Gradient index film fabrication using optical control techniques

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ABSTRACT

The wide range of optical thin film applications utilizing gradient index coatings has prompted the development of advanced optical control techniques. These include ellipsometric and photometric instruments capable of in-situ measurement of optical performance as the optical structure is being deposited. This paper discusses design sensitivity analysis and instrument configuration for development of a control strategy.

The ability to measure optical thickness, refractive index and mechanical thickness is a function of several instrument parameters including wavelength, number of wavelengths, angle of incidence, and complexity of measurement surface. The most critical control data in the fabrication of a particular rugate design, and the instrument parameters and techniques employed and how they affect the control strategy is presented in this discussion.

1. INTRODUCTION

The deposition of high performance optical coating structures requires a process and control system capable of high precision. The design under consideration has a set of performance criteria which, through a tolerance analysis, yields an error budget for the control system. Gradient index designs such as rugate filters and anti-reflection films require an extra dimension of control to the system. Refractive index is a variable parameter and needs to be controlled directly or indirectly.

At Hughes Danbury Optical Systems, (HDOS) we have been using optical methods to monitor and control the deposition of various types of gradient index designs.[1-5] Specifically, photometry and ellipsometry are employed in a control system as a primary element. Optical thickness is utilized in conjunction with mechanical thickness deposition rate to produce films of mixed materials. The composite film is obtained by depositing two pure materials and varying the relative rate between them. Relative rate determines mixing ratio which, in turn, determines refractive index.

In this paper we go through the steps of examining design sensitivities to come up with a control system strategy, illustrate the modeled response, and give examples of system output from the ellipsometer.

2. DESIGN EXAMPLE

The design example which we model is a narrowband reflective filter of the type used in a Raman system. In a Raman experiment, a laser excites a material producing a response signal frequency shifted from the laser frequency. To detect this signal the laser signal must be separated from the Raman signal. An inexpensive way of doing this is with a thin film optical filter of some type. A narrowband reflective filter at the laser line rejects the laser and passes the band of adjacent frequencies containing the Raman signal. The closer to the laser line the system can detect, the lower the energy of the Raman signal that can be probed. By reflecting the laser at the entrance aperture (and reducing scatter into the monochrometer) the better the discrimination obtained at the detector.

A design which achieves the desired response is a narrowband rugate. The refractive index of a fairly thick film is modulated in a sinusoidal form with the frequency of oscillation chosen to give a reflective peak at the laser frequency. A hypothetical example of one such design for 1.0 μm is shown in Fig. 1. This example shows the rugate response of a 43.6-μm thick film, average index of 1.72 immersed in a medium of 1.72, with an index excursion of amplitude 0.03. The modeling of the design in an immersed medium allows for emphasis of the rugate characteristics and not the matching film structure. The sideband oscillations of the design can be averaged to obtain an integrated throughput in the 1.00 to 1.03 μm region. This is the low frequency Raman region. The filter can also be tilt tuned to optimize the rejection ratio for a particular energy. The width of the rejection region is more than adequate to allow for several degrees of tuning which can give over three decades of signal rejection for energies corresponding to 1.005 μm on out.

The manufacturing sensitivities are obtained by using a model which incorporates the errors in the fabrication process. Examples of these are index errors, optical thickness errors, drift in average index and random fluctuations.

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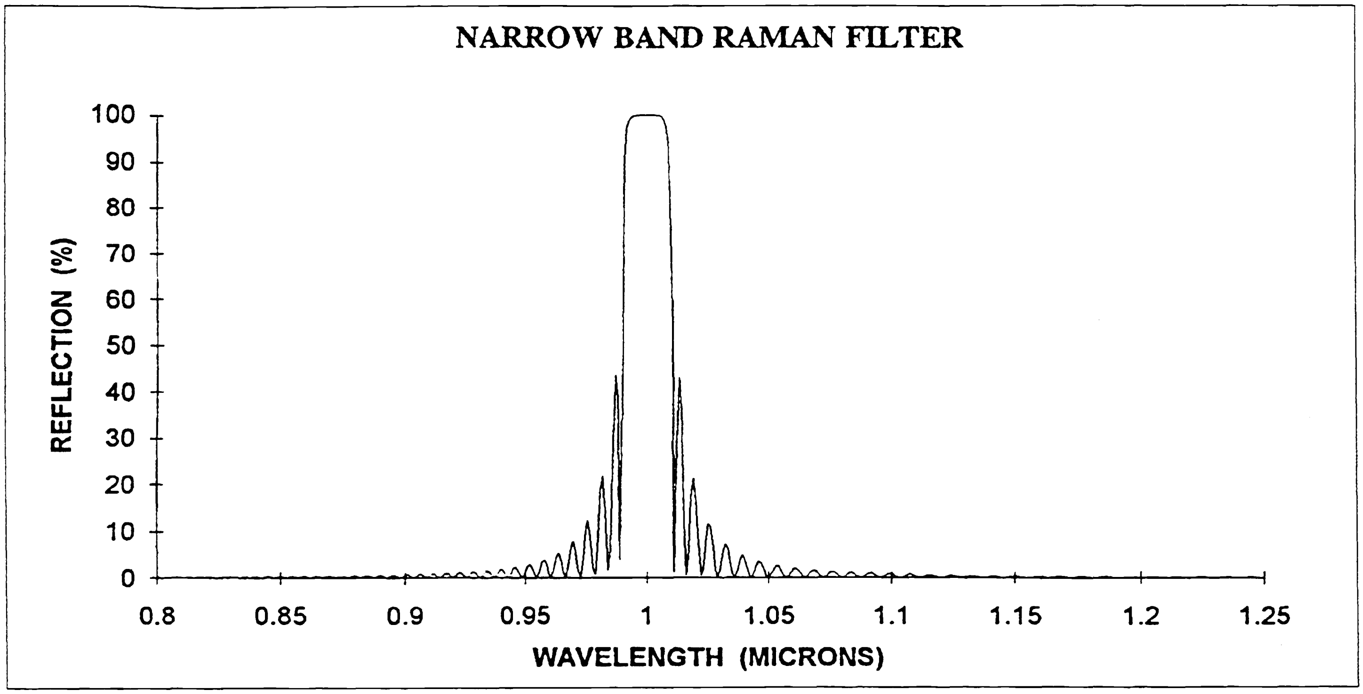


Fig. 1. Reflection spectra of a narrowband rugate filter. The design parameters are: $n_{ave} = 1.72$, $n_{peak} = 0.03$, 150 cycles, immersed in a medium of 1.72 index. Wavelength has been arbitrarily chosen to be 1.0 µm. The performance criteria is derived for a Raman spectrometer application.

Characterization of the control system and error budgeting quantifies the magnitude of these errors. As examples of this, we examine index errors and optical thickness errors. These reflect two contributions to the error budget. Statistical techniques are employed to yield the effect on design performance effect.

The performance can be modeled by dividing the structure into a series of very thin homogeneous layers with a constant index. This model provides an accurate representation of the inhomogeneous structure. The control system's inability to modulate the source rate accurately shows up as an index fluctuation. A perturbed design is obtained by changing each film index by a random amount. The magnitude of the perturbation is bounded by the specified standard deviation. Mechanical thickness is adjusted so as to keep the cycle optical thickness the same as the nominal design. A second perturbation that can be modeled are optical thickness errors. The ability of the control system to deposit an accurate optical half wave of an inhomogeneous film determines this error. Direct optical thickness measurement is necessary. Errors are modeled by statistically perturbing the cycle optical thickness while keeping the index variation nominal. This amounts to squeezing or expanding each cycle in a random manner.

Figure 2 shows the refractive index profiles of the nominal design along with the index perturbed and optical thickness perturbed designs. Also shown is an expanded version of the first five cycles. The refractive index variations are random fluctuations of the index variation about the average index. The optical thickness perturbations shown in Fig. 2(c) are not as obvious to the eye. However, the effect on spectral performance is dramatic. Figure 3 shows the spectral response of the three designs full scale and in an expanded version. The index perturbed design performs almost identically to the nominal in the spectral region under investigation, contrary to what the eye would suggest. The reason becomes obvious when we realize that the rugate response, when thought of in the Fourier sense, is dependent upon the Fourier decomposition of the refractive index profile. The index perturbed profile still has a very accurate representation of the nominal index profile at the frequency corresponding to the fundamental frequency of the Fourier expansion. The spectral response is "immune" to the noise represented by the index fluctuations. However, in the higher frequency regions (shorter wavelengths) this design can deviate substantially from the nominal. The response of the optical thickness perturbed design is dramatically effected by very small optical thickness errors. In analogy to the index variation discussion here, the Fourier decomposition results in a major smearing of the response throughout the region of interest.

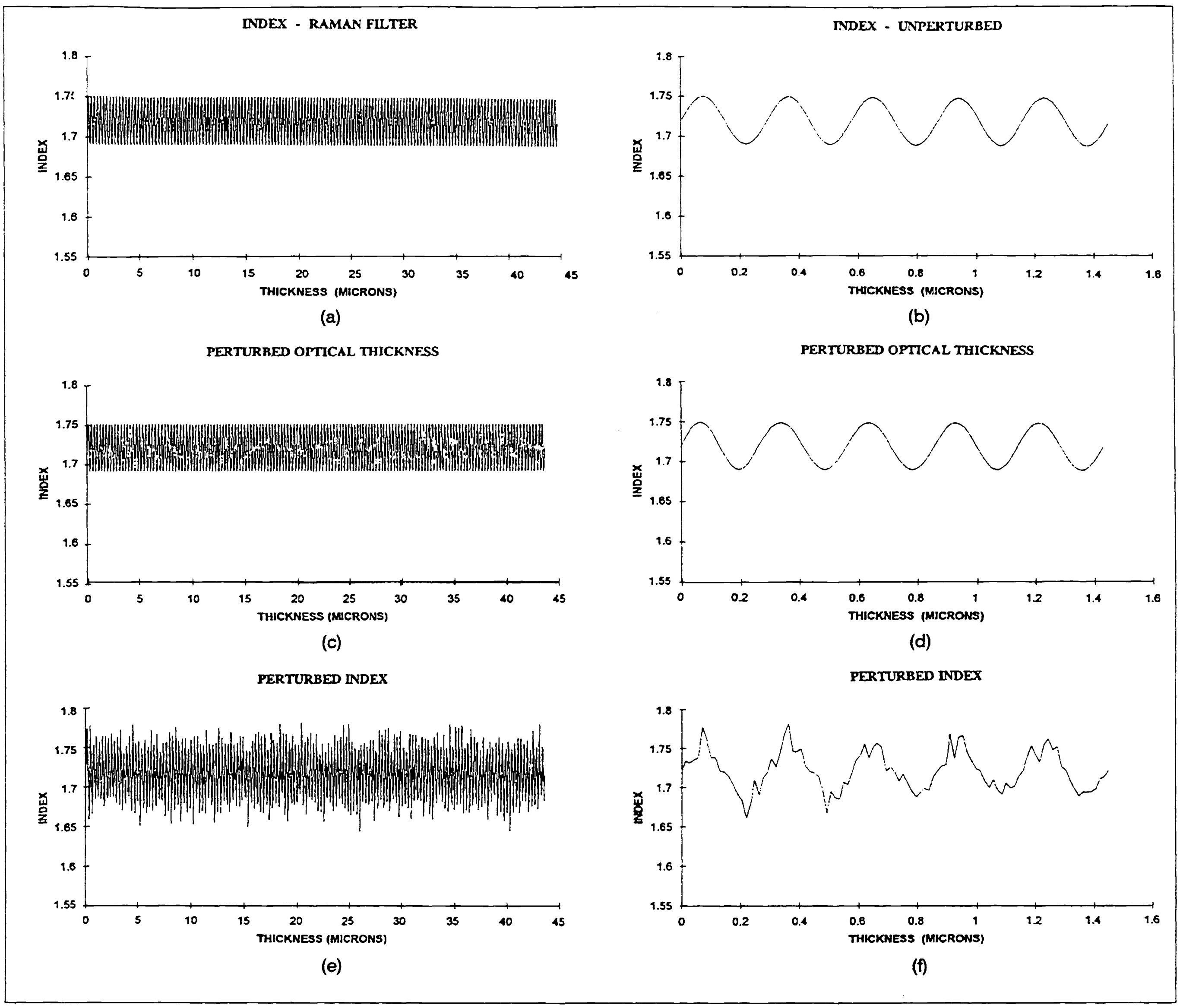


Fig. 2. Refractive index profile for the filter shown in Fig. 1. (a) and (b) are the nominal design, (c-f) are perturbed designs used in a sensitivity analysis.

e manufacturing sensitivity analysis of a design like the Raman filter is developed by generating many designs with different perturbations and extracting the relevant performance criteria. For example the degradation of the contrast ratio as the errors in optical thickness increase can be looked at. The contrast ratio is defined as the ratio of laser line rejection to the transmission in the Raman region. In a non-tuning mode this is an integrated average. For tilt tuning, discrete wavelengths can be compared (max contrast). Table 1 summarizes the results. Performance of filters with errors above 2.5% is degraded to where most are useless. A yield analysis would be the next step in a manufacturability assessment.

3. PROCESS CONTROL BY OPTICAL MEANS

The results of the sensitivity analysis are used in the control process strategy. Optical thickness control on a cycle to cycle basis is particularly critical. In this section we model the expected response of a photometer and ellipsometer used to control the deposition of the Raman filter.

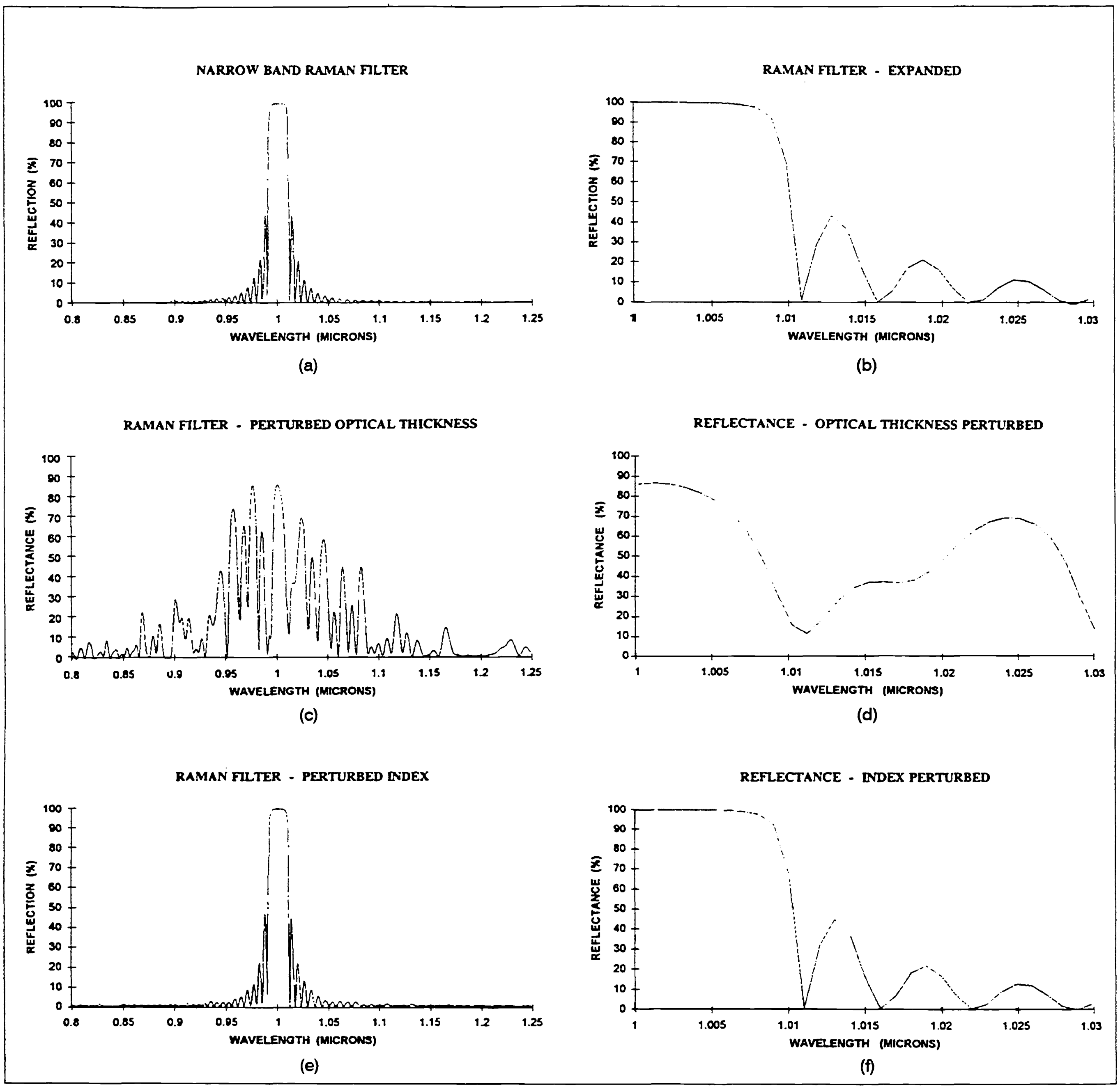


Fig. 3. Reflection spectra of the three designs shown in Fig. 2.

Table 1. Design Performance Changes As Errors Increase

Contrast	Nominal	2.5%	5.0%	10.0%
Integrated	5.27	2.90	1.45	1.09
Average Maximum	3200	26.2	–	–

There are several instrument parameters open to us for optimizing the precision of the control system. Among these are angle of incidence and wavelength. Angle of incidence is chosen to maximize sensitivity of the signal to the parameter under control. Wavelength is chosen for response characteristic. Figures 4 and 5 show the phometric and ellipsometric response during the first 20 cycles of the deposition. The data represents the response on-band, that is at the center of the rejection band. The design parameters (substrate index of 1.72 and average index of 1.72) yield large contrast for an incidence angle of 59.8 degrees. Figure 4 shows Rp and Rs for an index excursion of 0.03 and 0.06. The monitor response yields a large amount of information on several time scales. The rate of increase in peak Rs and average Rp is directly related to the peak index excursion. The lack of oscillation in the Rp curve is very sensitive to average index and small deviations from 1.72 quickly show up. The magnitude of the oscillation of Rs is independent of the index excursion to first order. The turning points in Rs correspond to optical thickness points separated by one-half cycle. This can be used as a set point trigger for the index cycle.

The ellipsometric response in Fig. 5 contains similar information but in a different form. The structure in both delta and psi show peaks and valleys as a function of thickness. The repetitive nature of this structure at well defined points in the refractive index cycle is used for control system queing of the rate controllers. Also note the cyclic nature of the delta signal after the initial several cycles. This is a very important aspect of phase monitoring. On-band, once the reflectivity is built up to the point where Rp and Rs are determined primarily by the film structure and not the substrate the phase difference becomes a cyclic function of optical thickness.[6] The amplitude is primarily a function of incidence angle and average index and only depends on the form of the refractive index variation in second order. This gives us a precise way of determining optical thickness irrespective of what the index profile looks like.

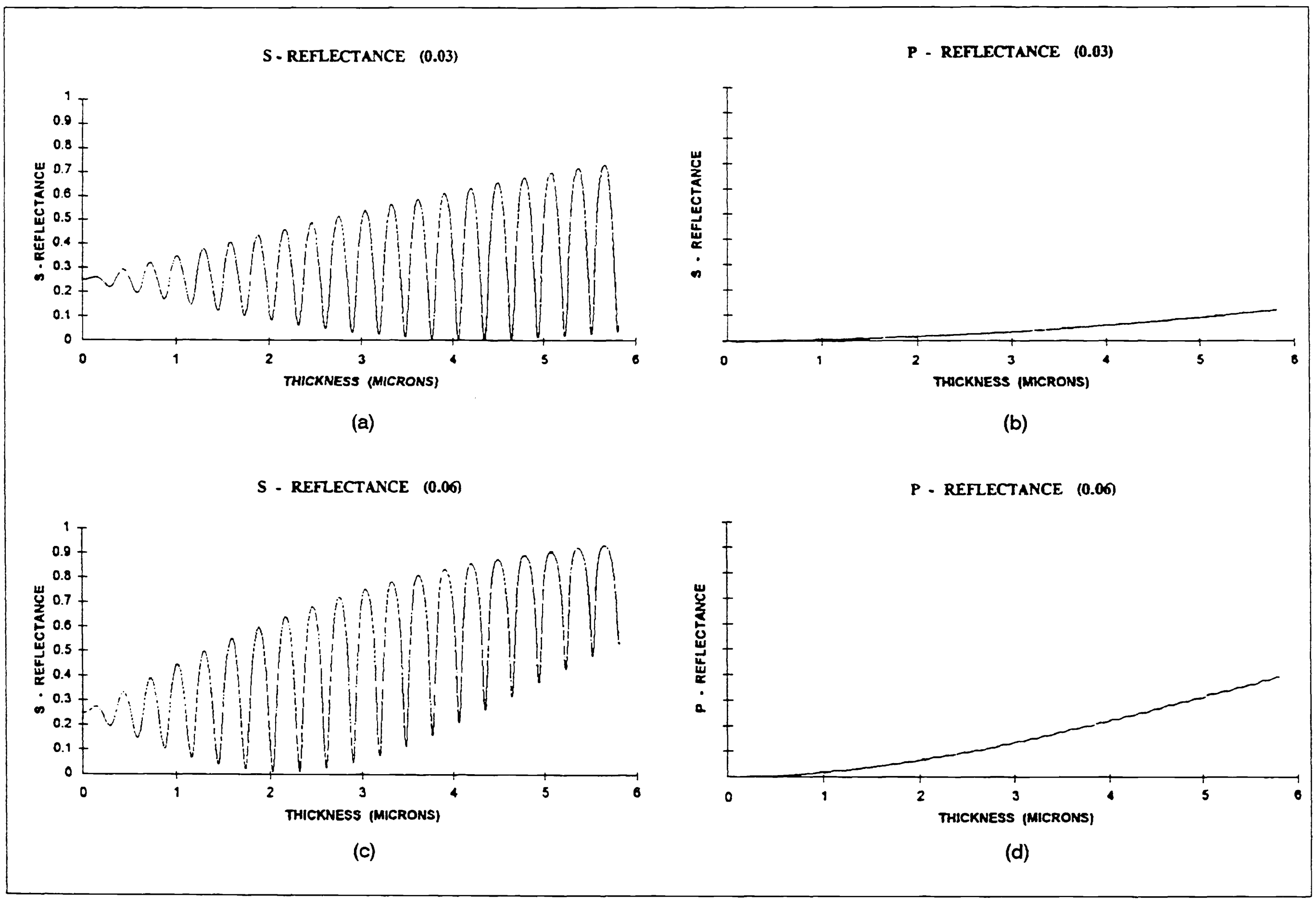


Fig. 4. Reflection signal R_s and R_p on band for the first 20 cycles of the deposition process. On-band refers to the equivalent wavelength of the peak wavelength at an incidence angle of 59.8 degrees. Index excursions of 0.03 and 0.06 are shown.

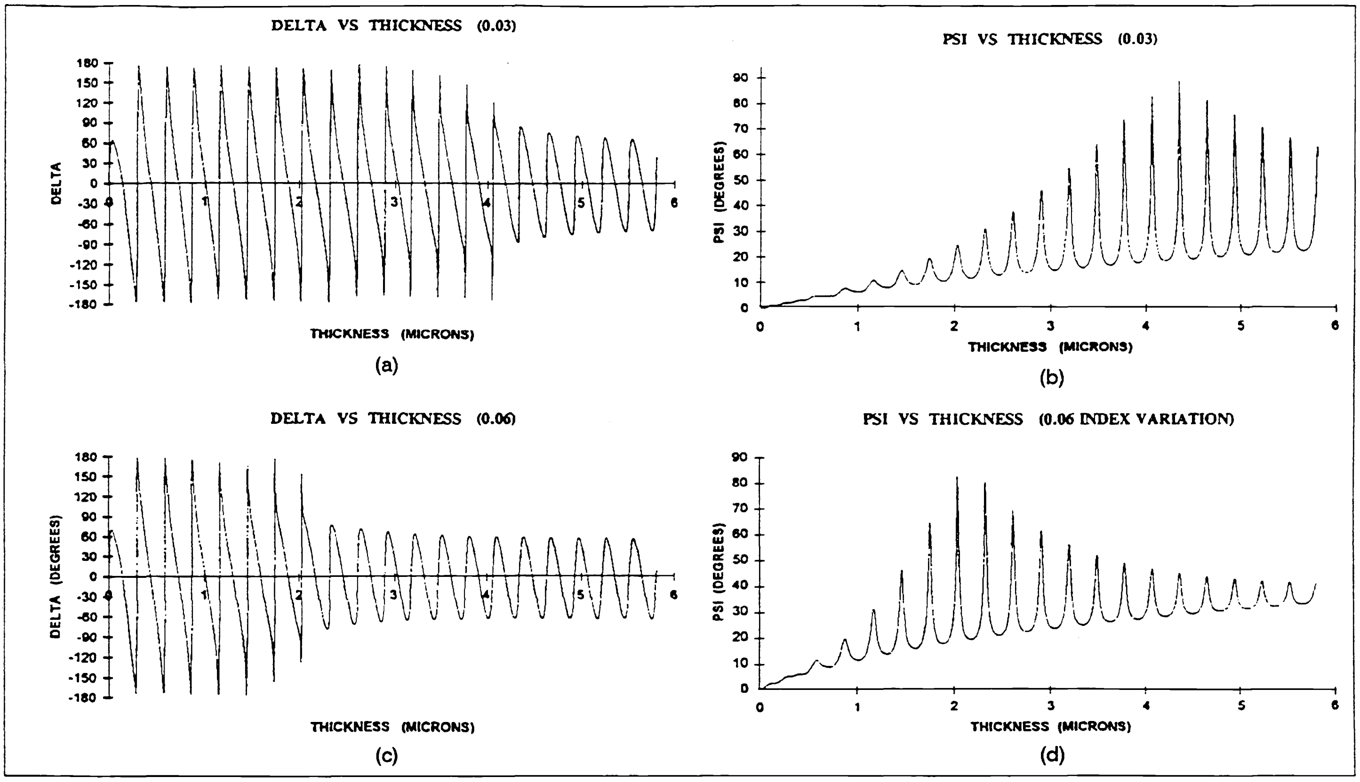


Fig. 5. Ellipsometric parameters Δ and Ψ on band for the first 20 cycles of the deposition process. Index excursions of 0.03 and 0.06 are shown.

3.1 Out-of-band response

The out-of-band response (or slightly off-band) contains both confirmatory and complementary information which can be used by the control system. For the same design example the photometric and ellipsometric data are shown in Fig. 6. With a broadband system the wavelengths can be arbitrarily chosen. The amplitude of the response is again a function of index excursion but instead of having major trends superimposed it maintains the initial character. This reflects the incidence angle, average index and most importantly the relative wavelength position. Figure 6 corresponds to a relative wavelength of 0.82. The modulation of the response is due to a beating of the design frequency and the probe frequency and, based on knowledge of the relative frequencies, yields control information.

4. ELLIPSOMETRIC DATA

An automatic ellipsometer has been used to control the deposition of various types of rugate and gradient index structures. Optical thickness control using index cycle phasing at turning points is the basic technique. For shorter timeframes optical thickness rate information can be obtained. Examples are discussed in the following paragraphs.

If monitoring directly on an optical part is necessary or desired, the type of data previously described for the Raman filter example is obtained. If the monitoring is on a remote sample that can be arbitrarily chosen then interesting responses can be obtained. For optical thickness control "on-band" monitoring of a high reflectance substrate delta becomes a simple cyclic function of optical thickness. (See Fig. 5 after several cycles). This form is achieved immediately on a high reflective film or substrate. Fig. 7 shows the theoretical response of a single frequency rugate being formed on an aluminum coated substrate. Figure 7(a) corresponds to the theoretical prediction. Figure 7(b) is 7(a) replotted as absolute value to take into account the inability of the instrument to discern the difference in plus or minus delta. Figure 7(c) is the output of the ellipsometer corresponding to the above. Four reset points per cycle are available.

Optical thickness rate information is available by translating the delta-time experimental data to delta-thickness data. This requires a conversion factor. For an arbitrary set of instrument and design parameters the conversion factor is a

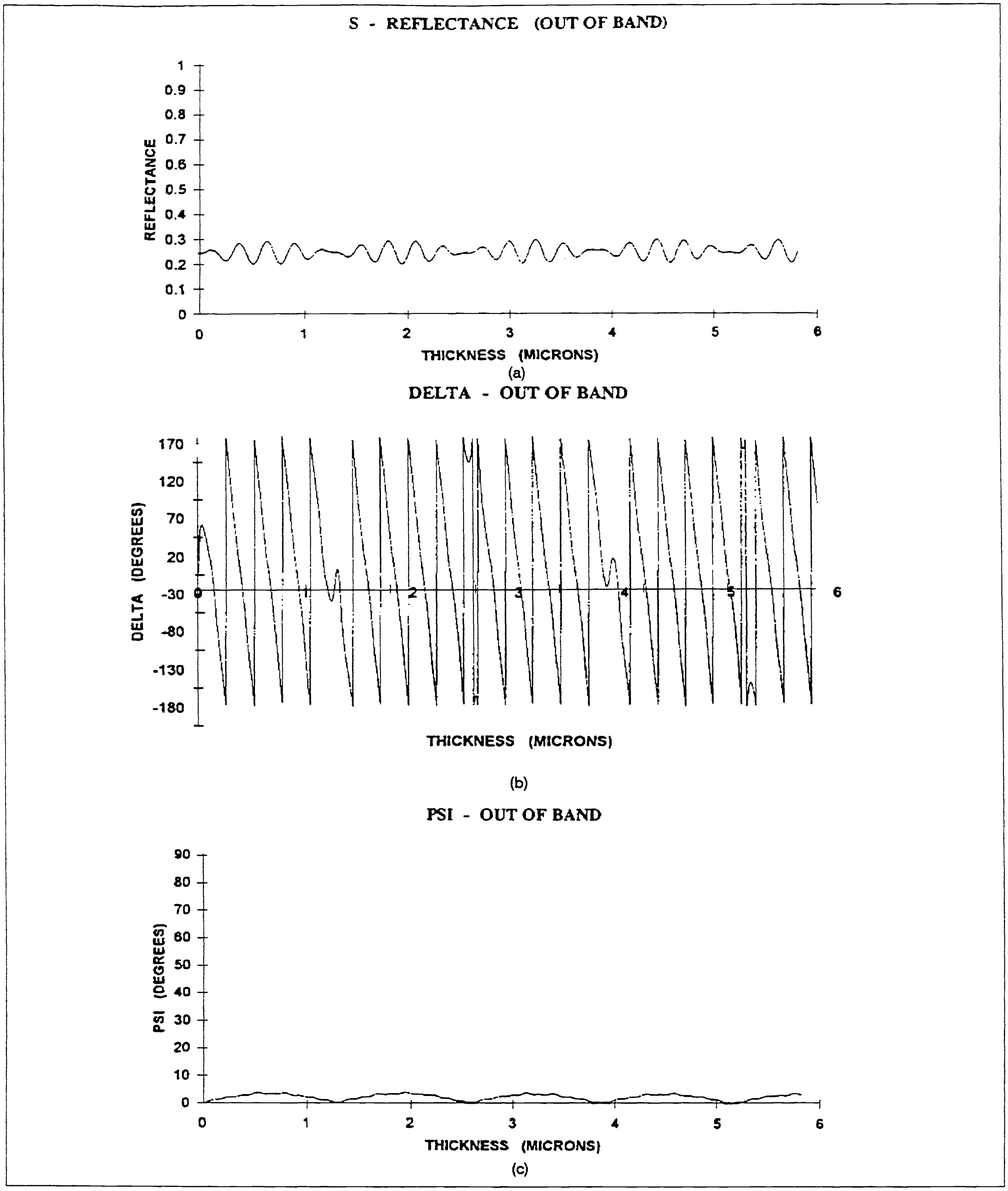


Fig. 6. Off-band response of R_S, Δ and Ψ at a wavelength arbitrarily chosen at 0.82 peak wavelength. R_P is not shown because of its small value is an absolute sense. The modulation of the parameter is a function of the ratio of probe wavelength to peak wavelength.

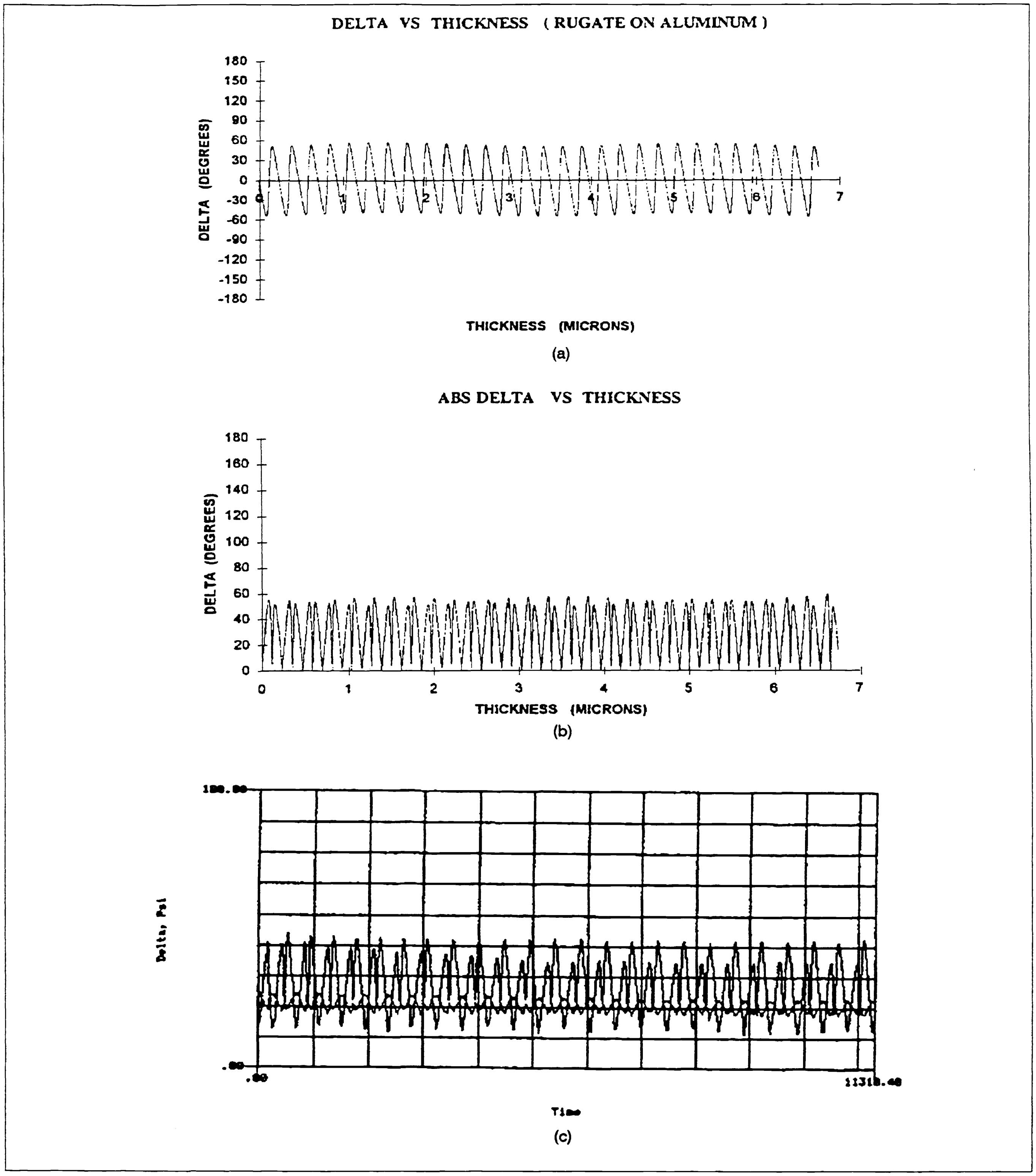
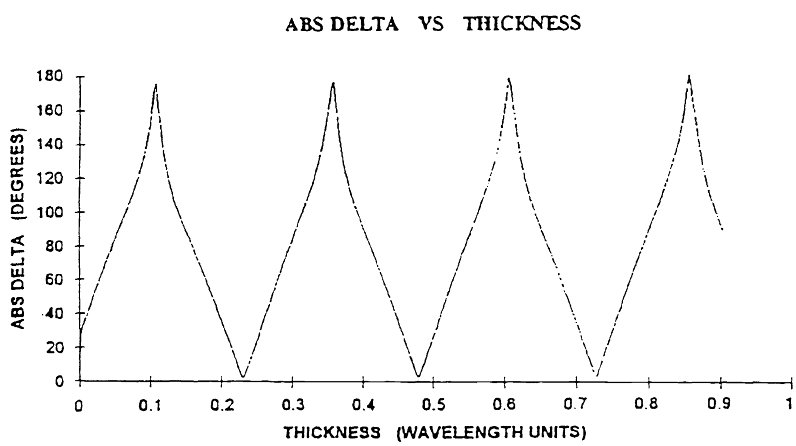


Fig. 7. Theoretical and experimental control signal, Δ for a single frequency rugate being monitored on an aluminum film. The underlying high reflectance of the aluminum film makes the dependence of Δ on thickness a simple functional form. The ellipsometer outputs the absolute value of Δ hence the form of (b). In (c) is an output for the first 26 cycles of a narrowband filter deposition. The functional form yields four turning points per cycle hence four rate ques. Also shown in (c) as an oscillation about 45 degrees is the Ψ-signal.

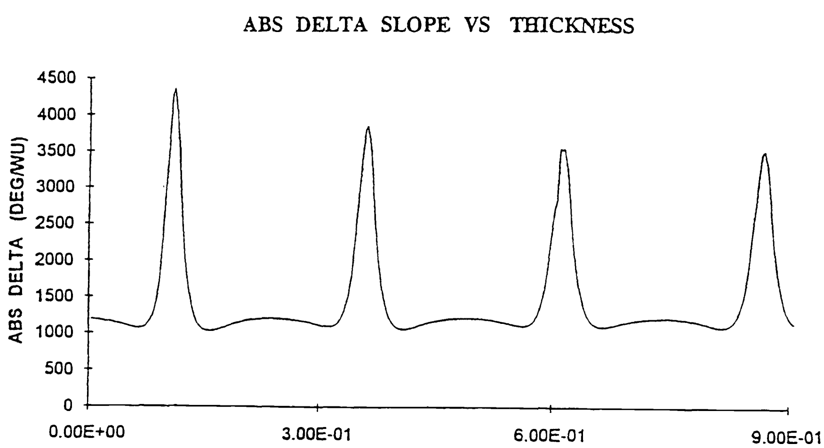
function of thickness and can be quite complicated. By the right choice of parameters, the variability can be minimized and the conversion factor made almost constant over extended thickness ranges. This amounts to linearizing the delta-thickness relationship.

In Fig. 8(a) the absolute value of delta is plotted as a function of thickness for a film of index 2.30 being deposited on germanium. The optical response is representative of a TiO2 film in the argon laser wavelength region. Over much of the cycle the response can be linearized for a first order result. The thickness scale can be used over several of the argon wavelengths by renormalizing to the laser wavelength being used. The dispersion of the film index and substrate index need to be corrected to achieve accurate quantitative results. However, the character of the curves do not change much. The slope of Fig. 8(a) is displayed in 8(b). Over a large portion of the cycle the sensitivity factor is relatively constant. The sensitivity factors derived from this curve can be used to translate delta rate into thickness rate and hence, for a mixed film, index variation.

Experimental data for the Fig. 8 conditions are shown in Figs. 9 and 10. A run was performed depositing TiO2 at varying deposition rates onto germanium. Figure 9(a), 9(b), and 9(c) show crystal rate, delta response and delta rate respectively. The crystal sensor was located adjacent to the monitor substrate. Crystal data was noisy but no attempt was made to smooth. The character of the delta data is as expected theoretically. There are instrument artifacts in the data. In particular, the configuration being used has minimum precision for values of delta near 0 and 180 degrees. To minimize noise in.



(a)



(b)

Fig. 8. Theoretical response signal and sensitivity parameter for a homogeneous film being deposited on germanium. The index of the film is 2.3. The sensitivity parameter is a function of thickness.

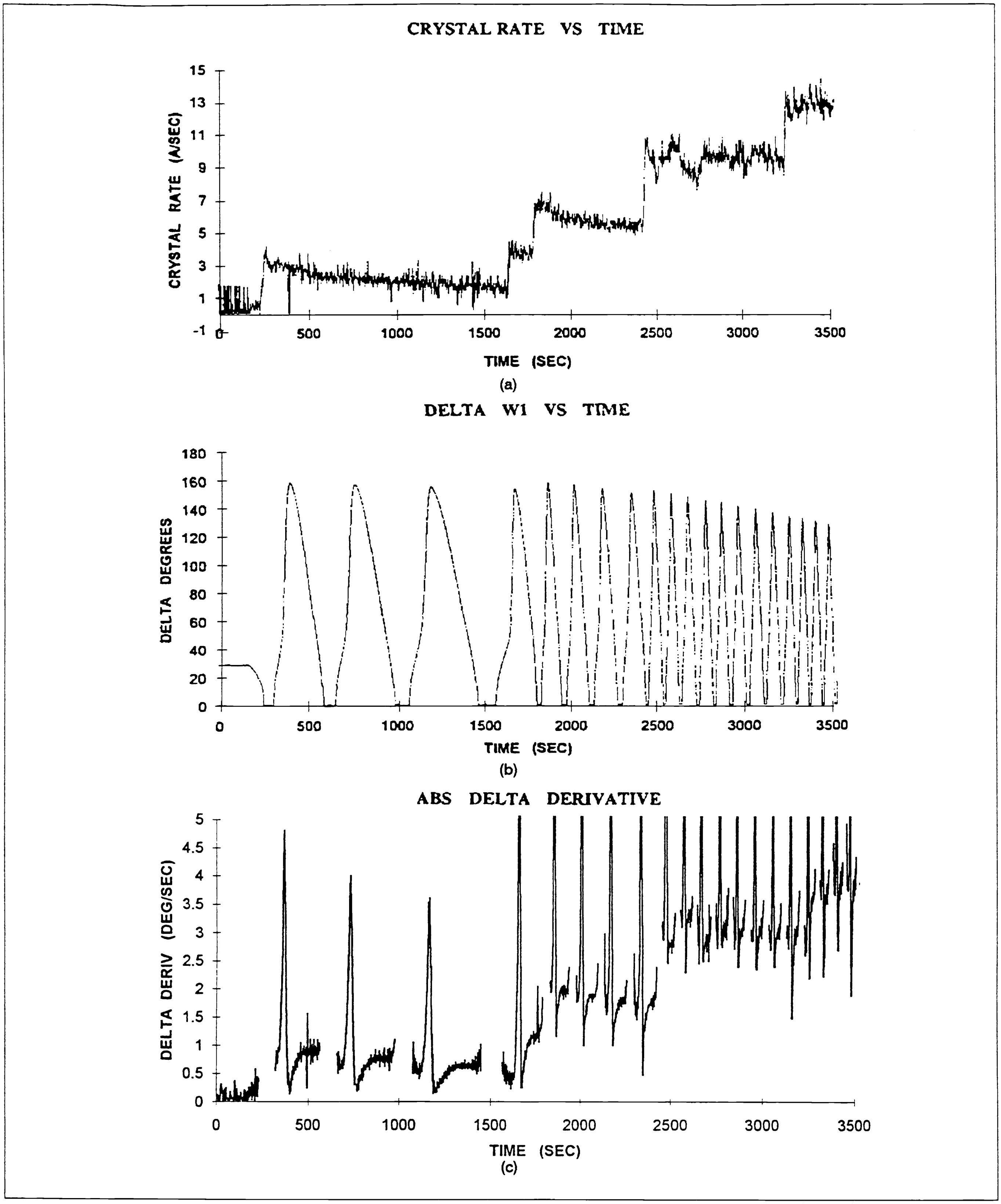


Fig. 9. Comparison of (a) measured crystal rate and that calculated, (c), using the Δ response shown in (b). The Δ derivative data does not have the sensitivity factor convolved into it. That is necessary to make quantitative comparisons.

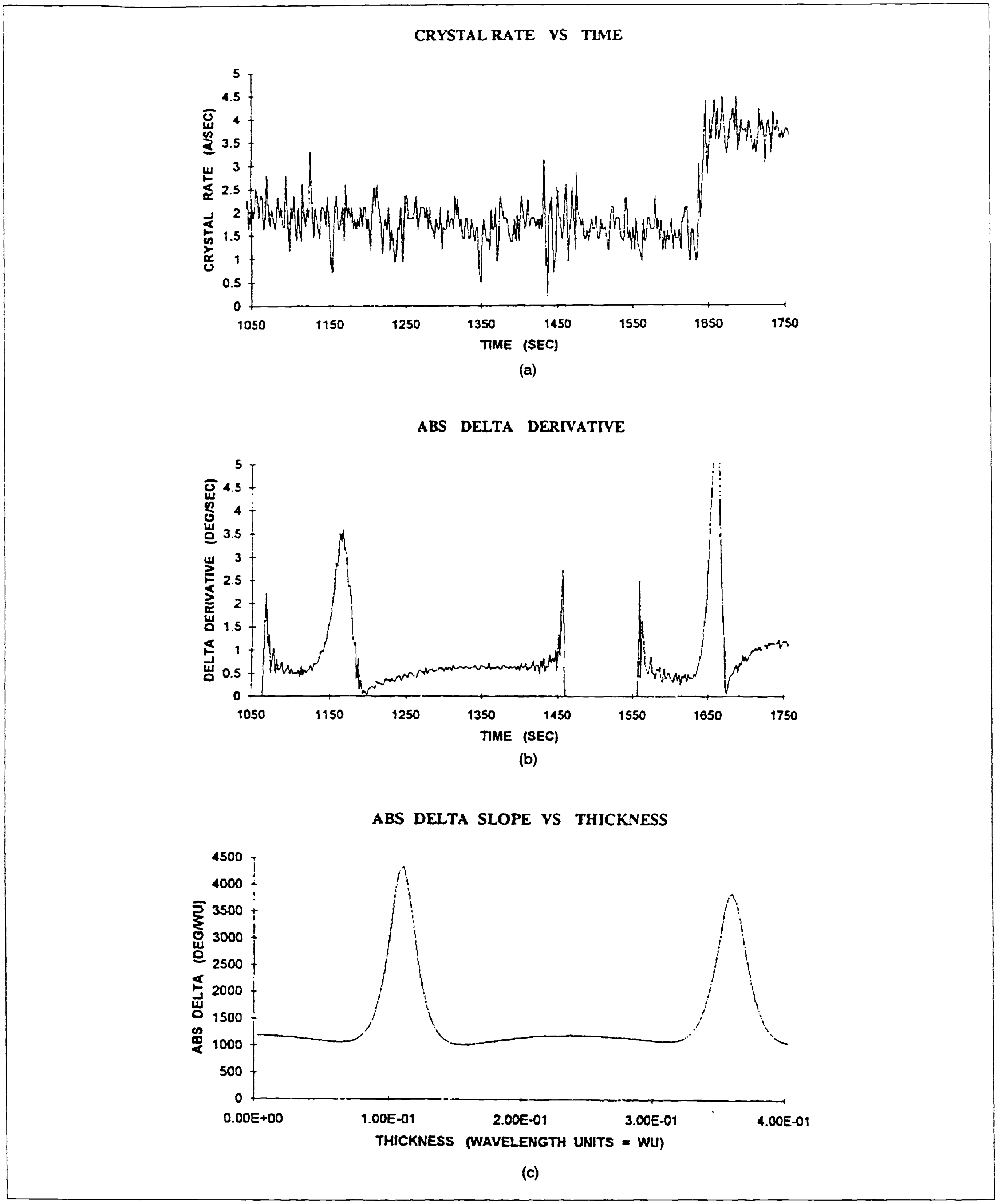


Fig. 10. Expanded version of (a) crystal data, (b) delta rate data, and (c) theoretical sensitivity factor.

the data, the software traps values of delta near 0 and sets them equal to zero. There are also fixed calibration offsets in delta which are determined by a two zone averaging. The calibration offset has not been applied to this data. The effect of this is to translate the delta curve upward on the ordinate axis. The artificial zero values manifest themselves as gaps in the rate curve. The delta rate data shown in Fig. 9(c) qualitatively represents the crystal rate data. The dynamic range is well captured and perturbations show up

The delta rate is better seen on an expanded scale. One time segment is shown in Fig. 10. Crystal rate, experimental delta rate and theoretical delta thickness rate are shown here. Several features are evident. The eye should extrapolate in the gap region and ignore the perturbations around it. The general shape agrees well otherwise. The crystal rate jump at 1650 seconds is easily discerned in the delta rate level at 1700 to 1750 seconds. The ratio of delta rate at 1750 to delta rate at 1350 is in good agreement with the crystal rate ratio. Convolving the inverse of the sensitivity factor curve in Fig. 9(c) flattens the delta rate curve over most of the cycle.

The change in character of the delta rate data when a constant index film is changed to a cyclic index film is of primary interest. We initially control individual source rates to obtain the desired mix ratio at the composite film. What we desire out of the delta data is the composite optical thickness rate and variability due to index change. The delta rate curve of an index perturbed film is shown in Fig. 11. Differences attributable to rate differences can be inverted to obtain index variations.

Several wavelengths can be used in a complementary fashion. The instrument precision is dynamic and the delta rate data not reliable over regions where the sensitivity factor is changing rapidly. The use of several wavelengths allows redundancy. The rate data from wavelengths corresponding to regions of smooth sensitivity factor can be given more weight than wavelengths corresponding to rapidly changing factor.

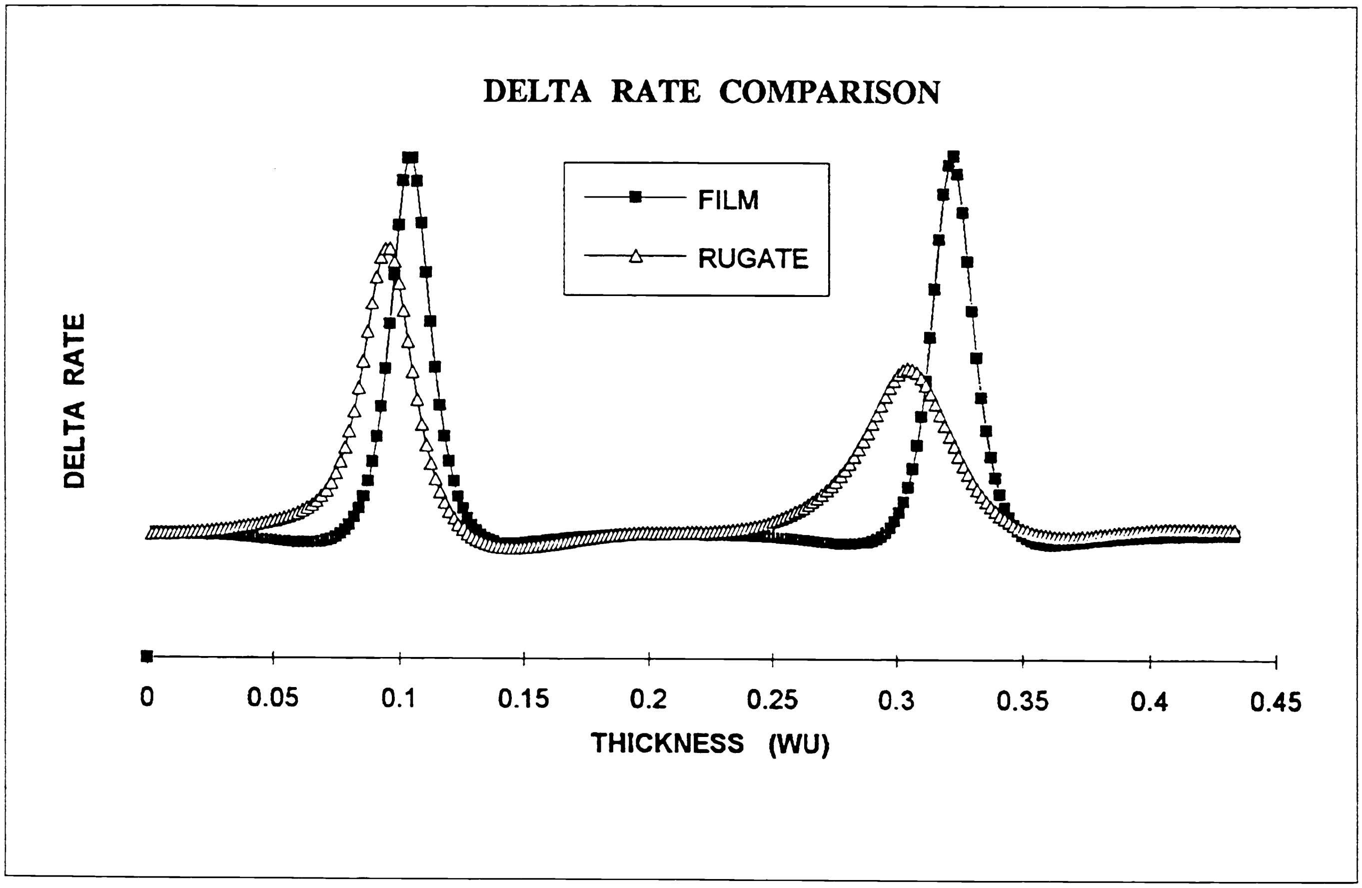


Fig. 11. Comparison of delta rate for homogeneous and rugate film.

5. CONCLUSION

The fabrication of rugate structures requires monitoring and control techniques specific to the design being fabricated. Having flexibility in the choice of instrument parameters and using complementary data can enhance the control precision. We have shown an example of a sensitivity analysis for a simple design to highlight the need to identify the most sensitive parameters to be controlled. Instrument configuration and monitoring technique is used to generate ellipsometric data in a simple form to be used for optical thickness and optical thickness rate.

6. ACKNOWLEDGMENT

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