COATINGS FOR COLORED GLAZED THERMAL SOLAR COLLECTORS AND SOLAR ACTIVE GLASS FACADES

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ABSTRACT

The architectural integration of thermal solar collectors into buildings is often limited by their black color, and the visibility of tubes and corrugations of the absorber sheets. A certain freedom in color choice would be desirable, but the colored appearance should not cause excessive energy losses. Multilayered interference filters on the cover glass can produce a colored reflection, hiding the corrugated metal sheet, while transmitting the non-reflected radiation entirely to the absorber. We investigate the potential of quarter wave stacks by simulation of their optical behavior, yielding the relative luminosity A, the solar transmittance T_{sol} , the figure of merit $M = A / T_{sol}$, and the CIE color coordinates. The proposed colored glazed solar collectors will be ideally suited for architectural integration into buildings, e.g. as solar active glass facades.

ZUSAMMENFASSUNG

Die Möglichkeiten der Eingliederung thermischer Sonnenkollektoren in die Architektur der Gebäudehülle sind oft durch die schwarze Farbe und die Form der Absorber (Rohrleitungen, gewelltes Blech) eingeschränkt. Eine gewisse Freiheit in der Farbwahl wäre erstrebenswert; hingegen sollte das farbige Aussehen nicht zu grosse Energieverluste verursachen. Durch Mehrschicht-Interferenzfilter kann auf dem Deckglas eine farbige Reflektion erzeugt werden, die das gewellte Absorberblech unsichtbar werden lässt. Dabei wird die nicht-reflektierte Strahlung vollständig auf den Absorber übertragen. Mittels numerischer Simulationsrechnungen der optischen Eigenschaften untersuchen wir das Potential von $\lambda/4$ Schichtstapeln; berechnete Grössen schliessen die relative Luminosität A, die solare Transmission T_{sol}, die Kennzahl $M = A / T_{sol}$ und die CIE Farbkoordinaten ein. Die vorgeschlagenen farbigen verglasten Kollektoren werden die perfekte Eingliederung thermischer Sonnenkollektoren in die Architektur der Gebäudehülle, z.B. als aktive solare Glassfassaden, ermöglichen.

INTRODUCTION

Architectural integration of solar energy systems into buildings has become a widely recognized issue now [1], regarding techniques from photovoltaics and daylighting to thermal solar energy conversion. Considerable activities have demonstrated the possibilities of building integration of photovoltaic cells [2,3], leading to a large product variety, and finally enhancing crucially the user acceptance of solar cells. Daylighting elements based on anidolic mirrors have been successfully introduced into building facades in an aesthetically pleasing way [4]. Thermal solar collectors, typically equipped with black, optical selective absorber sheets, exhibit in general good energy conversion efficiencies [5]. However, the black color, and sometimes the visibility of tubes and corrugations of the metal sheets, limit the architectural integration into buildings. One solution to this problem would be to color the absorber sheets. In this case, the absorber surface combines the functions of optical selectivity (high solar absorption/low thermal emission) and colored reflection. Alternatively, we propose to establish a colored reflection not from the absorber but from the cover glass. This approach has the advantage that the black, sometimes ugly absorber sheet is then hidden by the colored reflection. In addition to that, the functions of optical selectivity and colored reflection are separated, giving more freedom to layer optimization. No energy should be lost by absorption in the coating: all energy, which is not reflected, should be transmitted. Therefore, multilayer interference stacks of transparent materials are ideally suited for this purpose. A lot of literature exists about multilayer interference stacks for various optics and laser applications [see ref. 2 and refs. therein], but to the knowledge of the authors only few deal with the application as energy-efficient coloration of thermal solar collectors.

THEORY

The field of optics of thin films has been reviewed by various authors, e.g. Macleod [6]. Due to the multiple reflections between the different interfaces, the problem of the optical behaviour of a multilayered thin film stack is non-trivial. It can be treated, though, by the method of characteristic matrices, which defines one matrix M_r per individual layer (with the layer no. r). The whole layer stack is then represented by the matrix product.

$$\left\{\prod_{r=1}^{q} M_r\right\} = \left\{\prod_{r=1}^{q}\begin{bmatrix}\cos\delta_r & (i\sin\delta_r)/\eta_r \\ i\eta_r\sin\delta_r & \cos\delta_r\end{bmatrix}\right\} \quad , \tag{1}$$

employing the tilted optical admittance η_r and the phase shifts $\delta_r = 2\pi N_r d_r \cos\vartheta_r/\lambda$. Here, $N_r = n_r - ik_r$ is the complex refractive index, and ϑ_r the corresponding complex angle. From this matrix product, transmission and reflection spectra can be computed. For a complete treatment see e.g. Macleod [6]. Extended calculations are usually carried out by a computer.

The relative luminance A is a measure for the brightness of a surface as it appears to the human eye under certain illumination conditions. A white surface or a perfect mirror exhibits 100% relative luminance, colored or grey surfaces less. In this sense, a colored or grey Lambertian surface is compared to a white Lambertian surface, and a specular reflecting surface is compared to the perfect mirror. The determination of the relative luminosity A is based on the photopic luminous efficiency function V(λ) and depends on the choice of the source. We employ the standard illuminant D_{65}, and the hemispherical reflectance R(λ):

$$A = \frac{\int R(\lambda)\cdot D_{65}(\lambda)\cdot V(\lambda)d\lambda}{\int D_{65}(\lambda)\cdot V(\lambda)d\lambda} \tag{2}$$

The International Commission on Illumination (CIE, Commission Internationale d'Eclairage) described how to quantify colors [7]. All existing colors can be represented in a plane and mapped by Cartesian coordinates, as shown in the CIE Chromaticity Diagrams.

RESULTS

The human eye perceives only a small part of the solar spectrum; large spectral regions in the ultraviolet and in the infrared are invisible. This is illustrated by Fig. 1, showing the solar spectrum AM1.5 and the photopic luminous efficiency function V(λ). The basic idea is to create a surface, which reflects just a narrow frequency band in the visible range, thus giving rise to a colored appearance. For a colored solar collector, the nonreflected part of the solar spectrum should be completely converted to thermal energy. An idealized boxcar-shaped spectrum is added to Fig. 1. How bright will the colored reflection appear to the human eye, and how much energy will it cost?

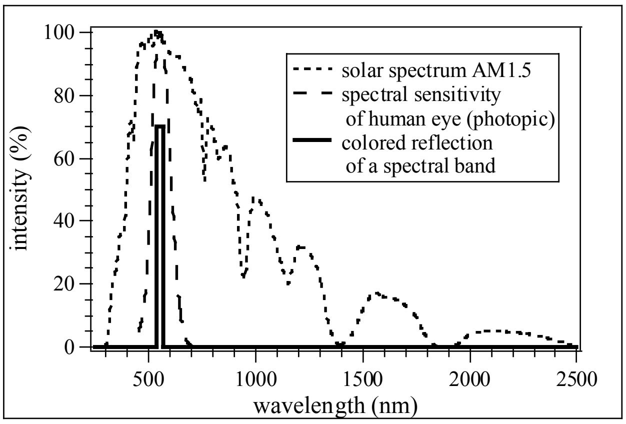

Fig.1: Solar spectrum AM1.5 , the photopic luminous efficiency function V(λ), and an idealized, boxcar-shaped spectrum of a colored reflection. In our treatment (see text) we consider the idealized case of the reflection of a just narrow spectral band, in the extreme limit a Dirac delta distribution δ(x).

In the extreme case, the reflectance spectrum can be represented by the product of a constant and a Dirac delta distribution:

$$R(\lambda) = C \cdot \delta(\lambda - \lambda_0) \quad , \tag{3}$$

where λ_0 is the wavelength of the infinitely narrow spectral band.

At this point it is useful to introduce a figure of merit. We define the ratio of the relative luminosity A and the solar reflection R_{sol} as figure of merit M. Being large in the case of high relative luminosities or low solar energy losses R_{sol}, this number describes the energy efficiency of the visual perception ("brightness per energy cost"). Following this definition, we obtain:

$$M = \frac{A}{R_{sol}} = \frac{D_{65}(\lambda_0) \cdot V(\lambda_0)}{I_{sol}(\lambda_0)} \cdot \frac{\int I_{sol}(\lambda) d\lambda}{\int D_{65}(\lambda) \cdot V(\lambda) d\lambda} \tag{4}$$

This expression depends no longer on the constant C, it is independent of the intensity of the reflection. The integrals just correspond to a normalization, the dependence on the wavelength λ_0 is simple. The shape of this curve, exhibiting a maximum at 550 nm (in the yellow green), is rather similar to the shape of the curve V(λ). However, the normalization is important: at the maximum, an absolute value of approximately six is reached. What does this factor six mean? In this ideal case, a relative luminosity of 6 % costs only 1 % of the solar energy. If we wanted a relative luminosity of 12 % , which is already considerable for a color (since 100 % corresponds to white), we would have to sacrifice only 2% of the incident energy. All possible reflection spectra can be approximated by a superposition of narrow spectral bands.

Because the corresponding integrals are linear, the factor six represents the principal upper limit for M.

Is it possible to produce such a narrow reflection peak in the visible spectral region? In order to color the reflected light, interference filters are perfectly suited. We consider quarterwave stacks, where all individual layers are of the optical film thickness $n \cdot t = \lambda_0 / 4$ (λ_0 is called the "design wavelength"). Usually layers of a high index material (H) alternate with layers of a low refractive index material (L), resulting in a stack of the form HLHLHL… . Often, these filters are employed as high reflectivity mirrors, exhibiting a nearly perfect reflection over a large frequency band. The larger the difference in the refractive indices, the larger is the spectral region of high reflection. We are interested in the opposite, a narrow reflection peak. Therefore we chose the refractive indices to be very close to each other (but not identical). Because the reflection at each interface is weak now, we need a considerable number of layers. Making the somewhat arbitrary choice of forty, our model has the form glass//(LH)^20//air. Having a design wavelength of 550 nm in mind, the following parameters have been chosen: for the low refractive index material n = 1.47 and a thickness of 93.5 nm; for the high index material n = 1.5 and 91.7 nm; for the glass substrate n = 1.52; and for the air n = 1. Neglecting the first interface air//glass, we computed the normal reflection of the system glass//coating//air with the aid of the methods described above. As expected, we generated the shape of a narrow peak at the design wavelength 550 nm, with a maximum reflectance around 30 % (see Fig.2). The full width at half maximum (FWHM) for this peak amounts 21 nm. The peak is emerging from a weak oscillation around the value of the uncoated glass (4 %). For a comparison, the photopic luminous efficiency function V(λ) and the solar spectrum AM1.5, both normalized, are added to the graph.

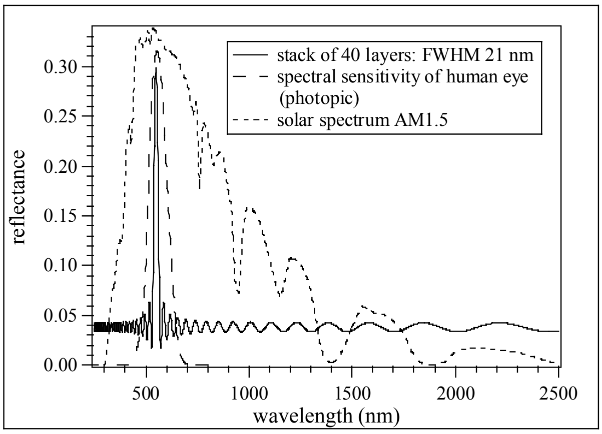

Fig.2: Reflectance spectrum (solid line), as computed for a quarter wave stack consisting of forty individual layers. The optical model has the structure glass//(LH)^20//air. The refractive indices amount to 1.5 and 1.47 for the high and the low index material, respectively. We simulate the reflection at the coated backside of the glass. For comparison, the solar spectrum AM1.5 , and the photopic luminous efficiency function V(λ), are added to the diagram.

The calculated reflectance curve, showing an isolated narrow peak and low reflectance in the rest of the solar spectrum, approximates satisfyingly the idealized boxcar-shaped function displayed in Fig.1. The spectrum yields the CIE color coordinates x = 0.31 , y = 0.47 (yellowish green), and the relative luminosity A = 9.1 % .

How many layers are necessary to produce a nice, isolated, and not too broad peak of reflection? In large area production, it is always advantageous to work with the least number of individual layers. In order to attain a considerable reflection at the interfaces, we choose a larger difference between the refractive indices, employing n(H) = 1.65 for the high index material H, and n(L) = 1.47 for the low index material L. These values also have the advantage that they correspond roughly to the two real materials silicon dioxide and aluminum oxide, respectively [14, 21]. The refractive index of the substrate (1.52) now lies between the indices of the two layer materials. For the reason of the phase jump relations at the interfaces, an odd number of individual layers is used here. The model has thus the structure glass//H(LH)^m//air, with m = 1,2,3,… Here again, H indicates the high index material and L the low index material. The resulting reflection spectra for m = 1,2,…7 (3 to 15 individual layers) are displayed in Fig. 3. For m = 1 (3 layers), a relatively broad feature around the design wavelength 550 nm is formed. A pronounced reflection peak emerges for five layers (m = 2). The corresponding spectrum is represented by the solid line. It is characterized by a maximum of reflectance of 23 % , with a FWHM of 156 nm. The reflection color is yellow-green (x = 0.35 , y = 0.45), the relative luminosity considerable (20 %), and the solar transmission rather high (91 %). Adding more pairs of layers to the stack yields narrower and more distinct peaks leading to an increase in color saturation and relative luminosity and to a slight decrease in solar transmission. The figure of merit M increases gradually from 1.8 (for 3 layers) to 3.4 (for 15 layers).

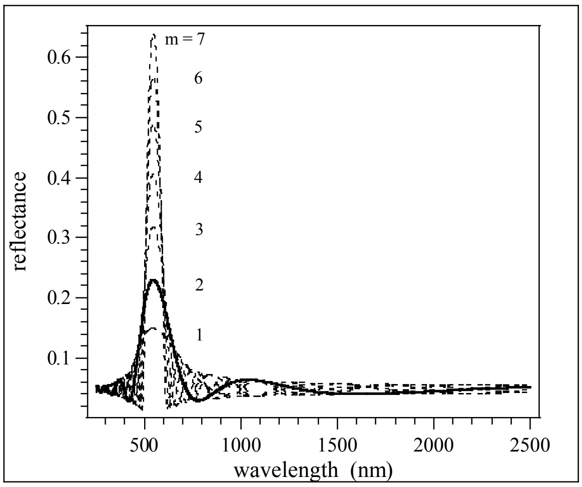

Fig.6: Computed reflectance spectra for fewer layers. The optical model has the structure (glass//H(LH)^m//air), with m = 1,2,3,… . Taking into account the phase jump relations at the interfaces, we use an odd number of individual layers. Adding more layer pairs to the stack yields narrower and more distinct peaks.

DISCUSSION

Common thin film deposition processes are magnetron sputtering, plasma enhanced chemical vapor deposition, vacuum evaporation, or SolGel dip coating . Transparent oxides such as silicon dioxide ($n \approx 1.47$), aluminum oxide ($n \approx 1.65$) , or titanium dioxide ($n \approx 2.2$) can routinely be deposited [6, 8, 9]. Intermediate refractive indices are accessible by the synthesis of mixed oxides. A very low refractive index ($n \approx 1.38$) is exhibited by magnesium fluoride MgF_2 , commonly produced by vacuum evaporation [10]. With all coating processes, care has to be taken for a superior film homogeneity, which is essential for interference filters. Vacuum processes yield in general high quality films, but a considerable investment into the vacuum coating machines is necessary already in the start-up phase. The scale-up of a vacuum process, which has been developed in the laboratory, is possible, but non-trivial [25]. This is much easier for SolGel dip-coating. Once the right solutions and withdrawal speeds are found, the size of the glass pane does not alter the basic process parameters. Here, one main problem is to avoid dust, which creates defects and harms the coating quality. Costs rise with the repeated baking of multilayered coatings on large glass panes. One way out can be special precursors, which enable a film hardening by ultraviolet light [26].

CONCLUSIONS

The general potential of colored thermal solar collectors is promising, and can be expressed by a figure of merit M defined as the ratio of the relative luminosity A and the solar energy losses by reflection R_{sol} . The principal upper limit for this figure M amounts to the value six, expressing low energy costs per perceived brightness. Multilayered interference filters are ideally suited for the considered application. The ideal reflection spectrum of an isolated, sharp reflection peak can be approximated by quarter wave stacks of numerous individual layers. Even with a realistic number of individual layers (e.g. five), reasonable performance can be obtained. The proposed colored glazed solar collectors will be ideally suited for architectural integration into buildings, e.g. as solar active glass facades.

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