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TITLE: **CAVITY RINGDOWN MEASUREMENTS OF HIGH-REFLECTION MIRRORS AT 1.06μm**

AUTHOR(S): L. John Jolin, Virgil R. Sanders, Thomas P. Turner

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Los Alamos National Laboratory
Los Alamos, New Mexico 87545

Cavity Ringdown Measurements of High-Reflection Mirrors at 1.06 μm

L. John Jolin, Virgil R. Sanders, Thomas P. Turner
Chemical and Laser Sciences Division
Los Alamos National Laboratory
Los Alamos, NM 87545

A 1064-nm-cavity-ringdown reflectometer was used to study reflectances of a variety of high reflectance dielectric coatings and silver mirrors. Reflectances of the dielectric coatings were measured at near-normal angle of incidence. The multilayer dielectric high reflectors included ZrO_2, HfO_2, SiN_4, TiO_2 and Al_2O_3, which were used in combination with SiO_2 in conventional quarter-wave designs. Reflectors from more than a dozen vendors were surveyed in this effort. Metallic reflectors investigated were silver and silver protected with a thin (10 Å) alumina overcoat. These reflectors were tested at both normal incidence and at high (grazing) angles.

The results of these studies show that, although high reflectances ($R > 0.9990$) can be achieved for 1064-nm-multilayer dielectrics, the majority are not of this caliber. Reflectances for dielectric designs ranged from 0.96 to >0.9990. The silver mirrors exhibited predictable behavior with reflectances of 0.992 at near-normal angle.

Key words: multilayer dielectrics; Nd:YAG; high reflector; reflectance; reflectometer; silver coatings; 1064 nm.

1. Introduction

Reflectance is a key parameter in understanding fundamental relationships between mirror characteristics and laser damage susceptibility. An accurate, high precision reflectance measurement capable of measuring reflectances that are near unity is essential. A cavity-ringdown reflectometer utilizing a 1.06-μm laser source has been developed for this purpose. Adapted for our use is the ringdown device thoroughly described by Anderson et al. [1] in 1984.

2. Experimental

The source for this reflectometer is a repetitively pulsed Nd:YAG laser operating at the fundamental wavelength of 1.06 μm. The repetition rate is variable but is set at 3,000 pps for these measurements to allow for long decay times. The laser temporal profile is near Gaussian with a time duration of 150 ns (FWHM). The average power is approximately 7 W (2.3 mJ per pulse).

Dielectric thin film polarizers are used, external to the laser cavity, to produce highly planar polarized light. At the test specimen the ratio of S polarized light (E vector perpendicular to incident plane) to P polarized light (E vector parallel to the incident plane) is greater than 300 to 1.

The reflectometer cavity is a folded configuration consisting of three mirrors – two end mirrors and the test sample (figure 1). The end mirrors are multilayer-dielectric coatings deposited on the concave side of a plano/concave fused silica substrate with a radius of 4.5 m. The test sample is flat. The cavity is folded about the test specimen at an angle of 2 degrees. Both end mirrors are equidistant from the test specimen creating a round-trip cavity length of 11.47 m. To accommodate insertion of the laser beam into the ringdown cavity the entrance end mirror has slightly lower reflectance than the second end mirror. Because the entrance mirror is a high reflector, a little less than 1% of the available laser light is actually coupled into the cavity. The remainder is reflected, dispersed and absorbed in a beam dump. In order to minimize atmospheric effects the entire reflectometer is encased in a Plexiglas housing. Figure 2 is a photograph of the ringdown device and laser source.

The cavity-intensity decay (ringdown) is monitored by measuring the leakage through the second end mirror. A commercially available InGaAs detector having a 2–mm diameter is used. A short focal length lens, in close proximity to the exit mirror, focuses the light to a small spot size on the detector. This conveniently corrects for minor cavity misalignments by resteering the misdirected light back to the detector. Accurate alignment is quite easily accomplished because misalignments are recognized by simple sinusoidal oscillations superimposed on the decaying signal as the light scans on and off the detector during subsequent bounces.

A low-power beam expander is used between the laser and the ringdown cavity to increase the laser-beam spot size on the test sample. The spot size on the test sample is approximately 3–mm diameter for near-normal angle testing.

Non-normal angle testing is accomplished by unfolding the cavity and increasing the size of the test specimen to 4–in. diameter to accommodate the elongated spot. As mentioned previously, the laser light at the test sample is S polarized. A shorter cavity is used for these measurements but is accounted for in the calculations.

Figure 3 shows the digital-storage oscilloscope display of a cavity-intensity decay. The quality of the ringdown and the decay constant is determined manually by using the inherent capabilities of the oscilloscope.

As described by Anderson, et al., the reflectance product of a ringdown cavity is,

$$R_p = \left(1 - \frac{1}{2\frac{C}{L}\tau_c}\right)^2 \qquad (1)$$

where τ_c is the cavity intensity decay time constant, L is the cavity round trip optical path length, and C is the speed of light. For the folded ringdown cavity represented schematically in figure 1 the reflectance product is,

$$R_p = R_1 R_u^2 R_3 \quad . \tag{2}$$

Thus,

$$R_u = (R_p/R_1 R_3)^{1/2} \quad , \tag{3}$$

where R_1 is the reflectance of one end mirror, R_3 is the reflectance of the second end mirror, and R_u is the reflectance of the unknown. Note that in a folded cavity there are two bounces on R_u for each round trip, accounting for R^2 in eq (2).

3. Calibration

The reflectance values for the two end mirrors are determined by using a two-mirror ringdown cavity. First the two end mirrors are used as the cavity mirrors. Next, each of the two curved mirrors is used in a cavity with a high-reflector flat as the second mirror. A reflectance product is measured for each of the three configurations. Given these values, the reflectance of any or all of the reflectors can be calculated. Finally, all three mirrors are placed in the folded cavity to measure the combined reflectance product. This confirms the earlier two-mirror cavity results. The flat mirror used in this set of experiments is used from that point on as the calibration mirror. When used as the third mirror of the reflectometer, a repeatable decay constant is expected. Shorter decays usually indicate cleaning is necessary, however, they (decays) could also indicate an increase in airborne particulates, moisture, scratched cavity mirrors, etc.

4. Test Samples

Multilayer-dielectric high reflectors for this effort were secured from more than a dozen vendors. In most cases the vendor was allowed to select coating materials and design, however, in a few cases the material was specified. In all cases the minimum reflectance specification was greater than or equal to 0.9970 at 1.06 µm. As a control, all of the substrates were supplied by Los Alamos. All of the silver and protected silver reflectors, including one 4-in.-diameter specimen used for the high-angle testing, were manufactured at Los Alamos National Laboratory. These coatings are 2,000 A of silver deposited on a silicon substrate with a 40-A-thick chromium binder layer. They are overcoated with a 10-A thick layer of alumina to prevent degradation. An NBS gold standard is available and was measured for comparison at the lower reflectance end of the measurement range.

5. Results and Discussion

The reflectometer has a demonstrated precision of ±50 ppm and, when R_u approaches unity, the absolute accuracy also approaches this value. Table 1 is a summary of reflectors measured at near normal (1 degree) angle of incidence. The quantity in run refers to the number of samples measured from a given run, and the mean reflectance shown is for measured samples from that run. For the most part, as indicated by the standard deviations, there is considerable variation in reflectors coated in the same run. However, although not reported here in any quantitative fashion, these same variations are generally observed on the individual specimens as well.

The TiO_2 / SiO_2 / ZrO_2 has results similar to the TiO_2 / SiO_2 / HfO_2 except that one of the reflectors is 0.005 below the mean of the corresponding three samples. However, all four samples are included here, which substantially decreases the mean.

Two pristine, bare silver reflectors from each of three runs were measured. The mean reflectance of all six samples is 0.992 ± 0.001. As seen in the table, silver coatings with an alumina overcoat demonstrate the same reflectance values as for the bare silver.

For rough comparison near the lower end of the reflectometer range, an NBS gold standard was measured. NBS reported R = 0.977; we report R = 0.97679. Only one site on the specimen was measured.

Figure 4 shows the increase in measured reflectance of the alumina-overcoated sample as the incident angle is increased. Although the coating process is theoretically the same, the reflectance for this sample, at near-normal angle, is slightly lower than for all other similar runs. Due to space limitations at the time, angles between 10 and 80 degrees were not possible to attain.

6. Conclusions

A 1064–nm ringdown reflectometer has been developed and is being used to measure the reflectance of high-reflection, multilayer dielectric reflectors and silver mirrors at that wavelength. The reflectometer has a demonstrated precision of 50 ppm when the reflectance is near unity.

We have seen that although multilayer dielectric reflectors of R > 0.9990 are available, a fair number of samples do not meet the minimum requirement of 0.997. We have also seen that some runs exhibit large intrarun reflectance variation, up to 9,000 ppm. Finally, silver reflectors with an alumina overcoat demonstrate a reflectance of 0.9916, which is quite near the value observed for similar mirrors without the overcoat.

7. References

[1] Anderson, Dana C.; Frisch, Joseph C.; Masser, Carl S. Mirror Reflectometer Based on Optical Cavity Decay Time, Appl. Opt. Vol. 23, No. 8, 1984.

Table 1. Measured reflectance values for a variety of reflector designs.

Coating Mat'l.	Mean Reflectance	± One Std. Dev.	Quantity In Run	Comments
ZrO_2/SiO_2	0.988	0.003	6	IBS
	0.996	0.002	6	
	0.998	0.002	3	IBS
	0.9959	0.0004	6	EBD, Si sub
	0.9962	0.0004	6	EBD, Si sub
	0.9971	0.0004	3	EBD
	0.9975	0.0002	6	EBD, Si sub
	0.99896	0.00003	3	IBS
HfO_2/SiO_2	0.990	0.009	7	EBD
	0.9977	0.0004	3	EBD
	0.9984	0.0004	3	PIP
	0.9989	0.0004	5	IBS
	0.9992	0.0003	3	EBD
	0.9964	0.0002	2	IAD
TiO_2/SiO_2	0.994	0.002	3	EBD
	0.9977	0.0004	5	IBS
	0.9997	0.0001	4	IBS
Al_2O_3/SiO_2	0.9984	0.0001	5	EBD
SiN_4/SiO_2	0.9987	0.0002	4	IBS
$TiO_2/SiO_2/ZrO_2$	0.998	0.002	4	EBD
$TiO_2/SiO_2/HfO_2$	0.9992	0.0003	3	EBD
$HfO_2/SiO_2/ZrO_2$	0.9966	0.0003	5	EBD
Ag/Al_2O_3	0.9916	0.0008	4	EBD, Si sub
Au	0.97679	—	1	NBS std. (0.977)

All substrates are C7940 unless otherwise noted
PIP = plasma ion plated
IBS = ion beam sputtered
IAD = ion assisted deposition
EBD = electron beam deposited

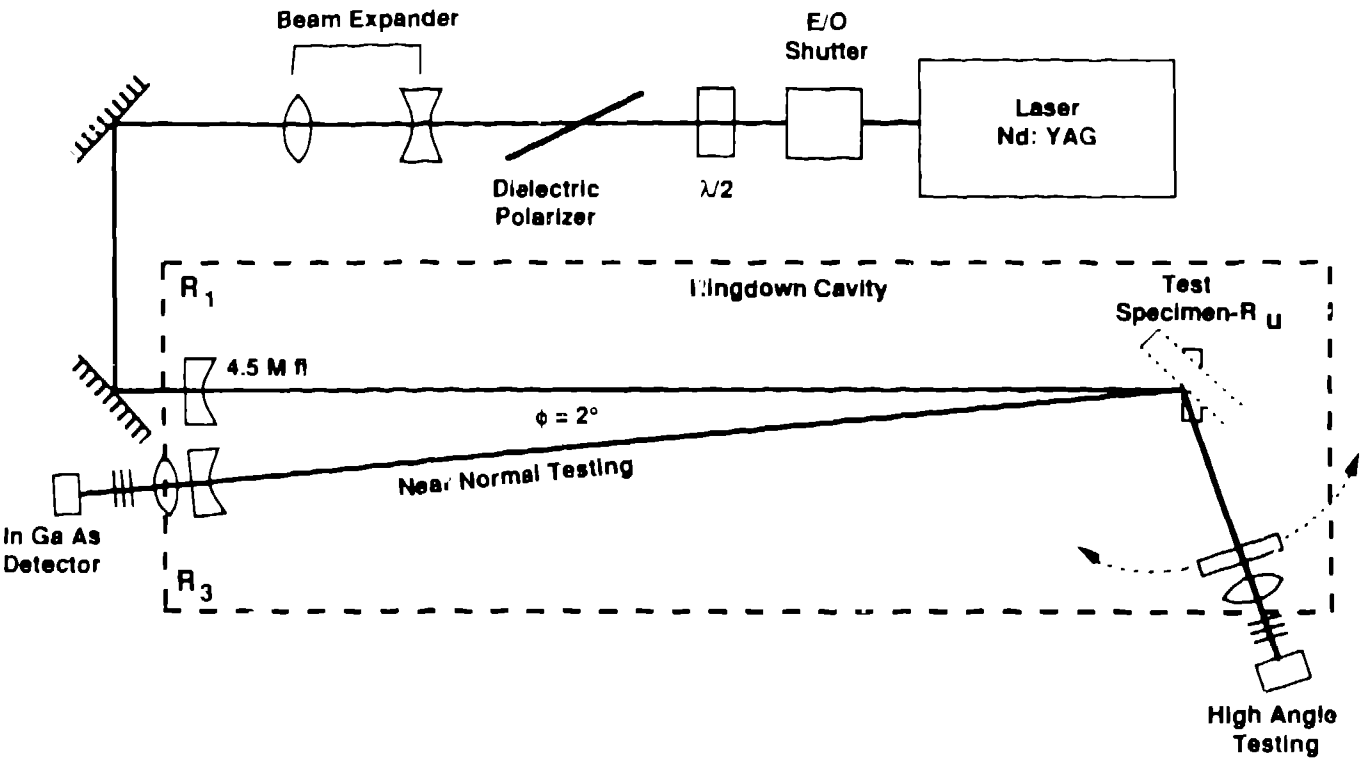

Figure 1. Schematic of the ringdown reflectometer system.

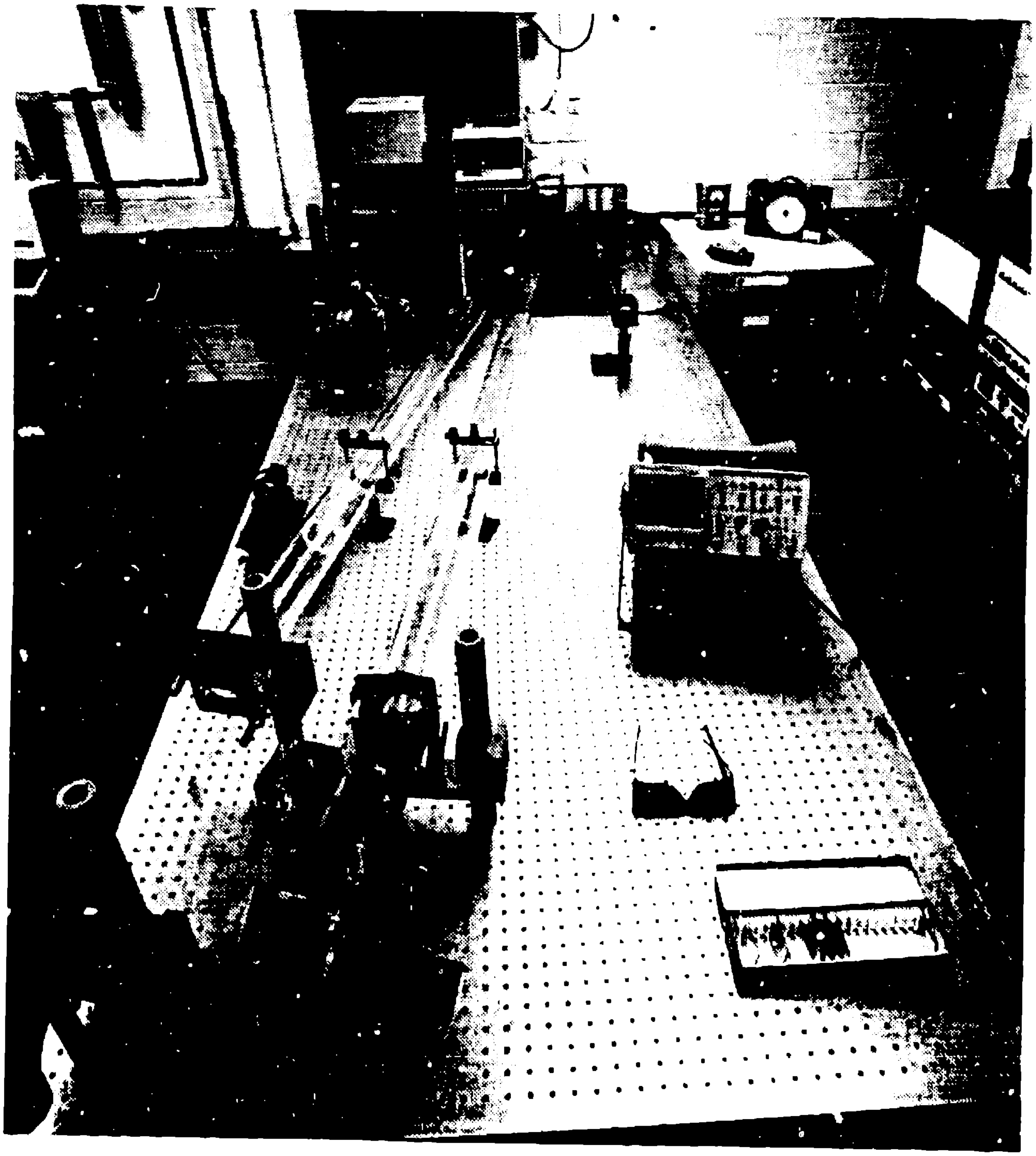

Figure 2. Ringdown reflectometer photo.

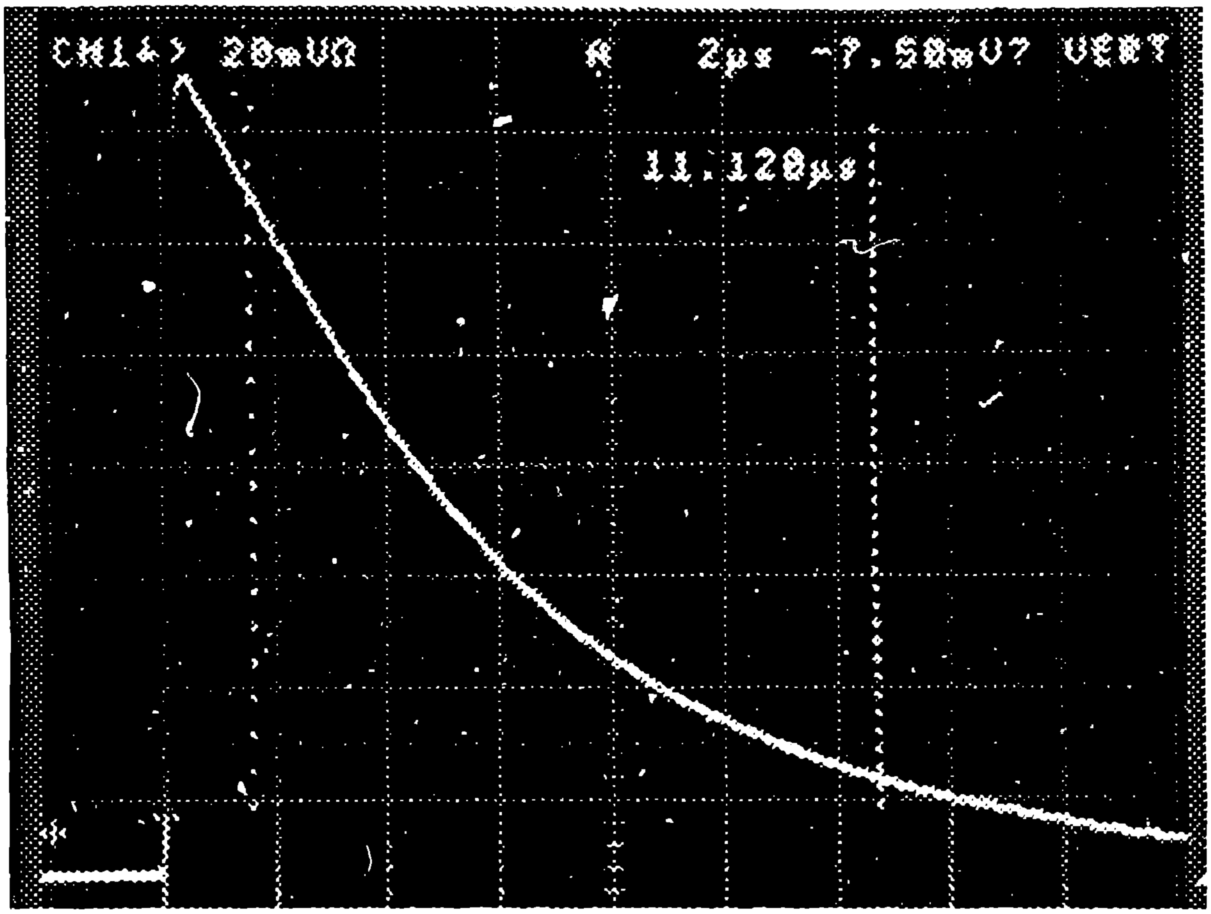

Figure 3. Oscilloscope output showing cavity decay time (11.120 μs = $2\tau_C$).

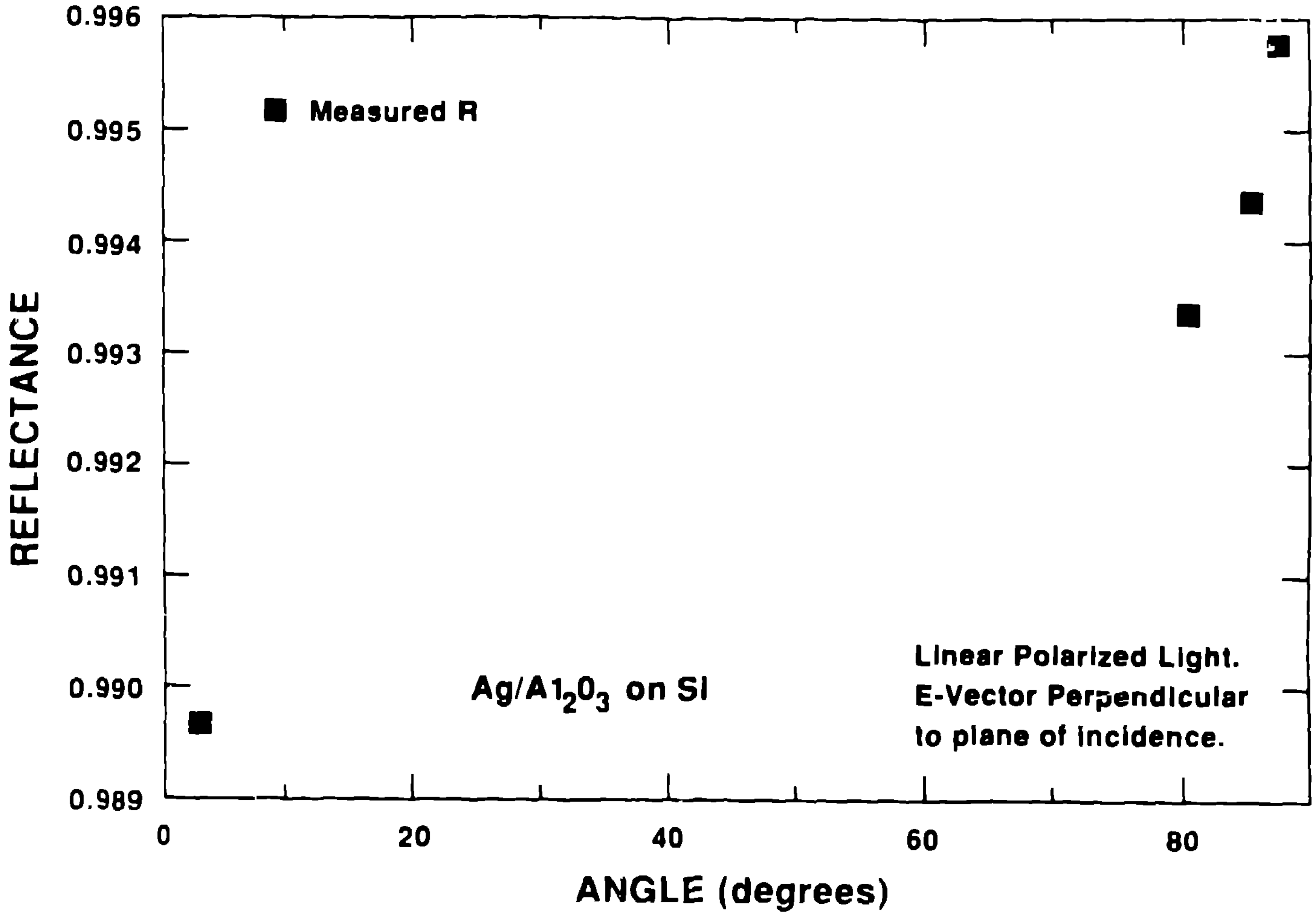

Figure 4. Measured reflectance of a protected silver reflector at various angles.