Effect of $\lambda/2$ SiO_2 overcoat on the laser damage of HfO_2/SiO_2 high-reflector coatings

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Received December 13, 2002

The effect of $\lambda/2$ SiO_2 overcoat on the laser damage characteristics of HfO_2/SiO_2 high-reflector (HR) coatings is investigated with 1-on-1 and N-on-1 laser damage test methods. The laser damage surface of 1-on-1 is analyzed by a step analyzer. The surface morphologies show that laser damage makes the coating damaged area protrudent and rough for HR coating without $\lambda/2$ silica overcoat, but concave and smooth for HR coating with $\lambda/2$ silica overcoat. The result of 10-on-1 multi-pulse irradiation on the same point of the coating shows that there is an energy density stage on the damage curve. If the laser energy density is within the range of the stage, HfO_2/SiO_2 HR coatings with $\lambda/2$ silica overcoat will not be damaged more than 2 times for multi-shots, and the surface damages are very slight so that there is no impact on the coating performance. Another interesting result is that the energy density stage extends from the damage threshold to the point of about 3 times of threshold, which is similar to the effect of the laser condition on coating.

OCIS codes: 140.3330, 240.0310.

Optical coatings can be catastrophically damaged in the circumstance of high laser energy density in high-peak-power laser systems. The damage threshold of the coatings determines and limits the maximum output power of the laser system[1]. At present, the optical coatings used in high-peak-power laser systems are mostly deposited by use of HfO_2/SiO_2 stacks because of their high laser damage threshold. In addition, laser damage experiments show that high reflector (HR) coating with $\lambda/2$ SiO_2 overcoat can dramatically improve the coating's laser resistance[2]. In this letter, we use the step analyzer to study the laser damage morphologies of HR coatings and analyze the reason of high laser resistance of the HfO_2/SiO_2 HR coating with $\lambda/2$ SiO_2 overcoat.

Experimental samples are deposited on BK7 glass substrate by reactive electron-beam deposition using HfO_2/SiO_2. The coating stacks are $G/(HL)^{11}H/A$ and $G/(HL)^{11}H2L/A$, and the reference wavelength is 1064 nm. Here G represents BK7 glass, H and L are high and low refractive index materials, respectively, and A is air. The damage experimental system consists of a single longitude mode Q-switch Nd:YAG laser, a He-Ne laser collimating source, a beam splitter, a 3-m focus, a translated sample stage, an energy meter, and a CCD camera. The output laser has the following specifications: TEM_{00} mode, wavelength of 1064 nm and pulse duration of 10 ns. The maximum energy per pulse is about 1.5 J. The sample mounted on the translated stage which can be moved precisely in $X-Y-Z$ directions in order to measure the laser damages in different areas of the coatings. The laser energy is measured by an EM500 meter with precision of $\pm 1\%$, and the effective area of the detective laser on sample measured by the CCD camera is about 1.045 mm^2.

The damage experiment for coatings is conducted using 1-on-1 and N-on-1 laser modes. The sites irradiated by laser are arranged as $m \times n$ matrix and the distance between sites is 3 mm. In order to locate the irradiated sites, the beginning and end sites in per row must be damaged to obvious marks. The damage surface is analyzed by a step analyzer and damage morphologies are

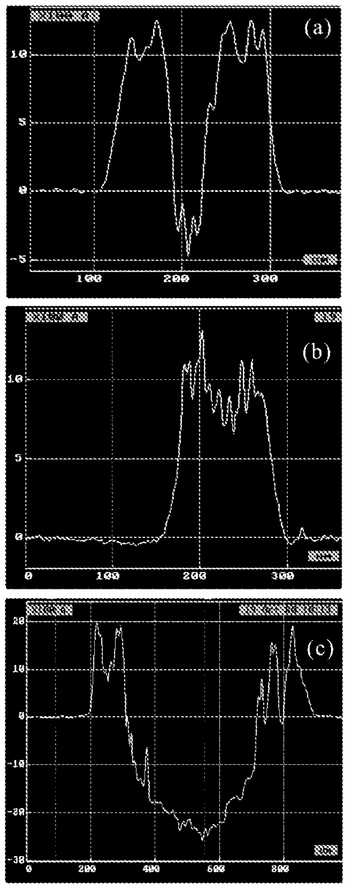

Fig. 1. The cross scan curves of coating damage with $\lambda/2$ SiO_2 layer, got by a step analyzer, the horizontal coordinate represents damage size in unit μm and the vertical coordinate represents damage height in unit Å (0.1 nm). The laser energy densities are 16 (a), 19.6 (b) and 33 J/cm^2 (c), respectively.

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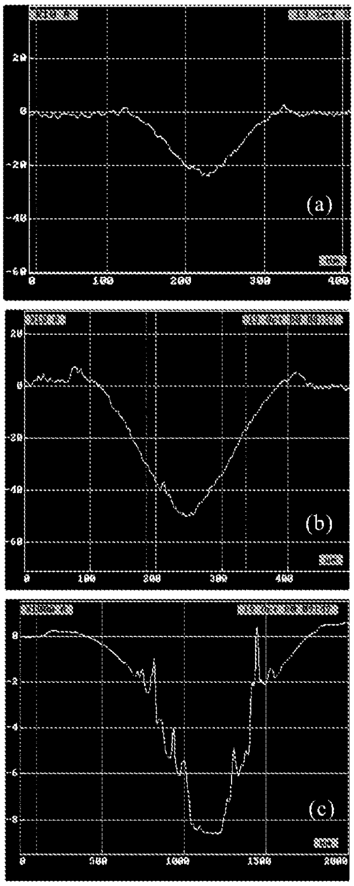

Fig. 2. The cross scan curves of coating damage with $\lambda/2$ SiO_2 layer, got by a step analyzer, the horizontal coordinate represents damage size in unit μm and the vertical coordinate represents damage depth in unit Å (0.1 nm). The laser energy densities are 23 (a), 37 (b) and 144 J/cm^2 (c), respectively.

induced by 1-on-1 laser pulse. As shown in Figs. 1 and 2, we find that laser damage makes the coating surface rough and convex for HfO_2/SiO_2 HR coatings without $\lambda/2$ SiO_2 overcoat. To the next laser pulse, the pinnacle on the rough surface can remarkably enhance the electric field on the coating surface, which resulting in increases of further catastrophic damage possibilities. Oppositely, the laser damage forms a smooth concave shape on the surface of HfO_2/SiO_2 coatings with $\lambda/2$ SiO_2 overcoat, which has little effect on enhancing the electric filed. The convex height and concave depth induced by laser damage is shown in Fig. 3. For the HR coatings without SiO_2 overcoat, the convex height is in the range of 100 − 200 nm when the laser energy density is between 15 and 33 J/cm^2. At densities of 33 J/cm^2 or more, the center of damage area is sunken and the fringe height does not increase, and the sunken depth is about 250 nm, as shown in Fig. 1(c). For the HR coatings with SiO_2 overcoat, the concave depth is as small as about 50 nm until the laser energy density is up to 60 J/cm^2. Thus the coatings with $\lambda/2$ SiO_2 overcoat have stronger capability to resist laser damage than those without overcoat. For example, a 16-J/cm^2 laser pulse can make coating surface deform about 120 nm vertically on coatings without overcoat, but the damage deformation on coatings

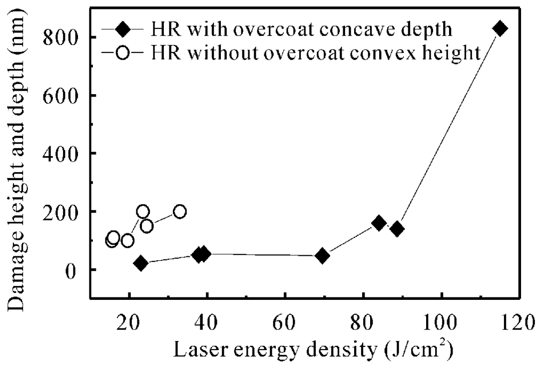

Fig. 3. The damage height and depth versus the laser energy density.

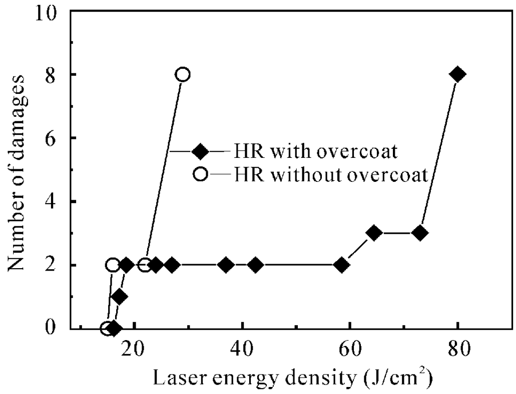

Fig. 4. Damage numbers in 10 pulse shots on certain site at certain energy density.

with overcoat is only about 20-nm-deep concave after a 20-J/cm^2 laser shot.

By using N-on-1 methods, with each test site of coating sample illuminated by N pulses with the same energy (in our experiment, N is set to 10), we find that some test sites are damaged by the first shot of the N pulses, but there is no further damage for the following shots. Figure 4 shows the number of damages versus pulse energy density for 10 pulses irradiating on the same point of the coating. As shown in Fig. 4, there is an energy density stage on the curve. That is, if the coatings are not damaged after two pulse shots, the subsequent pulses cannot further damage the coatings when the laser pulse energy density is within the range of this stage. If the first and second pulses damage the coatings, and the third and fourth pulse damage the coatings too, the subsequent pulse can usually cause further damages. This effect is more significant for coatings with the $\lambda/2$ SiO_2 layer, and the range of the density stage is larger. For example, HR coatings with $\lambda/2$ SiO_2 overcoat have a density stage from 18 to 60 J/cm^2 and can improve their thresholds up to three times. But the stage is only from 16 to 23 J/cm^2 for coatings without $\lambda/2$ SiO_2 overcoat. It should be noted that the maximum value is about 3 times of the minimum value of the stage range. This phenomenon is similar to the laser conditioning effect on HfO_2/SiO_2 HR coatings reported[3−5]. In practice, the thickness of the $\lambda/2$ SiO_2 overcoat is about 366 nm for 1064-nm HR coating. The damage morphologies of the step analyzer show that the first laser pulse shot with the energy density of

37 J/cm^2 only removes about 50-nm thickness, which has negligible effect on the HR spectrum; the second pulse shot usually damages another site of the area irradiated by the laser beam. Therefore we think that laser conditioning only has effects on the HfO_2/SiO_2 coatings deposited with $\lambda/2$ SiO_2 overcoat.

Based on the experimental results and analysis, we conclude that the $\lambda/2$ SiO_2 overcoat can significantly improve the damage resistance of HfO_2/SiO_2 HR coatings at 1064 nm. The reason is that for coatings with $\lambda/2$ SiO_2 overcoat, the damage surface is smooth concave, similar to defocus lens, which disperses the next laser pulse. This was proved by the N-on-1 laser damage experiment. The result of 10 pulses radiating on the same point of coatings shows that there is an energy density stage on the damage curve. If the laser energy density is within the range of the stage, HfO_2/SiO_2 HR coatings will not be damaged more than 2 times for multi-shots, and the surface damages are very slight so that there is no impact on the coating performance. Another interesting result is that the energy density stage extends from the damage threshold to about 3 times of threshold, which is similar to the improvement on the coating after the laser conditioning.

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