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Tuning of Laser Damage Threshold by Adjusting Field Zones in Multilayer Dielectric Coatings

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Abstract: There are many factors that influencing the laser induced damage threshold (LIDT) and one of them is damage induced due to standing wave electric fields generated inside the multilayer coating on the irradiation of the laser. HfO_2 and SiO_2 are preferred materials for high damage threshold coatings stack. (HL)^n, where "H" is quarter wave optical thickness (QWOT) for high index materials and "L" is quarter wave optical thickness (QWOT) of low index materials for high reflectance mirror to achieve high reflectivity at reference wavelength. One of the problems with such a stack is that the peak standing wave electric field falls on the interface of low and high index materials which reduces the laser damage threshold of the high reflectance mirror. In the present study, we have optimized the minimum number of layers in quarter wave stacks to go non quarter so that this standing wave electric field shifts away from the interface to the high damage threshold region.

Keywords: Standing wave electric field, Quarter wave thickness, Reflectivity, Bandwidth, Stack.

1 Introduction

Multilayer reflective thin films for laser experiment give rise to remarkable provocation since laser induced damage thresholds (LIDT) reduce conspicuously as the absorption extremity of the thin film materials is impenetrate and are influenced significantly due to the presence of high standing wave electric field at first junction face of the high and low index layers or inside a scantily damage resistant material of the stack. The effect of the electric field distribution is fully unequivocal, leaving as the basic requirement, improved damage threshold materials that may be deposited with low absorption, low defect density and better laser induced damage threshold [1].

The design reported here minimizes the standing wave electric field inside the greater refractive index part of the multilayer, which is normally the low damage resisting area of the coatings [2]. In multilayer films formed by absorbing or non-absorbing coating, the soaking of laser beam in a particular region evidently depends on the standing field intensity in such region and, hence, damage threshold will depend on the peak electric field intensity of incident region [3]. It has, therefore, been stated that the laser induced damage threshold of multilayer coating, that is weakly absorbing, is measured due to absorption of the laser radiation and consequent heating of materials to the point of melting [4].

However, the damage mechanism put forward here is thermal induced stress produced within the film, which requires comparatively lower temperatures than melting of the film. Here the absorption usually related with thin film materials and is proposed that material damage by short pulse lasers probably free from the absorption. The standing electric field intensity generated due to laser radiation is sufficient to initiate the process of absorption of heat from the laser beam and accrued it in the form of heat in the thin film.

The laser radiations absorbed in film is explained by non-linear absorption and is, therefore, measurable by non-conventional techniques [5, 6]. Also it is dependent upon the laser radiation intensity. According to this perspective, the electric field intensity at the first high and low index

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junction is compressed by modified thickness technique and due to this local thermal stress reduced below the critical value and coating withstand higher laser radiation [7].

2 Design of High Reflector

Coatings with high reflectivity have a greater capability to withstand high incident laser irradiation is constructed by alternate coatings of quarter wave optical thickness of hafnium and silicon oxide (one of the higher laser damage threshold materials reported so far), so that a mirror of more than 99% reflectivity is achieved at the wavelength reference. In our study, we constructed a design of mirror (HL)^15 H, with 31 alternate layers of hafnium and silicon oxide with quarter wave optical thickness which have peak reflectivity greater than 99% but in such design the peak standing wave electric field produced due to laser radiation lies on the first interface of high and low index materials, which is most prone to damage and, hence, the damage threshold of such design is low. To maintain the reflectivity and to shift the peak standing wave electric field, we adopted a design (HL)^12 (0.5H 1.5L)^3 H approach in which some pairs of top layers were allowed to go non quarter wave optical thickness and retaining most of layers quarter wave optical thickness. The peak reflectance at the central wavelength of a quarter wave stack (μ_s/(HL)pH/μ_o) is given by

$$R = \frac{\left(1 - k^{2p}\frac{\mu_H^2}{\mu_s}\right)^2}{\left(1 + k^{2p}\frac{\mu_H^2}{\mu_s}\right)^2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{[1]}$$

where “p” is the number of layer pairs, “k” is the ratio of the high index value to the low index one and “μ_H” is the index of the higher index material, “μ_s”, “μ_o” are the indices of substrate and air, respectively [8].

The bandwidth (B.W) for such high reflector made of low index μ_L and high index $\mu_H = \mu_L + \Delta\mu$ quarter wave layer, is determined using the following equation

$$\Delta g = \frac{2}{\pi}\sin^{-1}\left(\frac{\mu_H - \mu_L}{\mu_H + \mu_L}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{[2]}$$

where $g = \frac{\lambda_o}{\lambda}$, and it can be written with small index difference approximation as

$$B.W = \frac{2}{\pi}\frac{\Delta\mu}{\mu}\lambda_o \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{[3]}$$

where μ is the average refractive index of pair of materials, Δμ is their index difference, λ_0 is central wavelength [9].

3 Results and Discussion

In both of the above designs, the reflectivity remains almost the same i.e. greater than 99% and peak standing wave electric field remains at the interface in basic design and shifts to low index material in modified design, which is a high damage threshold region. We have compared the performance of HfO_2/SiO_2 stack with three other stacks using another pair of materials and the same number of layers i.e. 31 layers. For first we considered TiO_2/SiO_2 pair and found that this gives desired reflectivity/bandwidth as shown in Fig. 2 but the peak standing wave electric field is very high as shown in Fig. 1 and, hence, the damage resistance expected to be low and for pico second regime it is experimentally confirmed to be have 0.6 J/cm^2 value for the above stack [10].

In second stack using Ta_2O_5/SiO_2, pair, the reflectivity is still high enough but Ta_2O_5/SiO_2 has peak electric field is lower as compared to stack using TiO_2/SiO_2, which is shown in Fig. 3, 4 and Table 1 and, hence, better damage threshold than the high reflector made with TiO_2/SiO_2 pair. The damage threshold for Ta_2O_5/SiO_2 is 0.9 J/cm^2 [10].

We considered third stack using ZrO_2/SiO_2 pair, results of which are also shown in Fig. 5, 6 and Table 1. It loses very small reflectivity but obtains better result from the point of view of standing wave electric field than that of both the TiO_2/SiO_2 and Ta_2O_5/SiO_2 stacks. The threshold measured for ZrO_2/SiO_2 in nano second regime is 18 J/cm^2 [11]. Damage mechanism changes in different laser pulse widths, the impurity and heat diffusion play an important role in laser damage of coatings, in the nanosecond regime, whereas, in the pico second regime, laser damage threshold occurs due to ionization by the strong electric field. Damage threshold is lower in picosecond regime than in nanosecond regime [12].

However, for HfO_2/SiO_2 stack, the peak electric field intensity still remains to be lower than for all the other designs of stacks. This gives potential to stack using HfO_2/SiO_2 for the highest damage threshold amongst the common high damage threshold material pairs considered by us. The damage threshold for HfO_2/SiO_2 is 1.16 J/cm^2 [10]. This damage threshold value can be further improved if high field zones are shifted away from the interface and if possible inside the layer which has better damage resistance. There is a method in which non-quarter pairs are placed imminent to the substrate and called “substrate scheme”. The results show that at the first junction of two different coating material layers, the electric field can be suppressed substantially for this design and thereby raising the laser damage threshold of the high reflector [13]. In the present study, this can be achieved by allowing some of the pairs preferably at top of stack to have non quarter wave optical thickness, (HL)^12 (0.5H 1.5L)^3 H which shifts the electric field peak from the interface to low index region which has invariably high damage threshold while retaining almost the same reflectivity and comparable band width (full width at half maximum) as shown in the Fig. – 7, 8, 9 and 10. All simulations have been done with the help of Open Filter Software [14] and TFcalc (Thin Films Design Software). Reflectivity and band width are determined with help of equation 1, 3.

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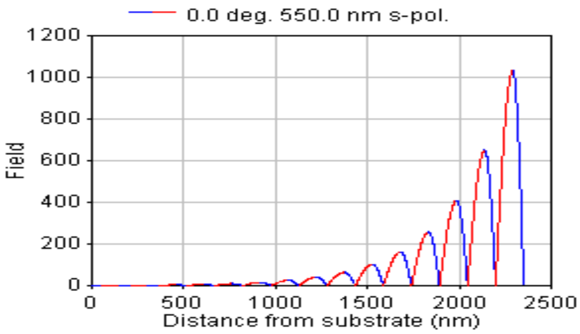

Fig. 1: Variation of electric field with the distance from the substrate in the stack of TiO_2/SiO_2 pairs. It is seen that the peak electric field is very high; hence, the damage threshold is expected to be low in this case.

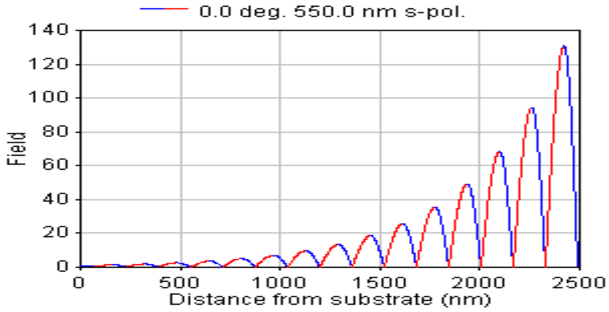

Fig. 3: The electric field variation in stack using Ta_2O_5/SiO_2 pairs with distance from the substrate.

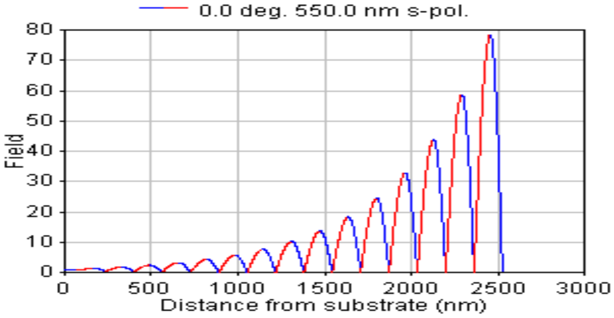

Fig. 5: Variation of electric field with distance in the stack of ZrO_2/SiO_2 materials.

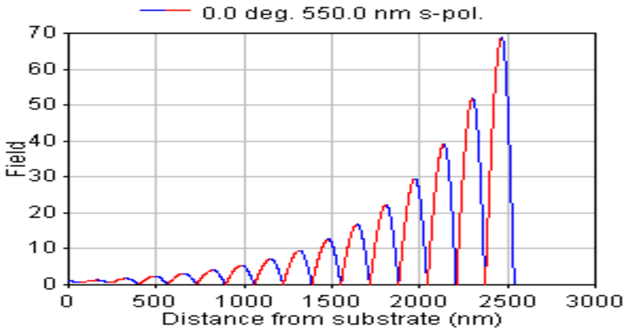

Fig. 7: The behavior of standing wave electric fields in (H L)^15 H stack of all quarter wave optical thickness of Hafnium oxide and Silicon oxide. Plot clearly shows that the peak electric field lies on the interface, which is the most damageable area of the design.

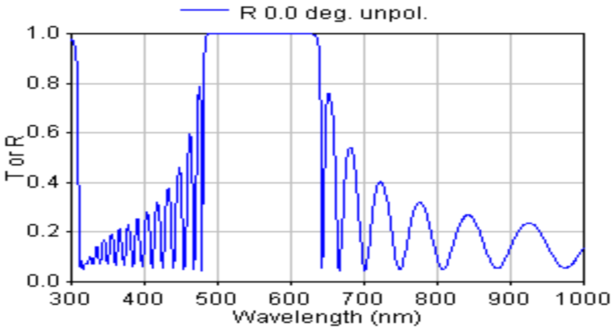

Fig. 2: Reflectivity of stack using TiO_2/SiO_2 pair.

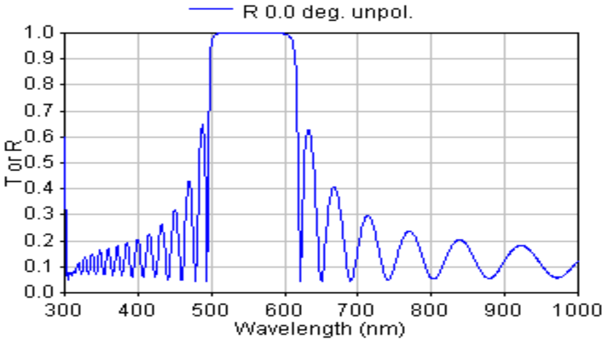

Fig. 4: The reflectivity plot of Ta_2O_5/SiO_2 stack.

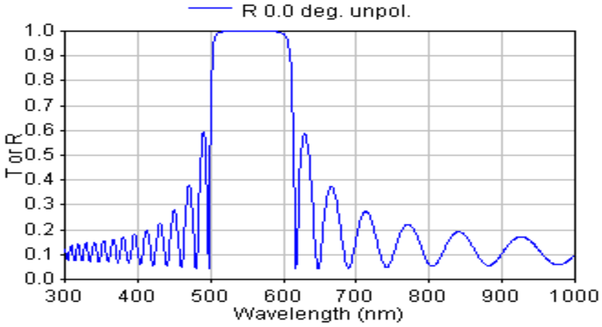

Fig. 6: The reflectivity plot of Stack using ZrO_2/SiO_2 pair with all quarter wave thickness.

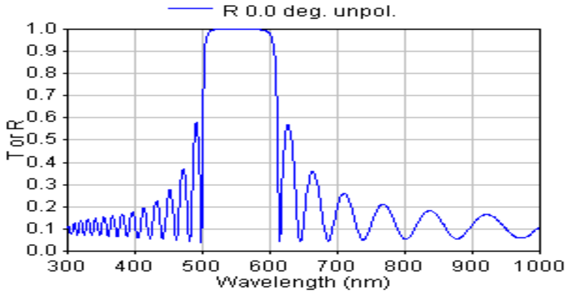

Fig. 8: The reflectivity of (HL)^15H mirror of 31 layers of Hafnium and Silicon oxides.

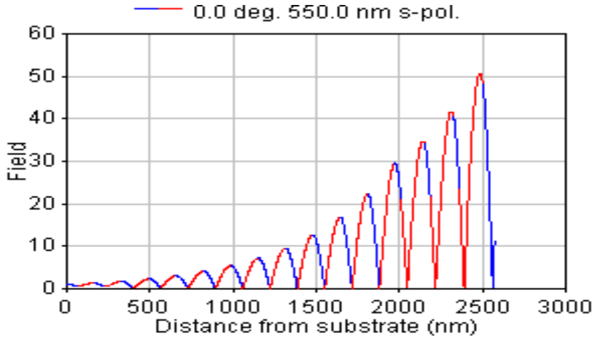

Fig. 9: The behavior of (H L)^12 (0.5H 1.5L)^3 H multilayer stack with the last three pairs of stacks with non- quarter wave thickness and peak electric field is shifted from the interface.

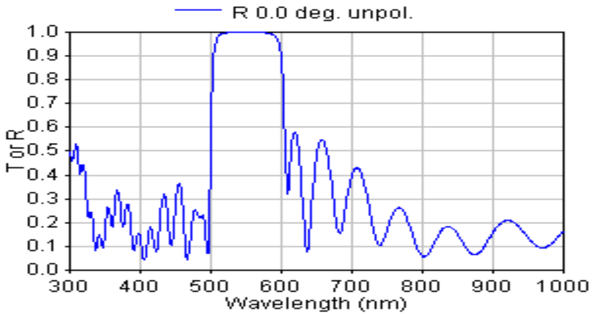

Fig. 10: The reflectivity of (HL)^12 (0.5H 1.5L)^3 H, where H stands for Hafnium oxide quarter wave thickness and L stands for Silicon oxide quarter wave thickness.

Table 1: Variation of electric field and other parameter in different stacks of materials.

Stack	Materials	Band width (nm)	Peak reflectivity (%)	Peak standing wave electric field (a.u.)
(HL)^15 H	TiO_2/SiO_2	174	99.99	1000
(HL)^15 H	Ta_2O_5/SiO_2	126	99.99	130
(HL)^15 H	ZrO_2/SiO_2	117	99.97	80
(HL)^15 H	HfO_2/SiO_2	114	99.96	70
(HL)^12 (0.5H 1.5L)^3 H	HfO_2/SiO_2	108	99.93	50

4 Conclusions

As the field affects withstand capability of multilayers and damage resistance is inversely proportional to the electric field, its effects have been studied in a series of most common stacks using different high damage materials such as TiO_2/SiO_2, Ta_2O_5/SiO_2, ZrO_2/SiO_2 and HfO_2/SiO_2. Electric field value is found to be the highest in TiO_2/SiO_2 stack and the lowest in HfO_2/SiO_2 stack making the former a preferred pair for designing multilayer coatings that can have the highest damage threshold value from field intensity considerations.

The damage threshold of such multilayer dielectric laser reflectors can be further increased by allowing few top of the stack layers to go non-quarter wave to fine tune the location of high field peaks away from the interface and if possible inside the higher damage resistant material layer out of the two materials chosen for a stack. This allows retaining production and monitoring advantages of all quarter wave layers and improvement in damage threshold with minimum variation.

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