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Optical characterization of damage resistant "kilolayer" rugate filters*

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ABSTRACT

Multilayer dielectric optical coatings produced by high temperature plasma-assisted chemical vapor deposition (PCVD) have been previously shown to have very high surface and bulk damage thresholds (above 40 J/cm²). Because these experimental coatings are deposited on tubular substrates, conventional wavelength scanning cannot accurately measure the coating peak reflectance and bandwidth. Measurement of the variation of transmittance with incidence angle at fixed wavelength permits analysis of the coating spectral response. The results indicate that the PCVD coatings behave as nearly "ideal" rugate filters. Their optical performance agrees well with that predicted for a rugate by Southwell's coupled-wave theory and by the characteristic-matrix model. These 1000-layer-pair filters have maximum reflectances exceeding 99.9%, peak reflectance wavelengths within 0.5% of the design wavelength, and FWHM bandwidths narrower than 10 nm. Minor perturbations to the ideal rugate sinusoidal profile do not appreciably affect the coating optical performance. Comparison with calculations suggest that the only significant deviation of the PCVD structure from that of an ideal rugate is a small (0.7%) drift in the index period. Excellent optical performance and high damage resistance makes PCVD rugate coatings potentially useful for several high power laser applications.

1. INTRODUCTION

The output of high peak power lasers is often limited by the damage thresholds of the multilayer dielectric coatings used on the various system optical components. Most multilayer dielectric coatings are prepared by physical vapor deposition (PVD) such as e-beam evaporation and consist of a number of alternating layers of metal oxides and/or fluorides of different refractive index. Coatings prepared by PVD suffer from lowered laser damage resistance likely as a result of thermal-mechanical and/or chemical incompatibility between layers, bulk and localized regions of high optical absorption, incorporation of light absorbing particulates, and presence of voids or microstructural defects.¹⁻⁶

High temperature ($T > 850^{\circ}\text{C}$) plasma-assisted chemical vapor deposition (PCVD) can be used to prepare multilayer dielectric coatings that do not appear to suffer from the above problems. Surface damage thresholds nearly equal to those of super polished fused silica have been demonstrated.¹ These fully dense, amorphous coatings are compositionally uniform and have no distinct material interfaces, possess low scatter, and are essentially defect free.

The PCVD coatings made to date nominally consist of 1000 or more quarterwave optical (QWOT) layers and are termed "kilolayer" filters. The coatings have been prepared by Schott Glaswerke using the same inside-tube deposition process that they use to fabricate optical fiber preforms.¹ The coating used in this study was deposited on the inside of an ~ 17.2 mm i.d. quartz tube. SiCl_4 and a halogenated dopant (e.g., GeCl_4) react with O_2 at high temperature in a microwave-driven plasma producing SiO_2 containing a variable concentration of dopant (e.g. GeO_2). Periodically mixing the dopant with SiCl_4 results in a variable composition (and hence refractive index) profile. Both SiCl_4 and the dopant flow are computer controlled. To date coatings with both sinusoidal and step-index profiles have been successfully prepared. Secondary ion mass spectroscopy has been

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used to analyze the approximate dopant deposition profile in the coatings. As will be shown below, the results from this study provide a far more accurate assessment of both the deposition profile and uniformity.

The nominal refractive index difference Δn between QWOT layers in PCVD rugate filters can range from as low as 0.001 to as high as 0.05 depending on the dopant and the dopant concentration. Control of the layer thickness (coating period) to within a few angstroms is possible at deposition rates of a few micrometers per minute.^{1,7,8} Ongoing research at Lawrence Livermore National Laboratory (LLNL) and Schott Glaswerke is aimed at translating the inside-tube deposition process to one compatible with large, planar substrates.^{1,9}

As also exhibited by step-index stacks, the Bragg reflections from sinusoidal-index coatings, or rugates, have very narrow bandwidth (e.g., ~ 1.8 nm for Δn of 0.005 and 1000 layer pairs).^{10,11} However, unlike step-index stacks, the sinusoidal index profile of a rugate produces a single reflectance band at the design wavelength, and harmonic reflections are strongly suppressed except for a small amount ($< 5\%$) at the third harmonic.

2. OPTICAL CHARACTERIZATION

Measuring the transmittance T as a function of wavelength λ at normal incidence is the preferable method of determining the spectral response of PCVD coatings. However, for coatings on highly curved substrates, this measurement cannot be made with a typical monochromator or spectrometer system. For a probe beam incident on a PCVD coating deposited on the inside of a tubular substrate, the incidence angle θ varies along a coordinate perpendicular to both the direction of propagation of the beam and the cylinder axis as shown in Fig. 1. The range in incidence angle θ is given by

$$\frac{\Delta\theta}{2} = \sin^{-1}(d/2R), \quad (1)$$

where d is the width of the beam and R is the radius of the cylinder. For our samples with a radius of 8.6 mm, the angular spread about normal incidence for a typical spectrometer beam ($d \cong 4$ mm) is $\sim 27^\circ$.

Tube I.D. = 17 mm

Figure 1. Schematic drawing showing the geometry for the incident beam from typical spectrometer onto a 17 mm-diameter curved, coated substrate. The drawing illustrates the magnitude of the variation in incidence angle across the sample.

For each wavelength interval λ , and for a spatially uniform incident beam, the sample transmittance $T(\lambda)$, is proportional to the integrated response over the range of incidence angles:

$$T(\lambda) \propto \int_{-\Delta\theta/2}^{\Delta\theta/2} T(\theta, \lambda) \cos\theta \, d\theta \quad (2)$$

An angular spread of 27° corresponds to a wavelength resolution of ~ 13.5 nm. Because of this angular blurring, a spectrometer cannot measure either the spectral width or the amplitude of the transmittance minimum associated with the truly spectrally narrow reflective maximum of a rugate filter.

To circumvent this inability to correctly measure the coating spectral response by monochromator scanning, we developed a laser-based technique to determine T as a function of incidence angle, θ , at a fixed wavelength, λ . The wavelength $\lambda_{\max}$ of the reflectance maximum shifts to shorter wavelength as θ increases.^{12,13} In effect, the reflectance bands of a coating can be mapped out by angle tuning if the coating has been designed to have $\lambda_{\max}$ in excess of the probe wavelength at normal incidence. Results from an independent study using elements of this approach have recently been published by Edmonds et al.¹²

3. MODELING

Unfortunately, a $T(\theta)$ spectrum obtained at fixed wavelength cannot be directly mapped into a $T(\lambda)$ spectrum at constant angle. The $T(\theta)$ data must be fitted to a model of the coating structure from which the corresponding $T(\lambda)$ response can be deduced. The coupled-wave theory developed by Southwell¹⁰ was first used to connect the general characteristics of the spectral response (maximum reflectance wavelength $\lambda_{\max}$, angular shift of $\lambda_{\max}$, maximum reflectivity $R_{\max}$, and bandwidth $\Delta\lambda$) to the structural parameters of the rugate coating (number of layers N , substrate refractive index n_s , average refractive index n_a , peak-to-peak index variation Δn , layer period $\lambda/2n_a$, and initial phase ϕ).¹⁰ Figure 2 describes a rugate defining these parameters. The initial phase ϕ correlates with the refractive index of the first QWOT layer deposited and is 0 for an index equal to n_s , $\pi/2$ for an index equal to the highest index material, and $3\pi/2$ for an index corresponding to the lowest index material. Generally, a silica QWOT is deposited initially and the initial phase is $3\pi/2$.

Figure 2. (a) Schematic drawing of a rugate coating illustrating the various terms used to describe the coating and its refractive index profile; and (b) the typical spectral response characteristics.

The Southwell analysis¹⁰ yields simple relations between the two sets of parameters, but is strictly valid only for ideal sinusoidal rugate coatings. However, the Southwell approach can be used to generate several rules of thumb that are useful for correlating spectral response with coating structure and incidence angle:

$$\lambda_{\max} = \sin^2 \theta_0 / 2n_s^2, \quad (3)$$

$$\Delta\lambda = \Delta n / 2n_s, \quad (4)$$

$$R_{\max} = \tanh^2 (\pi \Delta n N / 4n_s), \quad (5)$$

where θ_0 is the angle of incidence measured at the coating surface and the other terms are described in Fig. 2.

To permit analysis of the effect of arbitrary imperfections in the rugate structure, e.g., spatial period and refractive index variations, a characteristic-matrix approach was used for our primary calculation of the coating spectral response. This method assumes that the gradient-index profile can be represented as a sequence of thin homogeneous layers whose index provides a stepped approximation to the refractive index profile. The recent improvements in (and decreasing cost of) computational resources have answered some of the objections raised to this "brute force" but exact approach. In addition, a simple decrease in the step size in the model showed that no significant errors were introduced by using a stepped index approximation to the continuous (sinusoidal) index profile.

Coupled wave and characteristic matrix theories agree very closely

Figure 3. Calculated transmittance using coupled wave theory (— —) and characteristic matrix (—) vs. angle of incidence (at the coating surface) for a 2000 layer rugate coating with a sinusoidal index variation (QWOT $\approx 0.184 \mu\text{m}$ and $\Delta n = 0.01236$). The design wavelength for peak reflectance is 1.064 μm and the probe beam wavelength is 1053 nm.

The agreement of the predictions of the two models for an ideal sinusoidal rugate is demonstrated in Fig. 3. The characteristic-matrix model used in this case was a 20-step approximation for the profile over one period; a similar calculation using only 10 steps yielded an essentially identical result. In addition to establishing the validity of the discrete approach, this invariance with step size gives some indication that considerable profile imperfections can be allowed in kilolayer coatings without negatively affecting their spectral response.

4. EXPERIMENTAL

Figure 4 shows the experimental arrangement used to measure $T(\theta)$ for reflective coatings on cylindrically curved substrates. Because the PCVD coatings were deposited on the inside of 17.2 mm fused silica tubes, the tube was cut lengthwise into typically 2 cm by 1 cm sections. The sample was mounted on a stage that allowed its linear translation along horizontal and vertical axes that were perpendicular to the beam. In addition, the sample could be rotated about a vertical axis passing through the coating.

Figure 4. Experimental set-up for coating characterization using laser transmittance measurements as a function of incidence angle at fixed wavelength.

The wavelength of the probe laser must be shorter than the coating design wavelength to measure the $T(\theta)$ spectrum. The upper limit to the possible separation between the coating design wavelength and the probe wavelength is determined by the angular sensitivity of the coating as described by Eqn. 3. Our sample stage physically limited angle tuning to $\pm 35^\circ$, which corresponds to a wavelength range of $\sim 75 \text{ nm}$.

The p-polarized incident beam had a Gaussian spatial profile and was focused so that the waist was at the sample surface. For most of our experiments the focal length of the lens was 100 cm, and the measured waist diameter was 0.23 mm at e^{-2} in intensity. A reference beam was reflected from the front surface of a wedged, bare SiO_2 window in the incident beam. Silicon photodiodes were used to measure the intensities in the transmitted and reference beams. The incident beam pulses were generated by a single-mode Nd:YLF oscillator operating

at 1053 nm. The waveform of the pulse was rectangular and its duration was 4 ms. The pulse energy was 1 mJ.

During measurements, the sample was mounted with its cylinder axis horizontal, and translated vertically so that the beam was incident along a radius of the cylinder. $T(\theta)$ of the sample was measured as the sample was rotated, both clockwise and counterclockwise, about the vertical axis through an angle sufficiently large to allow observation of the reflectance maxima to each side of 0° . The "zero point" for rotation about the vertical axis was the point where the reirreflection was collinear with the incident beam. Half the angular separation between the two transmittance minima (i.e.; reflection maxima) to each side of 0° indicated the angular shift of $\lambda_{\max}$.

The transmittance at each angular interval was determined by dividing the ratio of transmitted to reference intensity by the background ratio measured with the sample removed:

$$T(\theta) = (I_t/I_r)_{\text{sample}} / (I_t/I_r)_{\text{no sample}} \quad (6)$$

Signals from the photodiodes were recorded by an oscilloscope, and measurements were made directly from the oscillograms. The maximum signal in the transmitted channel was 1200 mV. For transmitted signals exceeding 40 mV, signal amplitude could be determined to within 1% and the corresponding uncertainty in a ratio of transmitted to reference signals was about 2%. For the background ratio, this uncertainty could be reduced by averaging to within 1%, so, for $T > 40/1200 = 3\%$, the uncertainty in T is about 3%.

In some measurements, the transmittance approached zero. The least quantifiable signal was 0.5 mV and uncertainty in this measurement was 50%. The corresponding transmittance is $T = 0.0005 \pm 0.0003$. This minimum value, neglecting scattering, is a product of $T_s T_c$, where $T_s = 0.9663$ is the calculated transmittance of the bare rear surface of the substrate, and T_c is $1-R$, the transmittance of the coating. With these relationships, the maximum quantifiable reflectance is $R = 0.9995 \pm 0.003$ assuming negligible losses due to scatter.

5. DISCUSSION

The optical response of a high reflectivity (HR) coating made by high temperature PCVD was measured using conventional monochromator scanning and the laser transmittance technique. The coating is composed of 1000 periods of a sinusoidally varying composition with a maximum and minimum GeO_2 doping (in SiO_2) of 10.5 to 2.7 mol%. The design parameters for this coating are $1.064 \mu\text{m}$ peak reflectance at normal incidence, theoretical bandwidth ($\Delta\lambda$) of $\sim 4.23 \text{ nm}$, and Δn of 0.01236.

The $T(\lambda)$ spectrum measured using a conventional spectrometer is depicted in Fig. 5. $\lambda_{\max}$ appears to be longer than λ_{design} by 3 nm (0.3% deviation). Also note that the peak reflectance ($R_{\max}$) is much lower than expected (35% versus $> 99\%$); and $\Delta\lambda$ is much larger than that predicted for an ideal rugate with the design parameters ($\sim 23 \text{ nm}$ versus 4.2 nm). Due to the angular blurring that results with monochromator scanning, it is not unexpected that the measured $\Delta\lambda$ would be larger than the theoretical $\Delta\lambda$.

The measured $T(\theta)$ spectrum and the $T(\theta)$ spectrum calculated for an ideal rugate of the design above are shown in Fig. 6. In our data we observe two transmission minima (reflection maxima) distributed about the point of normal incidence (i.e. 0°). This is simply due to rotating the sample from "left-to-right" through the incident beam (see Fig. 4). Since the design wavelength ($\lambda_{\max}$) is shorter than that of the probe laser, the coating optical response is shifted in θ as described approximately by equation (3). As can be seen, $R_{\max}$ for the PCVD filter is shifted to $\sim \pm 14^\circ$ from normal incidence compared to the model prediction (for this rugate design) of about $\pm 13^\circ$. This increase in θ corresponds to a slightly longer $\lambda_{\max}$ than expected ($1.068 \mu\text{m}$ vs. $1.064 \mu\text{m}$) or $\sim 0.4\%$ deviation. If the PCVD coating was an ideal rugate, this result would indicate simply an increase in the half-wave period of the sinusoidal profile from $\sim 0.183 \mu\text{m}$ to $\sim 0.185 \mu\text{m}$. Note that the shift in $\lambda_{\max}$ agrees well with the $T(\lambda)$ measurement of $\lambda_{\max}$, which suggests that monochromator scanning does measure fairly accurately the wavelength of peak reflectance, but not the reflectance bandwidth, $\Delta\lambda$, or the peak reflectance.

Southwell's coupled-wave approach¹⁰ and the characteristic-matrix model were used to generate the $T(\theta)$ and $T(\lambda)$ spectra of a perfect rugate designed for maximum reflectance at $1.068 \mu\text{m}$. $\Delta\lambda$ determined from the $T(\lambda)$

Figure 5. Comparison of the measured transmittance (using a conventional spectrometer) of a rugate filter deposited on a cylindrical substrate with the predicted performance. The rugate coating consists of 1000 periods of a sinusoidally varying index profile ($\Delta n = 0.01236$). The poor agreement is due to the significant curvature of the substrate over the diameter of the spectrometer probe beam.

Figure 6. Comparison of measured and calculated transmittance vs. angle for a 1000-period rugate coating. The calculated results are from the characteristic matrix treatment.

spectrum appears to be still larger than that of the design calculation by ~ 48% (~ 6.2 nm versus ~ 4.2 nm). One possible, but unlikely explanation, for the increase in $\Delta\lambda$ is that Δn is much larger in the PCVD coating than expected from the design. The characteristic-matrix model was used to determine what Δn would be needed to match the experimental data. This calculation indicated that Δn of 0.017 would be necessary for good agreement with the observed spectrum. This increase in Δn corresponds to 13.4 mol% GeO_2 being deposited at the peak of the period instead of 10.5 mol%, an error of 28%. The thermal-mechanical properties of these multilayer stacks are so sensitive to doping concentration that such an unexpected increase in GeO_2 concentration would likely lead to a very highly stressed coating. This would likely produce either crazing or fracture. Moreover, previous measurements of the composition profiles of PCVD filters have indicated good agreement with the recipe concentrations.^{1,9}

The more feasible explanation and one that we have chosen to pursue first is that there exists a systematic variation in period (QWOT layer thickness) across the coating which would result in a $\Delta\lambda$ increase and a slight shift in λ_{max} from the design without altering R_{max} . This period variation could be due to at least two causes, one or both of which could be operational. First, an ideal rugate is characterized by a sinusoidal variation in refractive index with some constant period (λ) (see Fig. 2). Even though the PCVD process is likely very well-controlled, some statistical variation in layer thickness will occur. Second, because the coatings tested were deposited on tubular substrates and the PCVD process is sensitive to both flow rate (pressure drop) and gas density, it is difficult to maintain the layer thickness as the i.d. of the tube decreases from ~ 17 mm to ~ 15 mm during the course of the deposition run. Model calculations of the effect of systematically varying the period indicated that a 0.7% linear decrease in layer thickness across the full breadth of the coating could approximate the experimental data as shown in Fig. 7. This slight difference is well within that expected for flow and pressure variations during the PCVD coating deposition process.

Figure 7. (a) comparison of measured rugate $T(\theta)$ spectral response with that calculated but assuming an ~ 0.7% systematic variation in the coating period, and (b) schematic drawing of the coating showing the implied period thickness and variation from front to back.

The phase of the sidebands appears to correlate well with the calculated phase, even though $\Delta\lambda$ of the calculated curve is somewhat larger than $\Delta\lambda$ for the PCVD filter (7.0 nm versus 6.2 nm). This residual disagreement could be the result of other imperfections (e.g. refractive index variations) which are not currently included in the model.

6. CONCLUSIONS

A laser-scanning technique is described for analyzing the optical performance of "kilolayer" rugate coatings deposited on curved (tubular) substrates. The coating that was characterized in this study consisted of approximately 1000 periods of a sinusoidally varying refractive index profile produced by doping SiO_2 with GeO_2 during deposition. The laser technique used a small diameter, coherent beam that eliminates the problems caused by substrate curvature. By rotating the sample through the range of laser incidence angles (θ), a transmission vs. θ spectrum was generated, $T(\theta)$.

Both the coupled-wave and characteristic-matrix methods were used to calculate $T(\theta)$ and $T(\lambda)$ spectra for rugate coating structures. Comparison of $T(\theta)$ measurement with the $T(\theta)$ calculated for an ideal rugate provides detailed information on the PCVD rugate coating structure, its optical performance, and the reproducibility of the PCVD process itself. The results from this analysis showed:

1. Coatings made by high temperature PCVD are nearly ideal rugates. Reflectance exceeding 99.9%, peak reflectance wavelength within 0.5% of the design wavelength, and FWHM bandwidth narrower than 10 nm are observed.
2. The PCVD process is very well controlled. A systematic variation of less than 0.7% across the full thickness of the coating can begin to explain the shift in wavelength of peak reflectance and the increase in bandwidth without having to invoke large deviations in refractive index (and therefore, dopant concentration deposited) from the design. Further modeling to explain some residual deviation by permitting some index variation is under way.
3. PCVD "kilolayer" rugate filters can be accurately modeled by both the characteristic matrix model and coupled wave theory. The characteristic matrix approach has the advantage that it permits the effects of period variations, refractive index variations, and profile imperfections on the filter optical performance to be evaluated more precisely.

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REFERENCES

- [1] J.H. Campbell, J.L. Emmett, R.M. Brusasco, and F. Rainer, "Damage Resistant Optical Coatings Prepared Using High Temperature, Plasma Chemical-Vapor-Deposition", in Laser Induced Damage in Optical Materials: 1989, NIST Spec.Pub. 801, p. 426.
- [2] R.R. Austin, R.C. Michaud, A.H. Guenther, J.M. Putnam, and R. Harniman, "Influence of Structural Effects on Laser Damage Thresholds of Discrete and Inhomogeneous Thin Films and Multilayers", Laser Induced Damage in Optical Materials: 1972, NBS Spec. Pub. 372, p. 135.
- [3] M.R. Kozlowski, M.C. Staggs, C.R. Wolfe, and J.H. Campbell, "Large Area Laser Conditioning of Dielectric Thin Film Mirrors", in Laser Induced Damage in Optical Materials: 1989, NIST Spec.Pub. 801, p. 376.

- [4] C.R. Wolfe, M.R. Kozlowski, J.H. Campbell, F. Rainer, A. Morgan, and R. Gonzales, "Laser Conditioning of Optical Thin Films", in Laser Induced Damage in Optical Materials: 1989, NIST Spec. Pub. 801, p. 360.
- [5] D. Milam and R.A. Bradbury, "Laser Damage Threshold for Dielectric Coatings as Determined by Inclusions", *Appl. Phys. Lett.* 23, 654 (1973).
- [6] T.W. Walker, A.H. Guenther, and P. Nielsen, "Pulse Laser-Induced Damage to Thin-Film Optical Coatings-Part I: Experimental" and "Part II: Theory", *IEEE J. Quantum Electron.*, QE-17, 2041 (1981).
- [7] Th. Hunlich, H. Bauch, R. Th. Kersten, V. Paquet, and G.F. Weidmann, "Fiber Preform Fabrication Using Plasma Technology: A Review", *J. Opt. Commun.* 8, 122 (1987).
- [8] H. Bauch and V. Paquet, "Fibers with Pure SiO₂-Core Made by PICVD", *J. Opt. Commun.* 8, 136 (1987).
- [9] R.M. Brusasco, J.A. Britten, C.B. Thorness, M.S. Scrivener, W.G. Unites, J.H. Campbell, and W.L. Johnson, "A High Temperature, Plasma-Assisted Chemical Vapor Deposition System", in Laser Induced Damage in Optical Materials: 1989, LLNL report UCRL-101766, NIST Spec. Pub. 801, p. 443.
- [10] W.H. Southwell, "Spectral Response Calculations of Rugate Filters Using Coupled-Wave Theory", *J. Opt. Soc. Am.* A5, 1558 (1988).
- [11] A. Thelen, "Design of Multilayer Interference Filters", in *Physics of Thin Films*, G. Hass and R.E. Thun, eds. (Academic Press, New York, 1964), 5, p. 47-85.
- [12] L. Edmonds, P. Baumeister, M.E. Krisl, and N. Boling, "Spectral Characteristics of A Narrowband Rejection Filter", *Appl. Opt.* 29, 3203 (1990).
- [13] H.A. Macleod, *Thin-Film Optical Filters*, 2nd Ed., McGraw-Hill Publishing Co., New York, 1986, p. 21-29, 314-356.

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