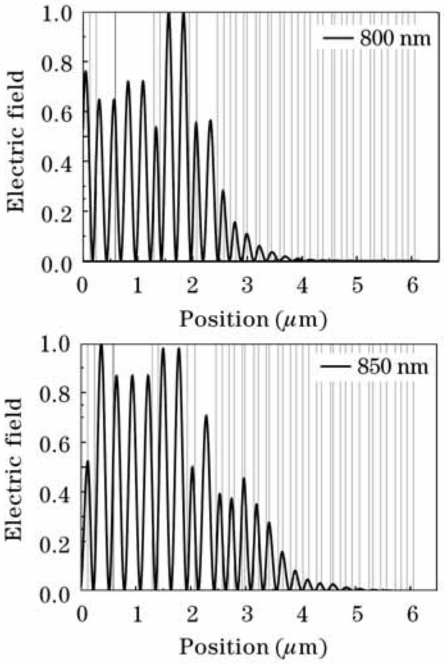

Fig. 7. Magnitude of the optical electric field inside the structure at 800 and 850 nm.

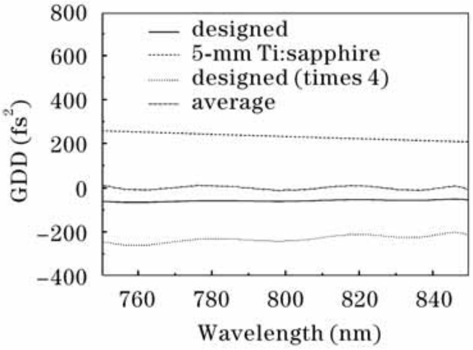

Fig. 8. GDD compensation of 5-nm Ti:sapphire.

As shown in Fig. 7, the electric field is mostly localized in the cavities, whereas it has relatively low intensities in the impedance matching layers between them. That is to say, the electric field is captured by G-T cavities. Just because of the combination of the two effects, the designed mirror can provide comparable level of GDD throughout the whole high reflectivity waveband, as shown in the Fig. 4.

Figure 8 shows the group delay dispersion compensation of a 5-mm Ti:sapphire crystal. In this paper, only GDD of a 5-mm Ti:sapphire crystal (dashed line) is considered in the laser. Obviously, the average GDD (dashed-dotted line) of a 5-mm Ti:sapphire and that of four bounces off our designed mirror is very close to zero, which oscillates between −12.7 and 13.7 fs^2 throughout the reflectivity band. In another words, the positive GDD of 5-mm Ti:sapphire crystal can be compensated perfectly with only four bounces off the designed mirror. So with the designed mirror, this fs laser with 5-mm Ti:sapphire crystal can obtain good dispersion compensation.

In conclusion, newly designed thin film mirror that employed both chirped effect and G-T effect to introduce dispersion was obtained by computer optimization with proper predesign structure. The calculated performance was fairly good. Therefore, they could be used to compensate the dispersion of Ti:sapphire fs lasers.

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