Laser-induced damage of high reflectors for Ti:sapphire laser system

Jianke Yao (姚建可), Weiqiang Zeng (曾维强), Zhengxiu Fan (范正修), Hongbo He (贺洪波), and Jianda Shao (邵建达)

R&D Center for Optical Thin Film Coatings,
Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800

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A broadband (~ 176 nm, $R > 98\%$, $\lambda_0 = 800$ nm) and high laser-induced damage threshold (LIDT = 2.4 J/cm^2) $TiO_2/HfO_2/SiO_2$ high reflector (HR) for Ti:sapphire chirped-pulse amplification (CPA) laser system is fabricated by the electron beam evaporation. The refractive index and extinction coefficient of TiO_2 and HfO_2 films are calculated from single-layer films' transmittance spectra. The properties of HR are mainly determined by the high refractive index material. The high refractive index leads to wide bandwidth. A low extinction coefficient indicates low absorption and high LIDT. The possible damage mechanism of HR is discussed.

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In the first half of 2006, a 120-TW, 36-fs laser system based on Ti:sapphire chirped-pulse amplification (CPA) was successfully established in China[1]. To achieve terawatt pulse width in the range of 15 − 20 fs, a broadband mirror with the working spectral bandwidth of $\Delta\lambda = 150 - 200$ nm at center wavelength λ_0 of 800 nm is required, because one of the limiting factors of the pulse width is the bandwidth of mirror in an amplifier chain[2]. Optical damage owing to the compressed pulses is a major concern in high-peak-power systems of this type[3]. Further increases in peak power available from such systems are now limited by damage to optical surfaces due to the intense short pulses. The laser induced damage issue in CPA laser system should take into account an important pulse duration occurring in 800-nm signal pulses with the duration of a few hundreds of picoseconds after the stretcher during the amplification. In this time domain, a laser-induced damage threshold (LIDT) higher than 1 J/cm^2[2] should be maintained.

The coating parameter that most strongly influences LIDT is the choice of materials used to produce a component. TiO_2 is a coating material with highly desired properties. It is hard and chemically resistant. It is transparent in the visible and near infrared (NIR) range, and it has a high refractive index which is useful for multilayer dielectric mirror[4]. HfO_2 is also one of the most commonly used high-index materials to realize laser damage resistance for its relatively high LIDT and good thermal and mechanical stability[5].

In this paper, a broadband high LIDT mirror is deposited by electron beam evaporation, using TiO_2 and HfO_2 as high refractive materials and SiO_2 as low refractive material. The optical properties and LIDT of this mirror are measured. Moreover, the possible laser damage mechanism of the mirror is discussed.

In experiment, the single-layer films' optical thickness is $4\lambda_1$, where λ_1 is 500 nm. The structure of TiO_2/SiO_2 high reflector (HR) is $(HL)^{13}H$, for HfO_2/SiO_2 HR it is $(ML)^{13}M$, and that of $TiO_2/HfO_2/SiO_2$ HR is $(HL)^{11}(ML)^9M$, where H stands for the quarter wavelength optical thickness of TiO_2, M stands for that of HfO_2, and L for SiO_2. TiO_2, HfO_2 and SiO_2 are used as high-, middle- and low-refractive-index materials, respectively. High-quality BK7 substrates were cleaned ultrasonically in an alcohol solution before deposition. All films were deposited by electron beam evaporation in the following process parameters. The base pressure was 2×10^{-3} Pa before deposition and the oxygen partial pressure was 3×10^{-2} Pa during deposition. The substrate temperature was kept at 300 °C during deposition. The deposition rate of TiO_2, HfO_2, and SiO_2 were 1.33, 1.33, and 0.2 nm/s, respectively.

The transmittance and reflectance spectra of samples were measured by Perkin-Elmer Lambda 900 spectrophotometer. Refractive index n and extinction coefficient k of films are calculated from the transmittance spectrum by the envelope method[6].

LIDTs of samples were tested using the chirped pulse train ($\lambda_0 = 800$ nm, $\tau_p = 220$ ps, 10 Hz, incident angle near 0°) from a 23-TW Ti:sapphire laser system[7]. The detailed test process is shown in Ref. [8]. The effective spot diameter was around 3 mm with the fluctuation of ±10%. The relative uncertainty of the LIDT-determination amounted to ±20%, which was mainly due to the uncertainty in the spot size measurements.

Figure 1 shows the transmittance spectra of films. At the wavelength corresponding to the optical thickness of one half wave, the transmittances of both TiO_2 and HfO_2 films are observed to be nearly the same as that of the substrate. The spectra of HfO_2 film shifts to short wavelength region and has a shorter cutoff wavelength ($\lambda_c = 264$ nm) than that of TiO_2 film ($\lambda_c = 315$ nm). The refractive index and extinction coefficient of films are shown in Fig. 2. It is shown that the refractive index and extinction coefficient of HfO_2 film are lower than those of TiO_2 film.

Figure 3 shows the measured reflectivity of HR. It is found that the bandwidth ($R > 98\%$, $\lambda_0 = 800$ nm) of $TiO_2/HfO_2/SiO_2$ HR (~ 176 nm) is almost equal to that

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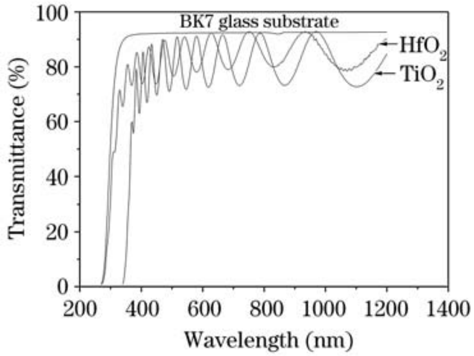

Fig. 1. Transmittance spectra of single-layer films.

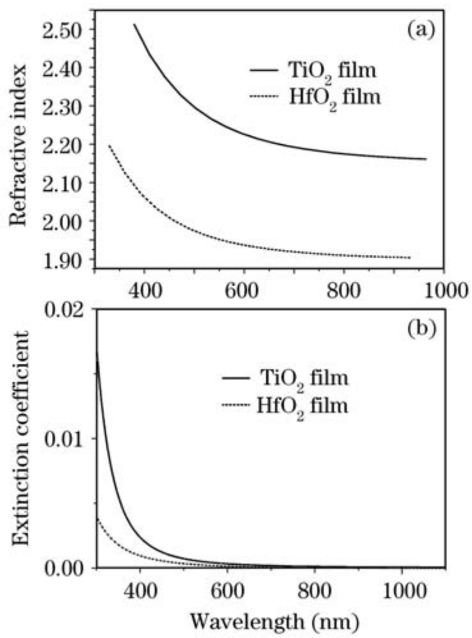

Fig. 2. (a) Refractive index and (b) extinction coefficient of TiO_2 and HfO_2 films.

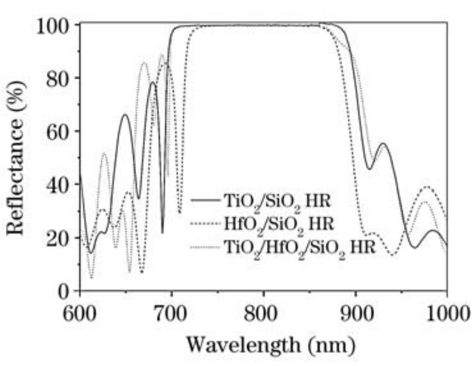

Fig. 3. Measured reflectivity of HRs.

of TiO_2/SiO_2 HR ($\sim$ 187 nm), and is wider than that of HfO_2/SiO_2 HR ($\sim$ 146 nm).

It has been established that the standing-wave electric field (SWEF) must be taken into account when evaluating laser damage resistance[9]. Breakdown most likely occurs at the location of the SWEF maximum in the film. The theoretical result of electric field distributions of $TiO_2/HfO_2/SiO_2$ HR calculated by the thin film design software TFCalc is shown in Fig. 4. It is found that the SWEF maximum occurs at the interface of the outermost layers of high- and low-refractive-index materials and SWEF decreases from air to substrate. The SWEF in TiO_2/SiO_2 stack is nearly zero.

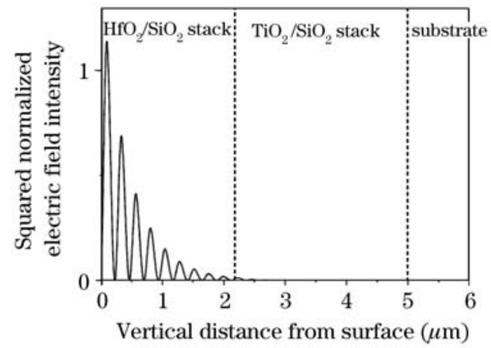

Fig. 4. Calculated electric field intensity in $TiO_2/HfO_2/SiO_2$ HR.

Table 1. LIDTs of Single-Layer Films and HR

High-Index	LIDT (J/cm^2)	
Material	Single-Layer Film	HR
TiO_2	0.61	1.20
HfO_2	1.09	2.20
TiO_2/HfO_2	–	2.40

Table 1 shows the LIDTs of deposited films. The LIDTs of single-layer HfO_2 film and HfO_2/SiO_2 HR are larger than those of TiO_2 single-layer film and TiO_2/SiO_2 HR, respectively. The LIDT of $TiO_2/HfO_2/SiO_2$ HR is almost equal to that of HfO_2/SiO_2 HR.

The absorption coefficient α can be calculated using the relation $\alpha = 4\pi k/\lambda$, where k is the extinction coefficient, λ is the wavelength. The cutoff wavelength λ_c is defined as the wavelength at which the transmittance is zero from the single-layer film's transmittance spectra. λ_c can be considered as a qualitative indicator of the degree of absorption[10]. So, a low extinction coefficient and a short cutoff wavelength indicate a low absorption. Figures 1 and 2(b) show that the absorption of TiO_2 film is larger than that of HfO_2 film.

According to the theoretical results on the temperature field distribution of a standard HR coating, the temperature rise peaks decrease from air to substrate. The highest temperature rise occurs at the interface of the outermost layers of high- and low-refractive-index materials, which causes massive heat deposition, and thus originates the laser-induced damage[11]. Moreover, the laser damage resistance of high-index materials is typically less than that of lower-index materials[12]. Damage is likely to occur first in the high-index layer. Thus the LIDT of HR is determined by the outermost high-index material. Table 1 shows that LIDT is absorption dominated. HfO_2 film has lower absorption than that of TiO_2 film, so the LIDTs of HfO_2 films are higher than those of TiO_2 films. Since the SWEF in TiO_2/SiO_2 stack is nearly zero in the $TiO_2/HfO_2/SiO_2$ HR, the LIDT of $TiO_2/HfO_2/SiO_2$ HR is determined by the outer

HfO_2/SiO_2 stack and the absorption of HfO_2, which increase the LIDT of $TiO_2/HfO_2/SiO_2$ HR to nearly equal to that of HfO_2/SiO_2 HR.

The bandwidth of HR is limited by several factors including the difference between high-refractive-index (n_H) and low-refractive-index (n_L) materials. The higher the n_H/n_L, the wider is the spectral bandwidth of the HR. The refractive index is closely related to the electronic polarizability of ions and the local field inside the material[13]. TiO_2 films have higher refractive index than HfO_2 films (Fig. 2) due to the different positions of the metals in the periodic table. Therefore, the bandwidth of TiO_2/SiO_2 HR is wider than that of HfO_2/SiO_2 HR.

In conclusion, we have fabricated a broadband high LIDT HR for terawatt CPA of ~ 36 fs pulses. The usable spectral range and LIDT of HR are traded off against each other. The higher index difference between high-refractive-index and low-refractive-index materials, the wider is the spectral bandwidth of the HR. The laser induced damage in subnanosecond pulses is absorption dominated and relates to material parameters such as extinction coefficient and cutoff wavelength.

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