Ultra-wide broadband dielectric mirrors for solar collector applications

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ABSTRACT

High efficiency solar conversion requires collection of a broad spectrum of wavelengths from the ultra-violet into the infrared. Solar collector mirrors must provide high reflection across this spectral band without degrading over time. This work presents the results of a high-performance 200 mm parabolic mirror coated with an ultra-wide broadband dielectric reflector. The mirror was developed to demonstrate high efficiency broadband solar collection and power conversion. Mirror reflection was measured within the limits of NIST capabilities, and averaged over 99.65% from 400 to 1800 nm with an acceptance angle of 30°. Plasma-assisted reactive magnetron sputtering was used to produce these high density and environmentally stable films. These hard oxide films can be repeatedly cleaned in the field. Salt spray, humidity and angle performance results are presented.

1. INTRODUCTION

Concentrating photovoltaics (CPV) typically employs mirrors or Fresnel lenses to focus the solar irradiation onto a specialized photovoltaic cell that is developed for high spectral utilization and high efficiencies. These types of cells are often complicated multijunction designs that are expensive to manufacture.[1] The use of concentrating mirrors and band separating optics allows the use of multiple cells optimized for different spectral regions. This design enables an unprecedented conversion efficiency[2] while potentially decreasing the cost of CPV (usually dominated by the cell cost).

Mirrors are a critical component of one of the most promising CPV approaches – the CPV power tower being developed by Australian company Raygen Resources[3]– as well as concentrating solar thermal (CST). Both of these solar technologies utilize a field of heliostat mirrors. Most mirrors in commercial use are second-surface mirrors made of shaped and silvered glass with an epoxy-based paint on the back side as a protective layer. One of the limitations of a reflector under glass is that without an anti-reflection coating, the top glass surface reflects 4% of the light to a different physical position than the underlying silver surface.[4] Depending on the geometry, this can be an automatic loss of 4%. The reflectivity of silver averages about 98% in the 450-1800 nm range. The light reflecting off the silver surface has to traverse the glass-air interface a second time to leave the mirror. Further loss occurs at this interface, reducing the reflectivity of the entire mirror assembly to about 90%.[5] If the protective epoxy backing layer is damaged, the silver can begin to degrade, further reducing reflectivity over time.

An entirely different approach to mirrors is to design a reflective interference coating instead of using a metal film such as silver. By alternating materials of high and low refractive index, one can design a first-surface reflector that is nearly 100% efficient over a desired wavelength range. Sputtered hard-oxide materials are used, which are durable enough to be exposed to the elements, eliminating ghosting and other degradation mechanisms.

2. DESIGN AND TESTING

The mirror was designed to have a reflectivity of 100% at wavelengths between 360 and 1870 nm using Optilayer design software. It consisted of 160 layers of Nb_2O_5 and SiO_2 prepared with a plasma-assisted reactive magnetron sputtering process monitored optically for the initial 18 layers, then based on an established rate of deposition (time) for the remaining 142 layers. The multilayer stack was applied to several 200mm diameter, 25mm thick BK7 parabolic substrates. Flat pieces of glass were coated simultaneously and the reflectance was measured on these using an integrating sphere with a diffuse scattering reference, or using a 10 degree specular reflectance attachment and a silver reference. As you can see in Figure 1, the manufactured part closely matches the mirror design. Figure 1 also illustrates that, unlike metal mirrors, thin-film interference mirrors are designed to reflect over a certain wavelength range, and begin to transmit outside of that range. Slight deviations from the design occur because of inhomogeneities in the film layers, deviations in refractive index from the values used during the design process and slight errors in the deposited thickness of the films.

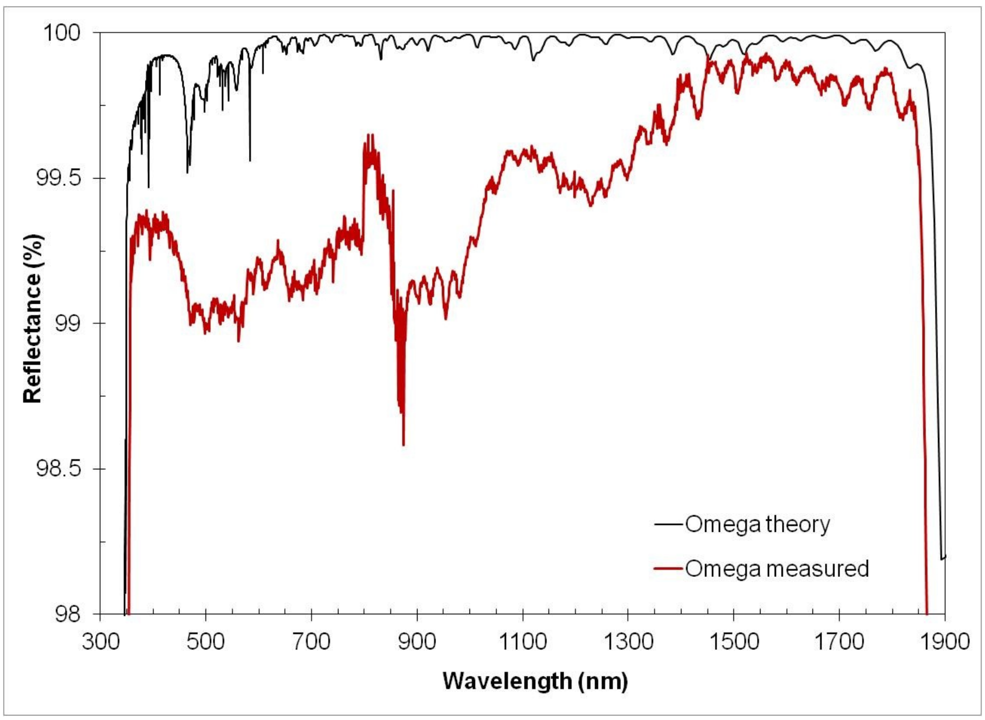

Figure 1. Thin-film mirror design at zero deg versus Cary measurement at 3 deg

Because measurements of absolute reflectance are difficult and dependent on the quality of the reference (silver, aluminum, etc.), the mirror was sent to NIST for evaluation. The reflectance was verified to be > 99.65% over the range 400-1800 nm (Figure 2).

The intended use of this mirror is outdoors. To simulate an outdoor environment, we subjected a sample to a 24-hour salt-fog / salt-spray test and also a 5-day heat and humidity cycling test and saw no change in reflectivity (Figure 3). For comparison, a protected first-surface aluminum mirror showed a decrease in reflectivity after temperature and humidity cycling (a five-day MIL810E test), especially at lower wavelengths (Figure 3).

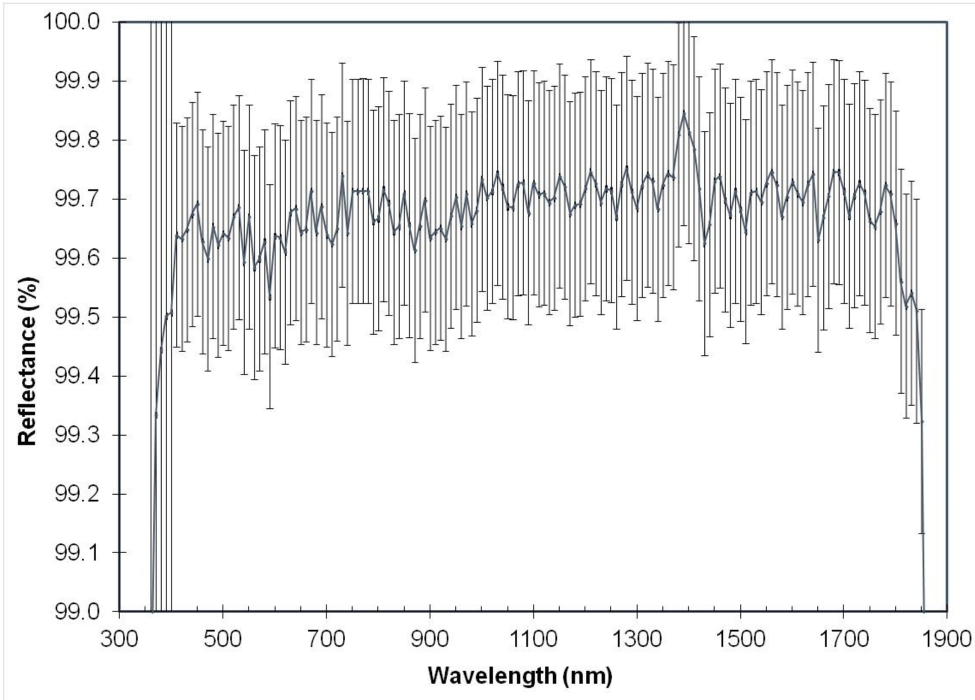

Figure 2. NIST measurement of dielectric mirror reflectance

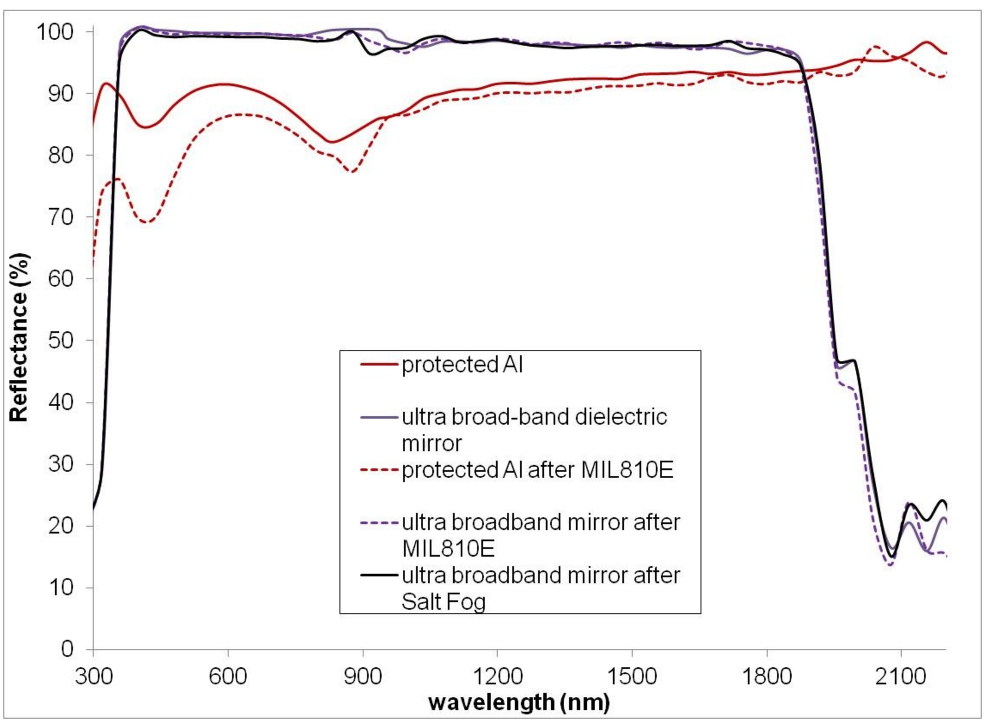

Figure 3. Temperature/Humidity cycling and 24 hour salt-fog results in dielectric mirror versus protected aluminum mirror, measured at 10 deg AOI with Cary 5

Interference mirror performance can depend on both angle and polarization of the incoming light. Figure 4 illustrates the effect of angle and polarization on the performance of this coating. It was initially designed to work at zero degrees AOI, so spectral defects begin to appear at angles > 30 deg, especially for p-polarized light. The s-polarized light performs well over all angles without a deterioration of reflectance (Figure 4a). Both polarizations show a diminution of the spectral reflectance range at high angle. The reflectance at the low wavelength limit is fixed by absorbance of the substrate and dielectric materials (Figure 4a), while the reflectance at the high wavelength limit is established by the design. The shift to lower wavelength with angle is characteristic of most dielectric thin-film stacks.

The design approach to achieve ultrawide spectral reflection employs multiple dielectric stacks with overlapping reflection ranges. At normal incidence a typical quarter wave stack of Nb_2O_5 and SiO_2 in the mid visible has a reflection range of approximately 170nm. At higher angles of incidence, the Fresnel equation predicted difference in s and p plane performance results in a narrowing of the p polarized reflection band, down to 150nm at 30 degrees AOI. This narrowing of each stack's p polarized reflection band width can be seen in the reflection dips that occur at the stack overlap points in Figure 4a.

Figure 4b illustrates the angle dependence of the dielectric mirror at discrete wavelengths and polarizations. The angle measurements were acquired in 5 degree intervals from zero to 80. Because the sensitivity of the power meter is greater at lower light levels, %T was measured and converted to %R by assuming that the dielectric materials do not exhibit absorption at these wavelengths (633 and 514 nm).

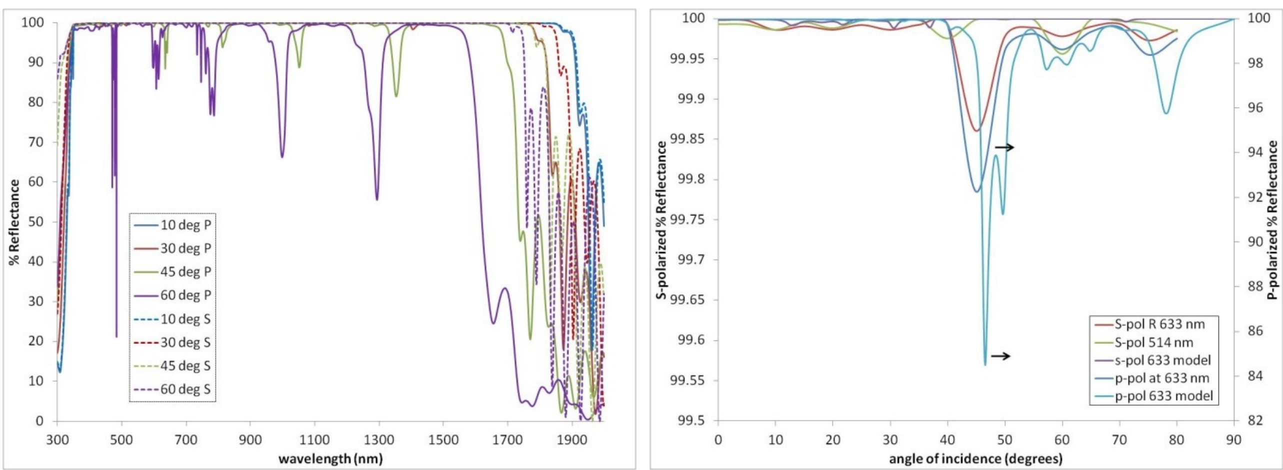

Figure 4. (a) Reflectance of S- and P- polarizations based on the model (b) Reflectance at all angles of incidence at 633 nm with S- and P- polarization and at 514 nm with P-polarization. Theory (model) versus measurement.

3. FIELD TESTING

The UNSW (University of New South Wales) spectrum splitting CPV prototype module uses a parabolic mirror to concentrate sunlight (365x) onto a dielectric bandpass filter and two solar cells (Figure 5 inset and Figure 6). A 40.4% world record was achieved in November 2014 – the first PV receiver to exceed 40% sunlight-to-electricity conversion efficiency[2] – using a mirror with an ‘enhanced silver’ coating (i.e. 2-layer dielectric Al_2O_3/Ta_2O_5 on Ag) deposited by Australian company Optical Coating Associates (OCA). The Omega Optical broadband dielectric mirror has near-perfect reflectance – the NIST results show a remarkable reflectance of 99.7% across a broad wavelength range 400-1800 nm – which is a significant improvement on the enhanced silver mirror (Figure 5).

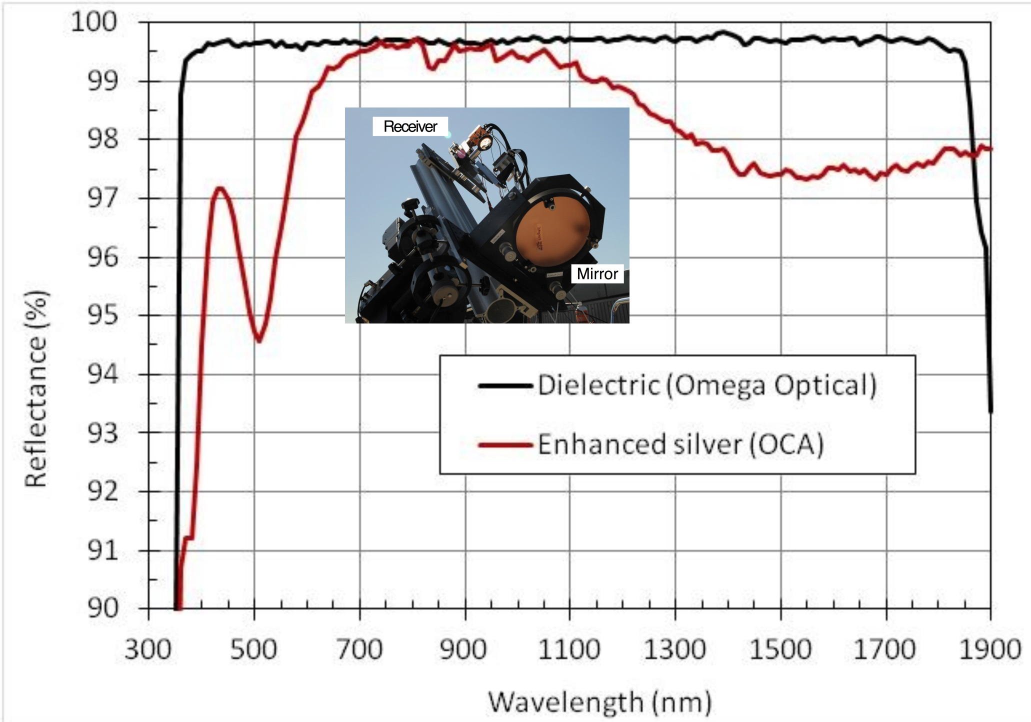

Figure. 5 Reflectance of old and new mirror coatings. The dielectric mirror R was measured by NIST. Inset shows the spectrum splitting CPV prototype during outdoor testing.

After outdoor testing and optimization at UNSW, the improved CPV prototype was independently tested by the US National Renewable Energy Lab (NREL) in Golden, Colorado, in March-April 2016 (Figure 6). The improved mirror reflectance gave performance exceeding that of the previous world record (Table 1).[6,7]

Figure 6. Mark Keevers and the spectrum-splitting CPV prototype during outdoor testing at UNSW (left) and NREL (right).

Table 1 NREL measured efficiency of spectrum-splitting CPV prototype. The performance improvement is largely due to use of the Omega Optical broadband dielectric mirror.

Date	AM1.5 efficiency*	Best efficiency, any air mass
Nov 2014	39.9 ± 2.8%	40.4 ± 2.8% (AM2.5)
Apr 2016	40.6 ± 2.0%	41.0 ± 2.0% (AM1.8)

* AM refers to air mass; AM1.5 is the accepted standard spectrum for solar photovoltaic measurements.

4. CONCLUSIONS

We were able to design a rugged all-dielectric mirror with extremely high reflectivity over the 400-1800 nm range. Because it is made from thin layers of oxide materials using a reactive sputtering process, the films are extremely dense and able to withstand heat and humidity cycling and salt spray environments. Mirrors of this type can be designed at other wavelength ranges to suit a variety of applications. The remarkably high broadband reflectance enabled a previous world record sunlight-to-electricity conversion efficiency to be surpassed, achieving a new record 40.6% under standard test conditions.

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