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A Spectrally Selective Window for Hot Climates

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Abstract

Rigorous coupled-wave analysis has been used to design a glazing for hot climates. The designed glazing is relatively simple and it transmits most of the visible light and reflects most of the infrared radiation. It does not need any external source of energy to control its optical properties. It consists of ITO and four periodic pairs of Si/SiO_2, deposited on a glass sheet. The optimum thicknesses of ITO, Si and SiO_2 are 0.1 µm, 0.15 and 0.4 µm, respectively. The glazing acts as an optically selective filter. It transmits about 80% of the visible light and reflects almost all the infrared radiation. The performance of the glazing is almost independent of the angle of incidence of solar radiation. This makes it suitable for all hours of the day. The fabrication of the glazing and the testing have been performed at the laboratories of the Faculty of Science, University of Witwatersrand, South Africa. Magnetron sputtering technique has been used for the fabrication. ITO, Si and SiO_2 have been used as sputtering targets. The experimental results are almost identical to the simulation results.

Keywords

Smart Windows, Electrochromic Windows, Thermochromic Windows, Hot Climates

1. Introduction

Buildings need to provide a pleasant living environment and at the same time to minimize the electricity requirements for lighting and cooling. Recently there is an increasing architectural trend towards more use of glass. Conventional glass, in hot climates, transmits most of the solar infrared radiation. This increases the electricity consumption for cooling.

The household sector in Sudan consumes about 46% of the total energy consumption [1]. The consumption of electricity for lighting and cooling is about

3.5×10^6 MWh per year.

The shape of a building influences the solar energy that it receives. The solar radiation incident on a building affects the energy requirement for lighting and cooling. By improving the glazing performance of windows, it is possible to reduce the electricity consumption. For more energy saving, the spectral selectivity of the glazing has to be modified. At present, this has been achieved by using eitherelectrochromic or thermotropic devices. The optical properties of these materials are either electrically adjustable or thermally self-adjusting.

Electrochromic windows change light transmission in response to an external applied voltage. The transition from clear to opaque could take 3 - 5 minutes, for a small window [2]. Hong and Chen [3] used nano-Prussian blue analogue/PEDOT/PSS: composites for a 10 × 10 cm^2 WO_3 electrochromic window. A maximum transmittance modulation of 61.6% at a voltage of 1.6 V was obtained. Kim and Taya [4] used V_2O_5 and poly (3,3-dimethyl-3,4-dihydro-2H-thieno [3,4-b][1,4]dioxepine) coatings. The window demonstrated electrochemical stability after over 150,000 cyclic switches, and that the response time for a 25 × 25 mm^2 window was 5 seconds for coloration and 4 seconds for bleaching. Similarly, Kim *et al.* [5] obtained highelectromatic contrast andoptical cyclic stability, when they used electrochromic windows based on anodic electrochromic polymesitylenes containing 9H-carbazole-9-ethanol moieties. Fernandes *et al.* [6] used glass/ITO/WO_3/electrolyte/ITO/glass layered configuration. That resulted on visible average transmittance variation and optical density change of 41.6% and 0.39%, respectively. Hee *et al.* [7] concluded that electrochromic windows are more suitable for applications in residential areas in cold climate regions. Brooke *et al.* [8] investigated the effect of oxidant on the performance of conductive polymer films. They concluded that the oxidant $Fe(Tos)_3$ produced superior device performance with respect to optical switching, switch speed and optical relaxation. Kim *et al.* [9] prepared transparent conductive ZnInSnO-Ag-ZnInSnO multilayer films for polymer dispersed liquidcrystal based smart windows. They obtained a lower operating voltage and a higher cutoff rate of infrared light, compared to ITO or ZITO-based smart windows. Khandelwal *et al.* [10] fabricated electrically switchable broadband infrared reflectors using polymer stabilized cholesteric liquid crystals. They predicted that their reflector can save more than 12% of energy compared to double glazing window and 9.3% compared to static infrared reflector. One of the drawbacks of electrochromic windows is their need for external biases to operate. Wang *et al.* [11] introduced a self-powered window. Aluminum was used to reduce Prussian blue to Prussian white in potassium chloride electrolyte. For self-recovering of the device to the blue appearance, the aluminum and Prussian blue electrodes could be disconnected. Lim *et al.* [12] studied the performance of tungsten-oxide-based electrochromic window. The results showed that the transmittance of visible light varied from 64% in the clear state to very low values in the colored state. They also concluded that there is little additional benefit from placing low emissivity coating on the electrochromic window.

Thermochromic windows switch from a clear state in low temperature to a diffuse reflective state in high temperature. The results of Long *et al.* [13] indicated that, in hot climate, the use of VO_2 window decreases the energy consumption for cooling compared to the case with ordinary window. Zheng *et al.* [14] designed TiO_2(R)/VO_2(M)/TiO_2(A) multilayer film to work as a smart window with antifogging and self-cleanig functions. Koo *et al.* [15] fabricated CeO_2-VO_2 bilayer to improve the optical properties of VO_2 window. The CeO_2 was employed as an antireflection layer of the VO_2 film. Kamalisarvestani *et al.* [16] studied the spectral selective properties of thermochromic windows and the effect of doping of VO_2 coatings with different dopants.VO_2 could be the most promising thermochromic material, but its drawback is the preparation cost and the stability. Batista *et al.* [17] concluded that tungsten was the most effective dopant on the reduction of the semiconductor-metal transition temperature of VO_2. More energy could be saved by using VO_2 double window. Long and Ye [18] suggested that an appropriate phase transition temperature is needed to make the VO_2 remains principally in its metallic state with low solar transmittance for summer application and in its semiconductor state with high solar transmittance for winter application. Zhou *et al.* [19] combined a VO_2 thermochromic window with solar cells operated by the scattered radiation from the window. However, the efficiency of the cell was too low to justify the additional cost.

Both electrochromic and thermochromic windows suffer from high cost, low transmission of visible light and slow response time. In tropical regions, the ideal window is the one which transmitsall the visible light to reduce the lighting load, and reflects all the infrared radiation to reduce the cooling load, with 0.78 μm cutoff wavelength.

In this paper we studied the potential of usingthin layers of periodic structure as a glazing with spectrally selective properties. The proposed structure is for hot climates. It consists of alternating layers of Si/SiO_2. The performance of the glazing was studied by using rigorous coupled-wave analysis method. The optimized structure was prepared by using magnetron sputtering technique.

2. Simulation

Rigorous coupled-wave analysis (RCWA) is formulated in the 1980s by Moharam and Gaylord. It is used for analyzing the diffraction of electromagnetic waves by periodic gratings [20]. RCWA is used in this study to calculate the radiative properties (reflectance and transmittance) of the periodically multilayer surfaces. It analyzes the general diffraction problem by solving Maxwell's equations accurately in each of the three regions (input, multilayer, and output), based on Fourier expansion [21]. In RCWA, diffraction efficiency for each diffraction order is calculated with incident wave properties regardless of feature size, structural profiles, and dielectric function of the materials. The dielectric function of the materials is expressed as, $\varepsilon = (n + ik)^2$ where n is the refractive index and k is the extinction coefficient. The accuracy of the solution computed depends solely upon the number of terms retained in space harmonic expansion of electromagnetic fields, which corresponds to the diffraction order. Any linearly-polarized incidence can be decomposed into the transverse electric (TE) and transverse magnetic (TM) mode. The normalized electric field of incidence E_{inc} can be expressed as:

$$E_{inc} = \exp\left(ik_x x + ik_z z - iwt\right) \tag{1}$$

The electric field in region I (**Figure 1**) is the superposition of the incident wave and the reflected waves; therefore

$$E_1\left(x,z\right) = \exp\left(ik_x x + ik_z z\right) + \sum_j E_{rj} \exp\left(ik_{xj} x - ik_{zj}^r z\right) \tag{2}$$

Similarly, the electric field in region II (E_{II}) is the a superposition of all transmitted waves

$$E_{11}\left(x,z\right) = \sum_j E_{tj} \exp\left(ik_{xj} x - ik_{zj}^t z\right) \tag{3}$$

The magnetic field in region I and II can be obtained from Maxwell's equation H

$$H_I\left(x,z\right) = -\frac{i}{\omega\mu_0}\left(\nabla \times E_I\right) \tag{4}$$

$$H_{II}\left(x,z\right) = -\frac{i}{\omega\mu_0}\left(\nabla \times E_{II}\right) \tag{5}$$

where ω represents the frequency and μ_0 the magnetic permeability of vacuum. The electric and magnetic field components in region M (**Figure 1**) can be expressed as a Fourier series:

$$E_M\left(x,z\right) = \sum \chi_{yj}\left(z\right) \exp\left(ik_{xj} x\right) y \tag{6}$$

$$H_M\left(x,z\right) = \frac{ik}{\omega\mu_0} \sum_j \left[\gamma_{xj}\left(z\right) x + \gamma_{zj}\left(z\right) z\right] \exp\left(ik_{xj} x\right) \tag{7}$$

where χ_{yj} and γ_{xj} are vector components for the jth space-harmonic electric and magnetic field in region M (multilayer region), respectively. Due to the structure periodicity, the relative dielectric function in region M, $\varepsilon\left(x\right)$ and its inverse $\frac{1}{\varepsilon\left(x\right)}$, can also be expanded in Fourier series:

$$\varepsilon\left(x\right) = \sum_p \varepsilon_p^{ord} \exp\left(i\frac{2p\pi}{\Lambda} x\right) \tag{8}$$

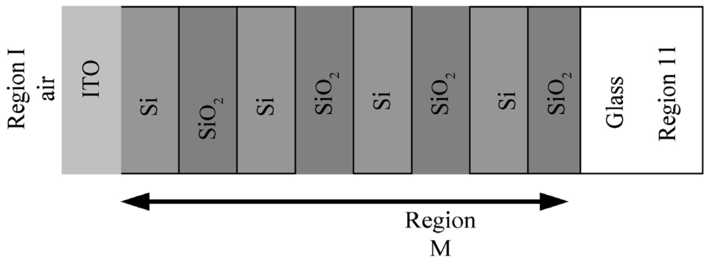


Figure 1. The proposed selective filter components.

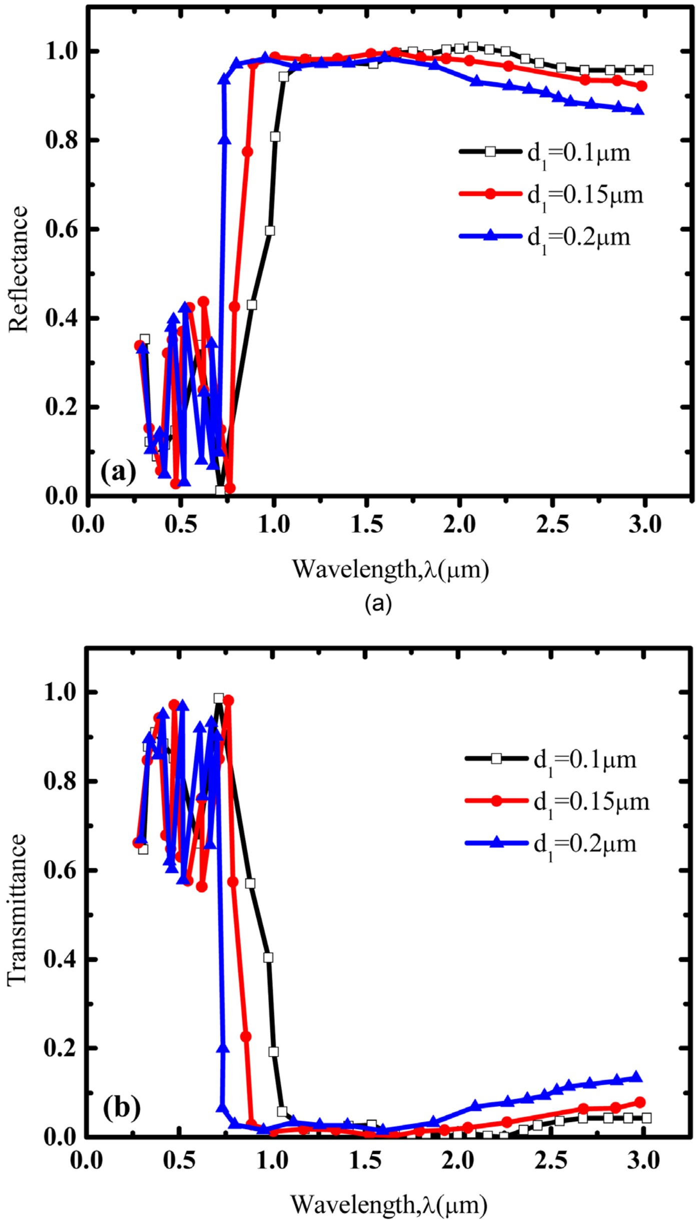
$$\frac{1}{\varepsilon(x)} = \sum_{p} \varepsilon_p^{inv} \exp\left(i \frac{2p\pi}{\Lambda} x \right) \tag{9}$$

where ε_p^{ord} and ε_p^{inv} are the jth Fourier coefficient for the ordinary and inverse of $\varepsilon(x)$, respectively.

3. Optimization of the Thicknesses

3.1. Optimization of Si Thickness

The glazing consists of ITO layer deposited on one-dimensional (ID) four pairs of Si/SiO$_2$ layers on top ofa1mm-glass sheet, Figure 2. The geometric parameters



(a)

(b)

Figure 2. The proposed selective filter for TM wave with different d_1 thicknesses. (a) shows the reflectance and (b) the transmittance.

used to illustrate the wavelength selective filter are the thicknesses of the layers.

The wavelength-dependent dielectric optical constants of ITO, silicon and silicon dioxide were obtained from Ref. [22]. The thickness of ITO was 0.1 μm and that of Si was d_1 = 0.1, 0.15 and 0.2 μm. The thickness of SiO_2 was fixed at d_2 = 0.4 μm. The normal reflectance and transmittance for the proposed selective filter were calculated numerically by using RCWA method in the wavelength range from 0.3 μm to 3 μm.

The normal reflectance and transmittance of the glazing, at normal incidence TM waves, is shown in **Figure 2**. The results show that the optimum thickness of the Si is 0.15 μm. It gives low reflectance (less than 30%) for wavelengths less than 0.8 μm and reflectance of nearly unity for higher wavelength values. This would transmit most of the visible light (to reduce the lighting load) and reflects nearly all the infrared (to reduce the cooling load).

3.2. Optimization of SiO_2 Thickness

Figure 3 shows the normal reflectance and transmittance of the glazing for normal incidence TM waves. The thickness of Si was taken to be 0.15 μm, while that of SiO_2 was changed, d_2 = (0.2, 0.3 and 0.4) μm. The results show that the optimum thickness for SiO_2 is 0.4 μm.

The glazing not only reduces the electricity consumption during daytime, but it also acts as an insulator during the cold nights of winter. It reflects the heat back inside the room. In the desert, the air temperature drops to less than 10˚C during the night. When the room temperature is about 30˚C, which corresponds to a peak wavelength of about 10 μm, there would be very little heat loss through the windows, **Figure 4**.

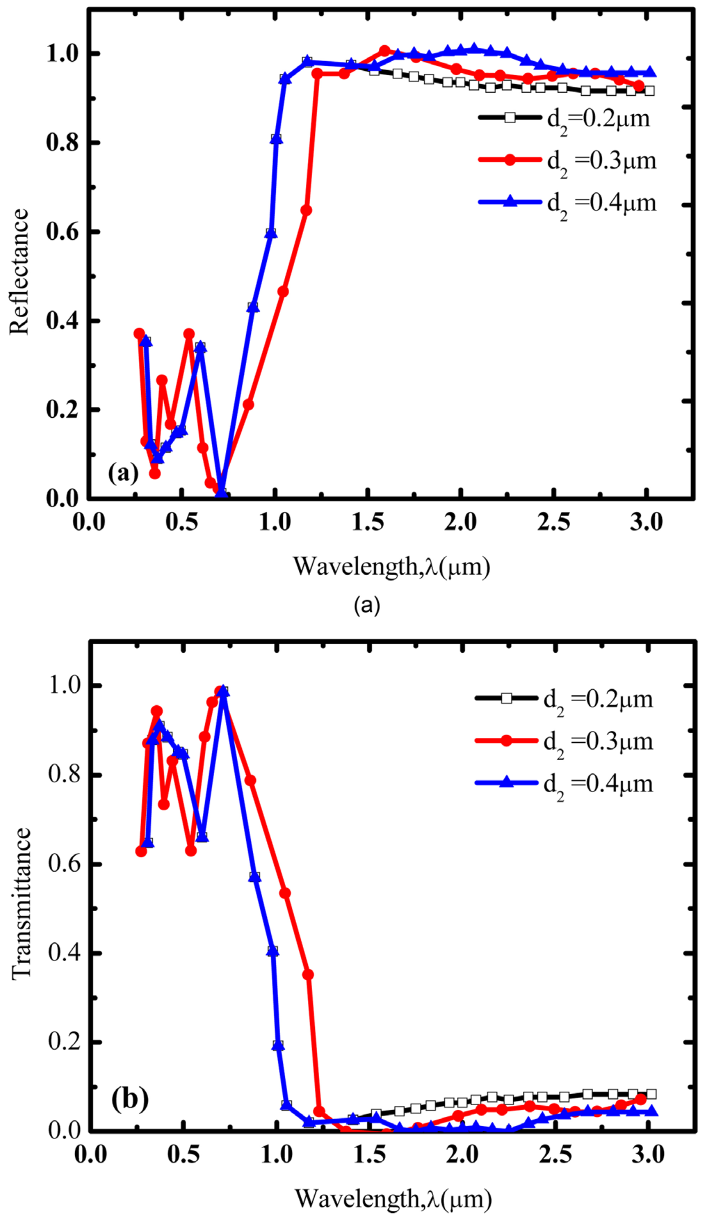
3.3. Effect of Angle of Incidence

The effect of the angle of incidence on the reflectance and transmittance is shown in **Figure 5**. It is seen that increasing the angle of incidence from 0˚ to 60˚ makes little difference on the reflectance and transmittance. The glazing seems to be suitable for all seasons and for both direct and diffuse radiation.

4. Experimental Work

The fabrication of the window and the measurements of its optical properties were performed at the laboratories of the Faculty of Science, University of Witwatersrand (Wits), South Africa. The filter consists of ITO layer deposited on four pairs of Si/ SiO_2 layers on top of a 1mm-glass sheet. The magnetron sputtering system, shown in **Figure 6**, was used to deposit a thin film from sputtering targets onto substrate.

The silicon (S) and silicon dioxide (SiO_2) were used as sputtering targets. The sputtering power and pressure were kept at 100 W and 140 W for silicon and silicon dioxide, respectively, and operation pressure at 5.7×10^{-3} Pa. The base vacuum level was 5.3×10^{-3} Pa. The argon gas flow rate was kept at 20 (standard cubic centimeters per minute) and controlled by amass flow meter. The



(a)

(b)

Figure 3. The glazing with different SiO_2 thicknesses. (a) shows the reflectance and (b) the transmittance.

transmittance and reflectance of the filter were measured by a system consisting of a powering system, light source, stepper motor, photo-detectors and analog to digital converter.

5. Experimental Results

The measurement of the reflectance and transmittance are shown in Figure 7. The optimum thicknesses of ITO, Si and SiO_2 were found to be 0.1 μm, 0.15 and 0.4 μm, respectively. The measurements have also shown that the filter transmits about 78% of the visible light and reflects nearly all the infrared. These results are almost typical to that obtained by the simulation.

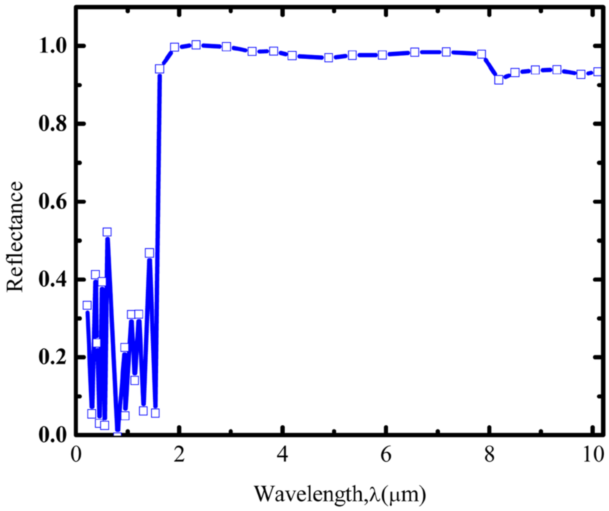
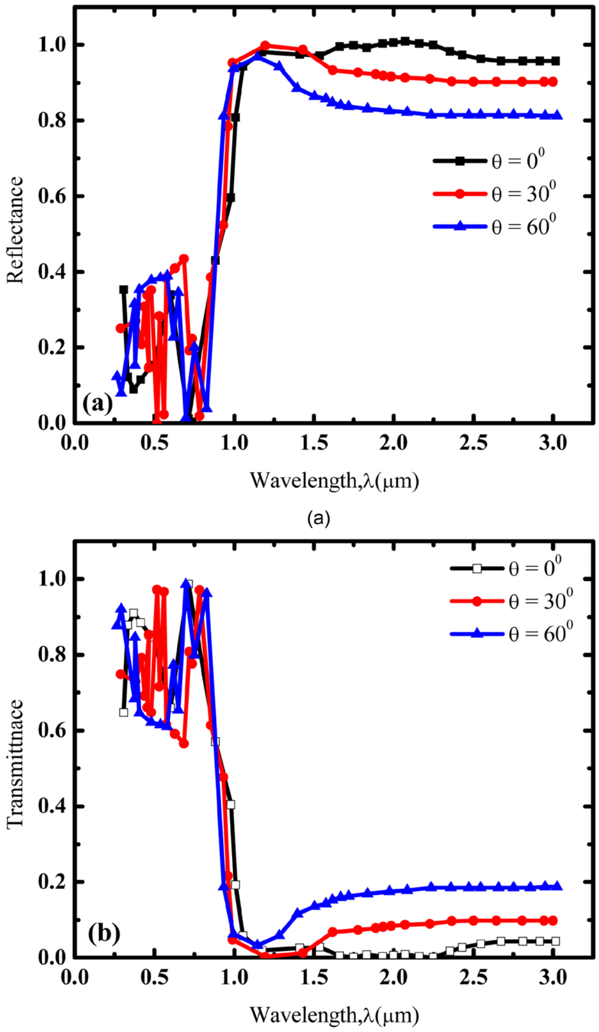


Figure 4. The optical properties of the glazing in the infrared range makes it a potential insulator during the cold nights.



(a)

(b)

Figure 5. The performance of the glazing for different incidence angles. (a) reflectance and (b) transmittance.

Figure 6. The sputter deposition system at laboratories of the faculty of science, University of Witwatersrand (Wits), South Africa.

6. Conclusions

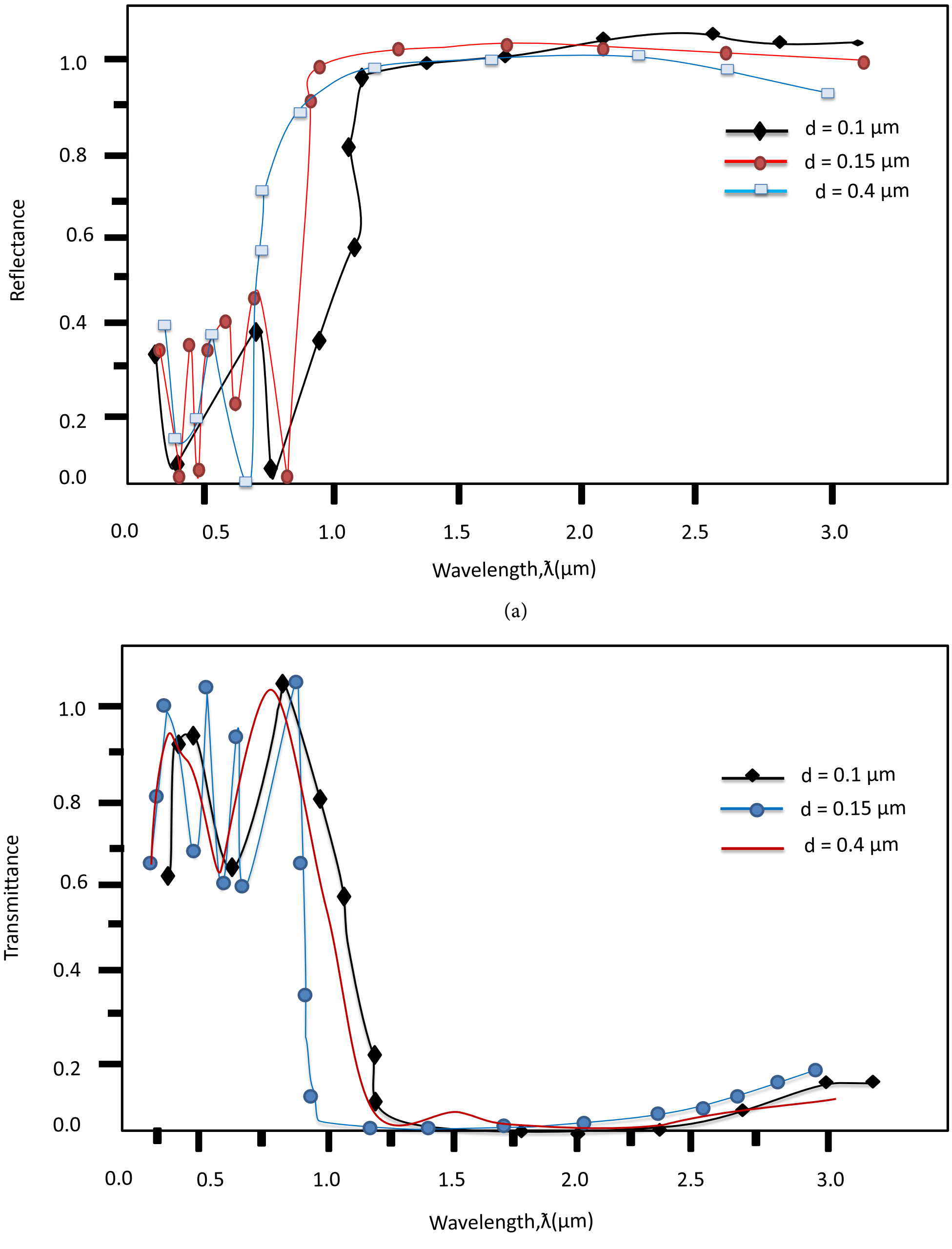
In summary, we have used Rigorous coupled-wave analysis (RCWA) to design a relatively simple and efficient glazing for hot climates. The glazing consisted of ITO and four periodic pairs of Si/SiO_2, deposited on a glass sheet.

RCWA was used to calculate the reflectance and transmittance of the different thicknesses of the layers. The optimum thicknesses of ITO, Si and SiO_2 were found to be (in both simulation and experimental work) 0.1 µm, 0.15µm and 0.4 µm, respectively. The glazing transmitted 78% of the visible light and reflected almost all the infrared radiation from the sun. The optical properties of the glazing hardly depended on the angle of incidence of solar radiation. This makes it ideal for all hours of the day. During the night, in winter, it could act as an insulator to reflect the heat back inside the room. It satisfies the conditions for comfort in both the hot days of summer and the cold nights of winter.

The preparation of the filter and the testing were performed at the laboratories of the Faculty of Science, University of Witwatersrand, South Africa. Indium tin oxide (ITO), silicon (Si) and silicon dioxide (SiO_2) were used as sputtering targets. The magnetron sputtering system was used to deposit a thin film from sputtering targets onto the substrate.

The experimental results were found to be in good agreement with the simulation results.

It can be concluded that the proposed filter has the advantage that it is relatively simple, efficient, and compared with commercial smart windows, it does not need any external source of energy to control its optical properties. It can be



(a)

(b)

Figure 7. Reflectance and transmittance of the filter.

used in hot climates in buildings and vehicles.

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