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Full Length Article

Enhanced thermomechanical stability on laser-induced damage by functionally graded layers in quasi-rugate filters

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ABSTRACT

Ta_2O_5-SiO_2 quasi-rugate filters with a reasonable optimization of rugate notch filter design were prepared by ion-beam sputtering. The optical properties and laser-induced damage threshold are studied. Compared with the spectrum of HL-stacks, the spectrum of quasi-rugate filters have weaker second harmonic peaks and narrower stopbands. According to the effect of functionally graded layers (FGLs), 1-on-1 and S-on-1 Laser induced damage threshold (LIDT) of quasi-rugate filters are about 22% and 50% higher than those of HL stacks, respectively. Through the analysis of the damage morphologies, laser-induced damage of films under nanosecond multi-pulse are dominated by a combination of thermal shock stress and thermomechanical instability due to nodules. Compared with catastrophic damages, the damage sits of quasi-rugate filters are developed in a moderate way. The damage growth behavior of defect-induced damage sites have been effectively restrained by the structure of FGLs. Generally, FGLs are used to reduce thermal stress by the similar thermal-expansion coefficients of neighboring layers and solve the problems such as instability and cracking raised by the interface discontinuity of nodular boundaries, respectively.

1. Introduction

To remedy the reliability and durability problems arising largely from high thermal stresses and poor bonding strengths of the interfaces between dissimilar materials, functionally graded materials (FGMs) as a new class of advanced composites have been developed [1–3]. FGMs were composed with the continuously changing ratio of two different materials. Functionally graded layers (FGLs) as an application of FGMs in optical coating contribute to effectively reduce the high thermal stresses caused by mismatch in thermal expansion coefficients of different materials and solve the problems such as instability and cracking raised by the interface discontinuity and nodular defects [4–7]. Nodular defects in "standard" (λ/4 stack structure) multilayer dielectric films have been widely studied in the nanosecond pulse regime [8–11]. Nodular defects grow from seeds (particulates) into an inverted conical shape, with discontinuous boundaries between nodules and surrounding films. During laser irradiation, thermomechanical damage occurs preferentially at nodules. The nodules lead to enhanced energy absorption due to electric field intensity (EFI) enhancement, and result in degraded mechanical stability due to discontinuous boundaries and interfaces [12,13]. Previous studies has focused on describing the significant impact of discontinuous interfaces on limiting the improvement of laser-induced damage threshold in the nanosecond pulse regime [14,15]. In recent years, researchers have proposed applying mixtures by co-evaporation or co-sputtering processes in Gradual Index Layers and Rugate Filters [16–18]. The coatings with gradual interfaces reveal a lower mechanical stress and a higher laser damage resistance when irradiated with high laser fluence. In this paper, focus was placed on the enhancement thermomechanical stability on laser-induced damage by functionally graded layers in Quasi-Rugate Filters. For the technical realization convenience, an approximation of a rugate filter through stepped index profile seems to be a suitable approach. It is based on a continuous variation of the refractive index in the depth of the layer. The effect of quasi-continuous interface on the laser-induced damage threshold is reported. A schematic diagram of phenomenological model is used to describe the enhanced thermomechanical stability on nanosecond laser damage by functionally graded layers.

2. Experimental procedure

The Ta_2O_5-SiO_2 quasi-rugate filters and HL stacks were deposited on BK7 substrates with a diameter of 50 mm via ion-beam

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sputtering. The rugate notch filter design was acquired and optimized by thin film design software developed by Laser Zentrum Hannover e.V. A two zone metallic targets of pure silicon and pure tantalum were sputtered by a radio -frequency ion source operated with Xe gas. A neutralizer was utilized for ion neutralization purpose. During the process, oxygen gas flow was supplied to ensure oxidation of the growing layers. Moreover, an broad band optical monitoring system was used to control the thickness of the multilayer coatings during the whole coating process. The mixture ratio was controlled by the relative position of targets in the ion source beam spot, as shown in Fig. 1(a).

By changing the target position in respect of the ion beam, the contribution of both materials to the mixture can be tuned continuously, as shown in Fig. 2(a). The volume fraction of each material in the mixture film can be expressed as:

$$f_i(x) = v_i \oiint I/(v_a \oiint_1 I + v_b \oiint_2 I) \tag{1}$$

where i can be either a or b, and v_a, v_b are the deposition rate of the two pure materials, respectively. I is the ion current of the beam spot. Furthermore, the Lorentz-Lorenz model is used to simulate the refractive indexes as a function of different volume ratios, as shown in Fig. 2(b). The Lorentz-Lorenz model is described in Eq. (2) [19]:

$$\frac{n^2-1}{n^2+2} = f_a \frac{n_a^2-1}{n_a^2+2} + f_b \frac{n_b^2-1}{n_b^2+2} \tag{2}$$

In the expression above, n_a, n_b are the refractive indexes of the two pure materials. The Lorentz-Lorenz model is suit for materials consisting of induced atomic point dipoles in vacuum. The measured refractive indices of the experimental mixture films are most close to the Lorentz-Lorenz (L-L) model, indicating that the microstructure of the mixture films is close to point-like and mixed well.

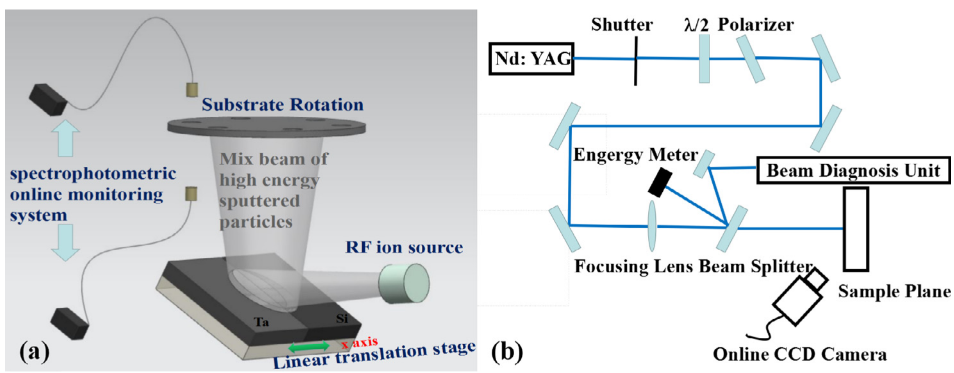

Fig. 1. (a) Schematic diagram of ion-beam sputtering process. (b) Schematic layout of laser damage test system.

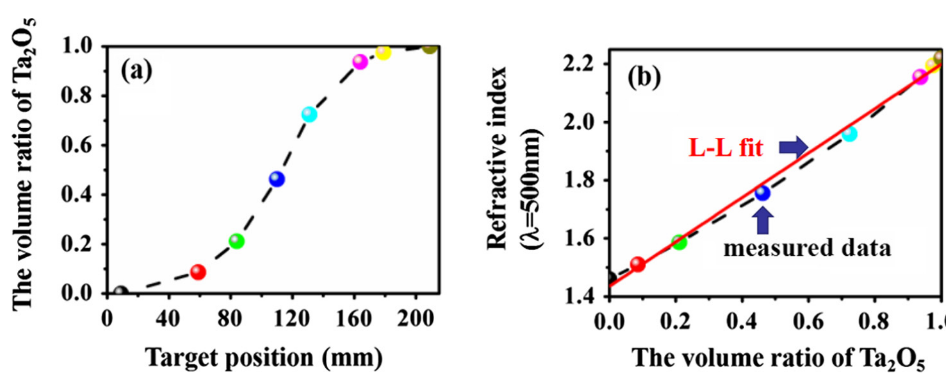

Fig. 2. (a) The volume ratio of Ta_2O_5 as a function of different target positions. (b) Relationship between the volume ratio of Ta_2O_5 and refractive index.

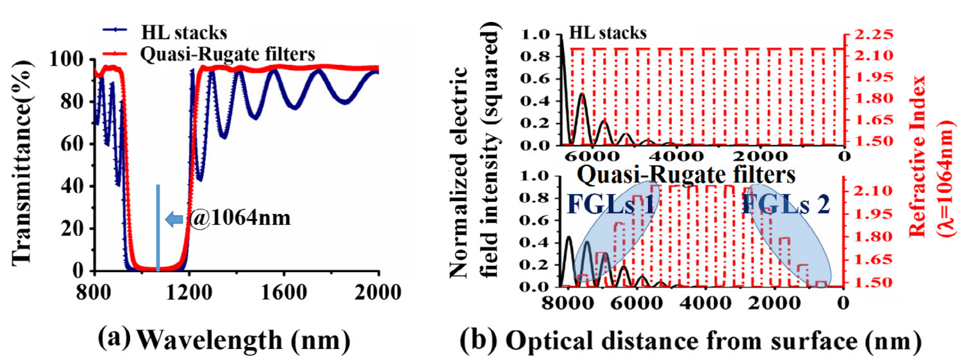

Fig. 3. (a) The transmittance spectra of Ta_2O_5-SiO_2 quasi-rugate filters and HL stacks, relatively. (b) Refractive index profile and electric field distribution of the films.