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Broad angle antireflection coatings and their damage threshold at 1064 nm

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Broad angle antireflection coatings (BAAR) have been designed, fabricated and their damage thresholds determined at 1064 nm. Two layer AR coatings as well as four layer BAAR systems were designed using a refining program. The performance of both the coating systems was compared. Reflectance at normal and different oblique incidence angles, absorption and damage threshold are reported.

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1. Introduction

In high power laser systems, especially for laser material processing where an angular tuning of the focusing lens is essentially required, reflection losses at different angle of incidences are considerable. The basic requirement for such an application is to produce high damage threshold AR - coatings with low absorption losses and minimum reflectance at large incidence angles. Moreover, in some other applications, optical components like beam splitter cubes and dielectric attenuators etc. also need minimum reflection losses at large incidence angles. For these purposes, broad angle anti-reflection coatings are often desired.

In order to design such type of coatings, a refining program is used to optimize the optical thicknesses as a function of angle of incidence. Various refining methods are known in the literature [1-11] for designing multilayer applications. Standard soft wares are also available for refinement purposes. However, we have used the refining method given by [12] and designed two and four layer AR - coatings which give minimum reflectance in a broad angular region. A comparison has been made between two and four layer systems as well as the results of four layer systems were also compared with some of the published data. For different multilayer stacks, high and low refractive index materials have been selected because of their better performance regarding absorption, scattering and damage thresholds [13] for Nd:YAG laser. All coating systems were designed at 1064 nm using HfO_2, Ta_2O_5 and CeO_2 as a high index layer and SiO_2 and MgF_2 as a low refractive index material.

2. Design

In order to optimize the layer thicknesses for broad angle AR-coatings as a function of angle of incidence and R = 0, a refining program is necessarily required. The computational method consists of a multilayer program for the calculation of reflectance and transmittance along with a least square fit algorithm. The start point is an arbitrary design. Film thicknesses can be varied by a Monte Carlo method or by a method based on selection of layers with the largest effect on the merit function. The merit function is defined by the sum of the squared deviation of actual calculated dependence from the demanded wavelength of the reflection coefficients and phase shifts. The optimization process is terminated if no further decrease from one variation step to the other is found. Input parameters contain a quarter wave stack (HLHL) of four layers as a start design, angle of incidence ranging from 0° to 60° in a step of 10° and for each angle of incidence reflectance is selected to be zero. In this way, two layer and four layer systems were optimized. Table 1 shows the starting and optimized optical thicknesses for two layer AR – coating designs with HfO_2, Ta_2O_5 and CeO_2 as high index layer while SiO_2 and MgF_2 as low index layer at 1064 nm.

Table 1. Starting and refined optical thicknesses (in λ/4 where λ = 1064 nm) for two layer AR-systems.

AR-2 (HfO_2/SiO_2)			AR-2 (Ta_2O_5/SiO_2)			AR-2 (CeO_2/MgF_2)		
Layer	Starting	Refined	Layer	Starting	Refined	Layer	Starting	Refined
Glass	------	------	Glass	------	------	Glass	------	------
HfO_2	1.00	0.46	Ta_2O_5	1.00	0.39	CeO_2	1.00	0.50
SiO_2	1.00	1.26	SiO_2	1.00	1.30	MgF_2	1.00	1.21
Air	------	------	Air	------	------	Air	------	------
Refractive index of HfO_2 = 1.95 Refractive index of SiO_2 = 1.46 Design Wavelength = 1064 nm Nearly 0 % Reflectivity: (0º - 20º)			Refractive index of Ta_2O_5 = 2.05 Refractive index of SiO_2 = 1.46 Design Wavelength = 1064 nm Nearly 0 % Reflectivity: (0º - 20º)			Refractive index of Ce_2O = 1.79 Refractive index of MgF_2 = 1.38 Design Wavelength = 1064 nm Nearly 0% Reflectivity: ≈ (0º - 20º)		

Table 2 displays the optical thicknesses and characteristics of starting and refined designs of four layer AR-coatings for three different combinations BAAR - 1, BAAR - 2 & BAAR - 3 systems designed with similar materials as in case of two layer AR – coating systems. If we compare the two layer systems with four layer systems it is clearly evident that with a two layer designs we could obtain nearly zero reflectance in a very small angular region i.e. 0 to 20 degrees, while four layer system with HfO_2 / SiO_2 (BAAR -1) show broader angular region i.e. 0 to 50 degrees. The other two designs for Ta_2O_5 / SiO_2 (BAAR -2) and CeO_2 / MgF_2 (BAAR -3) behave in a similar fashion and exhibit nearly zero reflectance in an angular region from 0 to 40 degrees and 0 to 30 degrees respectively.

Table 2. Starting and refined optical thicknesses (in λ/4 where λ = 1064 nm) for three different four layer AR- systems.

BAAR-1			BAAR-2			BAAR-3		
Layer	Starting	Refined	Layer	Starting	Refined	Layer	Starting	Refined
Glass	------	------	Glass	------	------	Glass	------	------
HfO_2	1.00	2.11	Ta_2O_5	1.20	0.26	CeO_2	1.00	0.19
SiO_2	1.00	0.59	SiO_2	1.00	0.35	MgF_2	1.00	0.32
HfO_2	1.00	1.51	Ta_2O_5	1.20	1.22	CeO_2	1.00	1.41
SiO_2	1.00	0.83	SiO_2	1.00	0.96	MgF_2	1.00	0.92
Air	------	------	Air	------	------	Air	------	------
Refractive index of HfO_2 = 1.95 Refractive index of SiO_2 = 1.46 Design Wavelength = 1064 nm Nearly 0 % Reflectivity: (0º - 50º)			Refractive index of Ta_2O_5 = 2.05 Refractive index of SiO_2 = 1.46 Design Wavelength = 1064 nm Nearly 0 % Reflectivity: (0º - 40º)			Refractive index of CeO_2 = 1.79 Refractive index of MgF_2 =1.38 Design Wavelength = 1064 nm Nearly 0 % Reflectivity: (0º - 30º)		

3. Experimental

All the coatings were deposited on Suprasil II substrates at a base pressure of ~ 1.0 × 10^{-5} mbar in a vacuum coating unit from two electron gun sources. Thickness was controlled by optical method using two test glasses, one for each set of layers. Reflections were measured at different angles of incidence ranging from 0 to 60 degrees by Perkin-Elmer Lambda 19 spectrophotometer with a variable-angle reflectance measurement accessory. A high reflection dielectric mirror at 1064 nm was taken as reference. Absorption was measured by a very sensitive thermo-graphic laser calorimeter, developed by Ristau et al [14]. With a laser power of 200 watts and an error of 10%, the sensitivity limit of this device was ≤2.5 ppm. The details of damage threshold measurements is reported elsewhere [13], however, a brief description of main damage parameters are given in Table 3.

Table 3. Description of main laser damage parameters.

Test wavelength	1064 nm
Spot diameter at sample (1/ e^2 intensity)	300 micron
Laser energy (max)	250 mJ
Pulse duration (FWHM)	14 ns
Damage detection	He-Ne scattering Nomarsky & SEM

4. Results and discussion

Two and four layer systems were designed and deposited as mentioned in Table 1- 2. With two layer systems, a very broad angular region of minimum reflectance is not obtained. AR-2 (HfO_2 / SiO_2) gives zero reflectance from 0 to 20 degrees while AR-2 (Ta_2O_5 / SiO_2) also show a region of nearly zero reflectance from 0 to 20 degrees and AR-2 (CeO_2 / MgF_2) display even less angular reflectance. However, four layer systems (BAAR 1, 2 & 3) show nearly zero reflectance at an incidence angle from 0 to 40 degrees and 0 to 30 degrees respectively. However, their effective useable range as an AR- coating is much larger. Experimental results support this statement (Table 4).

Table 4. Results of reflection, absorption and damage threshold measurements of AR-2 and BAAR-1, 2 and 3 coating systems at 1064 nm.

Design	Reflectance (%) at different angle of incidences							Absorption (ppm)	Damage threshold (J/cm^2)
	0º	10º	20º	30º	40º	50º	60º		
AR-2 (HfO_2/SiO_2)	0.03	0.04	0.07	0.16	0.44	1.05	2.30	748	46 ± 3
AR-2 (Ta_2O_5/SiO_2)	0.02	0.03	0.13	0.16	0.70	2.09	5.51	1242	43 ± 1
AR-2 (CeO_2/MgF_2)	0.43	0.50	0.75	0.90	1.50	2.76	5.88	451	39 ± 5
BAAR-1	0.09	0.07	0.09	0.27	0.09	0.50	19.40	696	23 ± 6
BAAR-2	0.54	0.07	0.16	0.90	0.06	30	73	738	31 ± 3
BAAR-3	0.50	0.07	0.06	0.54	1.50	4.80	7	857	39 ± 12

If we compare the published results of similar type of coating designs by A. Permoli and M. L. Rastello [11], it is evident that our designs cover a broader incidence angle region in which only two materials have been used and each coating system consists of only four layers, where as reported results show 8, 9 & 13 layer AR- systems with three materials. The 8 & 9 layer coatings show nearly zero reflectance at 0 & 30 degrees incidence angle while 0 & 40 degrees incidence angle has been achieved by a 13 layer system. Therefore, it is clear that our results show much better performance with only 4 layers and two materials which are extremely easy to evaporate. The only difference between our designs and their design is regarding wavelength region. They have designed their coatings for Visible to NIR region while we have designed our coatings for Nd:YAG laser i.e. for 1064 nm. Infact, it is not possible to compare all the data such as absorption and damage thresholds because they were not reported in their paper.

Measured values of reflection, absorption and damage threshold are given in Table 4 for the AR-2 systems with HfO_2 / SiO_2, Ta_2O_5 / SiO_2 and CeO_2 / MgF_2 as well as BAAR-1, 2 & 3 systems. In AR-2 systems, best results were obtained with HfO_2/SiO_2 in terms of reflectance measurements as a function of angle of incidence. In BAAR systems, BAAR-1 showed the best results.

Fig. 1 shows the comparison of measured values of reflection at various angles of incidence of AR-2 (HfO_2 / SiO_2) and BAAR-1(also with HfO_2 / SiO_2) coating system. Plot shows that four layer design is much better than 2 layer system as far as reflectance in a wide angular region is concerned.

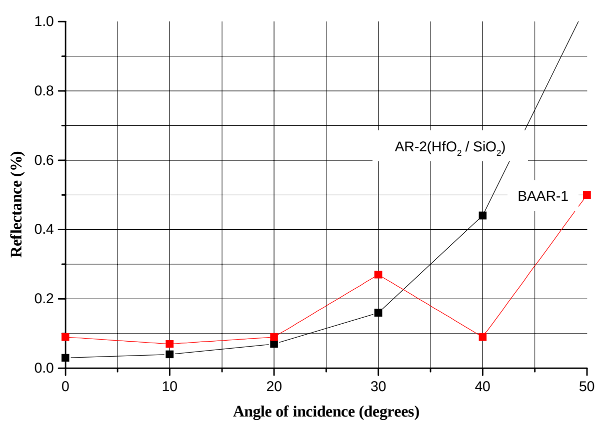

Fig. 1. Comparison of measured reflectance of AR-2 (HfO_2 / SiO_2) and four layer (BAAR-l) coating Systems as function of angle of incidence.

Fig. 2 shows the measured values of reflections at various angles of incidence of BAAR-1, 2 & 3 systems only. It is evident from the plot that design with HfO_2 / SiO_2 gives the best reflection performance.

This coating system can be very effectively used as an AR-coating from 0 to 50 degrees. At 50 degree incidence angle the value of reflectance i.e. 0.5% which seems to be a little bit higher. But as this value is acceptable in broad band AR coatings, we can safely say that with this coating design we can cover the region of minimum reflectance from 0 to 50 degrees. The other two designs with Ta_2O_5 / SiO_2 and CeO_2 / MgF_2 show minimum reflectance from 0 to 40 and 0 to 30 degrees respectively. Among the three AR-2 coating designs lowest absorption was noticed in CeO_2 / MgF_2 design and highest absorption value is obtained with Ta_2O_5 / SiO_2 design. The damage threshold for three AR-2 systems lies between 39 and 46 J / cm^2. The highest value of damage threshold is obtained with HfO_2 / SiO_2 AR-2 coating. In BAAR systems, lowest absorption is measured in HfO_2 / SiO_2 system and highest value of absorption is observed in CeO_2 / MgF_2 coatings. Now, if we compare the values of absorption and damage threshold for two and four layer systems independently, no correlation between absorption and damage threshold can be established. This is in accordance with the published results for single layers of these materials [13]. The absorption coefficients of HfO_2 and SiO_2 are 0.3 cm^{-1} and 0.1 cm^{-1} respectively. The HfO_2 / SiO_2 (AR-2) gives highest value of damage threshold i.e. 46 J/cm^2. However, HfO_2 / SiO_2 (BAAR-l) does not show highest value of damage threshold (23 J/cm^2). This suggests that the damage threshold does not depend on absorption only. Probably, damage mechanism is governed by some other factors. One of the reasons could be the number of layers. As the number of layers increase interface absorptions [15] also increase. However, damage threshold of all three BAAR-l, 2 & 3 systems are found to be the same within their error limits.

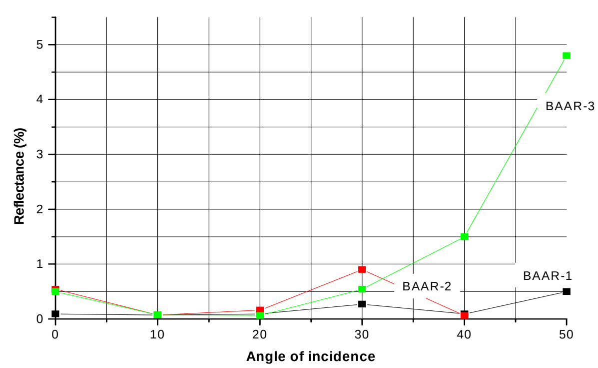

Fig. 2. Measured reflectance of BAAR-1, 2 & 3 coating systems for various angle of incidences at 1064 nm.

Morphological observations of BAAR systems with SiO_2 and MgF_2 as an outer layer, display a removal of upper low index layer which is mainly due to absorption and stress respectively. This sort of peel off or de-lamination indicates a poor adhesion at film-film interface. Silica is amorphous and shows a damage due to absorption while Magnesium Fluoride layer develop stresses during evaporation. When such layers are exposed to intense laser radiation damage is produced due to stress showing a parquet structure [13].

As an example, scanning electron micrograph for HfO_2 / SiO_2 design is shown in Fig. 3.

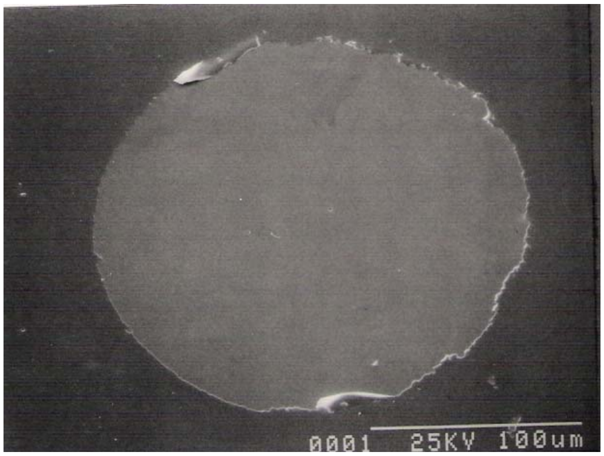

Fig. 3. Scanning electron micrograph of BAAR-1(Hafnia / Silica) on BK-7 at an energy density of 19 J / cm^2.

It is evident from the picture that damage is produced due to purely absorption. No craters, pinholes or inclusions are visible. In a high energy damage spot, strong delamination of the upper layers is observed. A small portion of the delaminated area has been enlarged and is shown in Fig. 4. It can easily be noticed that adhesion between the upper and lower layers is very poor. The number of delaminated layers cannot be counted.

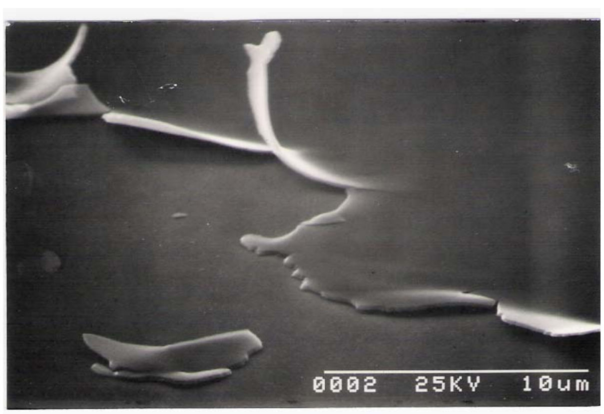

Fig. 4. Scanning electron micrograph of an enlarged portion of high energy damage at BAAR-1(Hafnia/Silica) on BK-7 at an energy density of 62 J / cm^2.

4. Conclusions

The refining of broad angle AR coatings for laser beams at 1064 nm is presented. Such coating systems are necessarily required for Nd-Lasers used in material processing. Experimental data reveals that the refined systems BAAR-1, 2 and 3 can be used in a very broad region of incidence angles from 0 to 50, 0 to 40 and 0 to 30 degrees, respectively, according to their specific angular requirements. A comparison of two and four layer systems was also done. However, BAAR-1 coating design with HfO_2 / SiO_2 covers the maximum angular region where reflectance was found to be in the acceptable limits. In material processing, high power lasers are generally used. Therefore, AR coatings should be designed according to their damage threshold requirements. All three coating systems BAAR-1, 2 and 3 proved to be highly damage resistant at 1064 nm. However, their damage threshold values are found to be the same within the stated uncertainties.

References

[1] O. S. Heavens, H. M. Liddell, Opt. Acta. **15**, 129 (1968).
[2] H. Zycha, Appl. Opt. **12**, 979 (1973).
[3] P. Baumeister, R. Moore, K. Walsh, J. Opt. Soc. Am. **67**, 1039 (1977).
[4] A. L. Bloom, Appl. Opt. **20**, 66-73 (1981).
[5] J. F. Tang, Q. Zheng, J. Opt. Soc. Am. **72**, 1522 (1982).
[6] J. A. Dobrowolsky, F. C. Ho, A. Belkind, V. A. Koss, Appl. Opt. **28**, 2824 (1989).
[7] A. Thelen, Design of Optical Interference Coatings, McGraw-Hill, New York, (1989).
[8] J. A. Dobrowolsky, R. A. Kemp, Appl. Opt. **29**, 2876 (1990).
[9] A. Premoli, M. L. Rastello, Appl. Opt. **31**, 6741 (1992).
[10] A. Premoli, M. L. Rastello, Appl. Opt. **31**, 1597 (1992).
[11] A. Premoli, M. L. Rastello, Appl. Opt. **33**, 2018 (1994).
[12] D. Ristau, S. M. J. Akhtar & J. Ebert, Proc. 18-th Anl. Symp. on Opt. Mat. for High Power Lasers, Boulder, Colorado, NIST Specl. Publ. No. 752, Boulder, USA, 1986. p 300.
[13] S. M. J. Akhtar, D. Ristau, J. Ebert, H. Welling, phys.stat. sol.(a) **115**, 191 (1989).
[14] D. Ristau, J. Ebert, Appl. Opt. **25**, 4571 (1986).
[15] Ristau D, Dang XC, Ebert, J., Laser induced damage in optical materials, Nat. Bur. Stand.; US Specl. Publ. No. 727, 1984, p 298.

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