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A new strategy for improved spectral performance in solar power plants

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Abstract

One method of achieving improved electrical conversion efficiencies in solar power plants is to employ a spectrally selective filter that splits the collected beam into optimised components for two or more spectral receivers. The added cost of supplementary optics and receivers can only be justified if the filter has high performance in operation. The design and manufacture of broadband, low-loss filters however, face several challenges. One of these is the wide range of incidence angles at which the collected beam hits the beam splitter, as the performance of common filters degrades when the incidence angle deviates from the design angle. Dish receivers and micro-tracking Fresnel concentrators, such as the heliostat field in a central receiver design, may provide a fixed distribution of incidence angles across the receiver surface so that the filter can be spatially optimised for a defined angular and energy flux distribution pattern. This paper will discuss the theory and application of such a strategy based on flux mappings produced by raytracing methods for a Multi Tower Solar Array central receiver system planned for construction in Newcastle, Australia.

Keywords: Solar power; Hybrid; Spectral beam splitting; Interference filter; Wide-angle; Thickness tapering

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1. Introduction

In order to improve electrical conversion efficiency, a solar power plant may operate two or more receivers in parallel by employing a spectrally selective filter that splits the collected beam into separate components, optimised for the various receivers (Imenes and Mills, 2003; Imenes and Mills, 2004). The added cost of supplementary optics and receivers in a beam splitting system can only be justified if the filter has high performance in operation. For solar concentrating systems, a dielectric thin film interference filter, capable of handling the high fluxes involved, offers a high degree of design flexibility and its characteristics are well-documented and understood (Macleod, 2001). The practical design and manufacture of broadband, low-loss interference filters however, face several challenges. For solar applications, in particular where a wide-angle radiation field is

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Nomenclature

d	thin film thickness	μ	mean weighted angle
d_c	corrected thin film thickness	ω	energy of incident ray
n_1, n_2	refractive index of materials 1, 2	σ	standard deviation of the mean weighted angle
n_H, n_L	high and low refractive index	N	number of rays traced to a given point
n_s	refractive index of substrate	i	ray counter
θ	incidence angle		

incident on the filter, one of the major problems is the degradation in performance experienced by the filter when the incidence angle increases and deviates from that of the design angle.

In the case of a central receiver solar power plant, this is of concern as the angular profile of the collected energy will be dominated by the large angles of incidence originating from light reflected by the mirrors towards the rim of the heliostat field. One way to overcome this problem is to give the beam splitter a complicated surface shape so that sunlight from different reflectors is received at substantially the same angle of incidence at respective locations on the beam splitter surface (Yogev et al., 1996). However, beam splitters having complex surface shapes are difficult to fabricate. We propose here an alternative design strategy that allows the use of a flat beam splitter in dish receivers or micro-tracking Fresnel concentrators with a well defined, fixed distribution of incidence angles across the receiver surface. This paper will discuss the theory and application of such a strategy based on flux mappings produced by raytracing methods for a Multi Tower Solar Array central receiver system (Mills and Schramek, 1999; Mills et al., 2002) planned for construction in Newcastle, Australia.

2. Thin films and angular properties

A dielectric multilayer stack refers in general to a large number of non-absorbing or low-loss thin films of alternate high and low index materials, deposited onto a substrate by means of physical or chemical deposition techniques. The properties of thin film optical coatings have been treated in detail by several authors, see for instance Thelen (1989), Dobrowolski (2001), Macleod (2001). There is currently no analytical solution that can be applied to transform the desired reflectance or transmittance characteristics of a complex broadband coating into a refractive index profile for real materials with dispersion and absorption (Poitras et al., 2002). Experience and a set of known starting designs are often used in conjunction with numerical optimisation techniques to approach the ideal solution iteratively (Bloom, 1981; Tang and Zheng, 1982). With today's computer capabilities it is possible to design complex thin film multilayer coatings that can achieve almost any desired spectral performance, with very small deviations to the target function, although these coatings frequently consist of tens or hundreds of layers of different thicknesses and indices (Dobrowolski, 1988; Sullivan et al., 1998; Dobrowolski et al., 2002a).

Of particular interest in solar applications is the design of broadband, wide-angle coatings such as antireflection (AR) and bandpass filters. Common bandpass filters are however intended for use at near-normal incidence (Thelen, 1966; Beauchamp and Tuttle-Hart, 1995; Aguilera et al., 2000; Ortabasi et al., 2002). Whereas various broadband high reflectors have been investigated at oblique angles of incidence (Popov et al., 1997), a recent study performed by Dobrowolski et al. (2002b) concluded that, with present-day technology, broadband wide-angle AR-designs for air–substrate interfaces can not be implemented because there are no coating materials that yield solid films with sufficiently low refractive indices when deposited by conventional methods. The optical admittance of a thin film layer changes as the angle of incidence is increased; this change may however be compensated by adjusting the thickness of the film and hence the optical path length. The corrected thickness d_c of a thin film at a non-normal angle of incidence θ is thicker relative to the film thickness d at normal incidence:

$$d_c = d\left[1 - \left(\frac{n_1}{n_2}\right)^2 \sin^2\theta\right]^{-0.5}, \tag{1}$$

where n_1 and n_2 are the refractive indices of the incident medium and the thin film, respectively. If the layer thicknesses are kept constant while the incidence angle is increased, the transmittance maximum of a typical bandpass filter moves towards shorter wavelengths, and the maximum transmittance and half-width of the bandpass will start to deteriorate due to a split in the transverse magnetic and electric polarisation components of the reflected light. These effects may have a large impact on performance if a filter designed for normal incidence is operated under off–normal conditions.