

Optimization Design of Four-Layer Composite Ultraviolet Protective Glass Based on AM1.5G Spectrum

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Abstract. Along with the popularization of the healthy building concepts, the indoor ultraviolet radiation control has attracted increasing attention in architectural optical design. Traditional household glass product design is usually empirical or based on fixed-thickness single-layer glass to produce multilayer glass. To solve this problem, this paper designs a four-layer film, glass, glass, film (FGGF) composite structure. Considering optical interference and material absorption under the standard solar spectrum (AM1.5G) provided by the American National Renewable Energy Laboratory (NREL), it established an optimization model that minimizes the weighted average transmittance value in the ultraviolet band (280–400nm). Based on the ant colony algorithm, it can obtain the optimal thickness value for each glass layer. Under the condition of a total thickness less than 10 mm, it can reduce the weighted average transmittance of ultraviolet light by about 14.4% compared with ordinary 10 mm single-layer glass. The proposed framework also has good universality for materials. After applying the algorithm to other materials, a better thickness design can still be obtained, which has an algorithm reference value for the production of daily glass.

Keywords: Ultraviolet protection, Ant colony algorithm, Thickness optimization

1. Introduction

Ultraviolet (UV) radiation acts as a harmful part of the solar spectrum that exerts significant effects on building materials and the skin of humans. A large number of studies indicate that exposure to UV wavelengths (280–400nm) for a long time not only accelerates the degradation of substrates and induces color fading but also increases the risk of cutaneous malignancies and cataracts [1, 2]. Therefore, architectural glass, as the main interface between indoor and outdoor environments, determines the health of humans and the lifespan of indoor furniture and electronic devices.

Traditional UV protection strategies predominantly rely on absorption-based additives or reflection-based coatings. While absorption-typed glass enhances intrinsic UV attenuation via doping with rare-earth ions or transition metal oxides, using this method will increase people's living costs and reduce the transmittance of visible light, which will result in less indoor lighting [3]. Another method is to use the principle of thin-film interference, such as a Bragg reflector composed of stacked multiple layers of dielectric materials [4]. However, these architectures often need

complicated deposition processes and exhibit high sensitivity to incident angle variations, which may constrain their universality.

Recently, a new design integrating thin-film absorption with bulk material interference has gained increasing attention. Combining functional films with conventional glass substrates makes this strategy achieve spectral selectivity without significantly increasing costs [5, 6]. However, new problems will also have to be faced: how to determine the optimal thickness of each layer to achieve efficient protection against the actual solar spectrum rather than monochromatic light, and also meet the requirements for light-weight design. The synchronous optimization of multiple thicknesses belongs to a multivariable, nonlinear, discrete problem, and traditional numerical optimization methods do not perform well here, making it difficult to find the global optimum. Although the ant colony optimization (ACO) algorithm has demonstrated powerful global search capabilities in combinatorial optimization problems [7-9]. This has not often been used in the design of optical properties for architectural glass using composite materials, which include nano-films on a millimeter substrate, especially when taking into account the true weighted solar spectrum.

2. Methods

The first and foremost aim of this work is to reduce the average transmittance in the solar ultraviolet range (280–400 nm), which can be achieved by finding the best thickness of each layer of a four-layer Film-Glass-Glass-Film (FGGF) system. For this purpose, it has introduced a systematic approach consisting of three fundamental steps: modeling of the four-layer optical system, developing a single-layer transmittance equation based on the principle of optical interference, and incorporating empirical knowledge of the standard AM1.5G solar spectrum. Finally, it used an Ant Colony Optimization (ACO) technique for exploring the optimization space and determining the optimal thickness values [10].

2.1. Specific four-layer composite architecture(FGGF)

Target Architecture for Optimization Problem The target architecture for optimization is the above-mentioned FGGF design that is expected to be assembled successively from the light source side as follows: L_1 - UV absorbing film; L_2 - glass substrate; L_3 - glass substrate; and L_4 - UV absorbing film. It can see, although Layers 1 and 4 are identical nanometer-sized films that are responsible for the bulk of the UV absorption process, Layers 2 and 3 serve as glass substrates, whose main function lies in the interference of light. **Optimization Problem Variables** The variables for the optimization problem consist of the layer thicknesses vector $L = [L_1, L_2, L_3, L_4]$. In addition, the requirement to make the product as lightweight as possible is very important and imposes a firm constraint on the overall thickness of no more than 12 mm.

2.2. Formulation of single-layer transmittance

The transmittance of light passing through this uniform material is affected by reflection, absorption, and interference. It can use the following formula to calculate it:

$$T(\lambda, L) = \frac{(1-R)^2 \cdot e^{-aL}}{(1-R)^2 + 4R \cdot \sin^2\left(\frac{2\pi nL}{\lambda}\right)} \quad (1)$$

λ is used to represent the incident wavelength in this formula, whereas L stands for the physical thickness of the film. R is used to denote the reflectivity coefficient for reflection of light at the air-

film interface where $n_0 = 1.0$, $R = ((n - n_0)/(n + n_0))^2$. Meanwhile, α refers to the linear absorption coefficient. It must be mentioned that the $\sin^2$ factor in the denominator is used to describe the effects of interference caused due to phase differences.

Extending this principle to the proposed FGGF architecture, the total spectral transmittance $T_{total}(\lambda)$ derived as the product of the individual layer transmittance:

$$T_{total}(\lambda) = T_1(\lambda) \times T_2(\lambda) \times T_3(\lambda) \times T_4(\lambda) \quad (2)$$

2.3. Construction of spectral weighting based on Gaussian fitting to AM1.5G

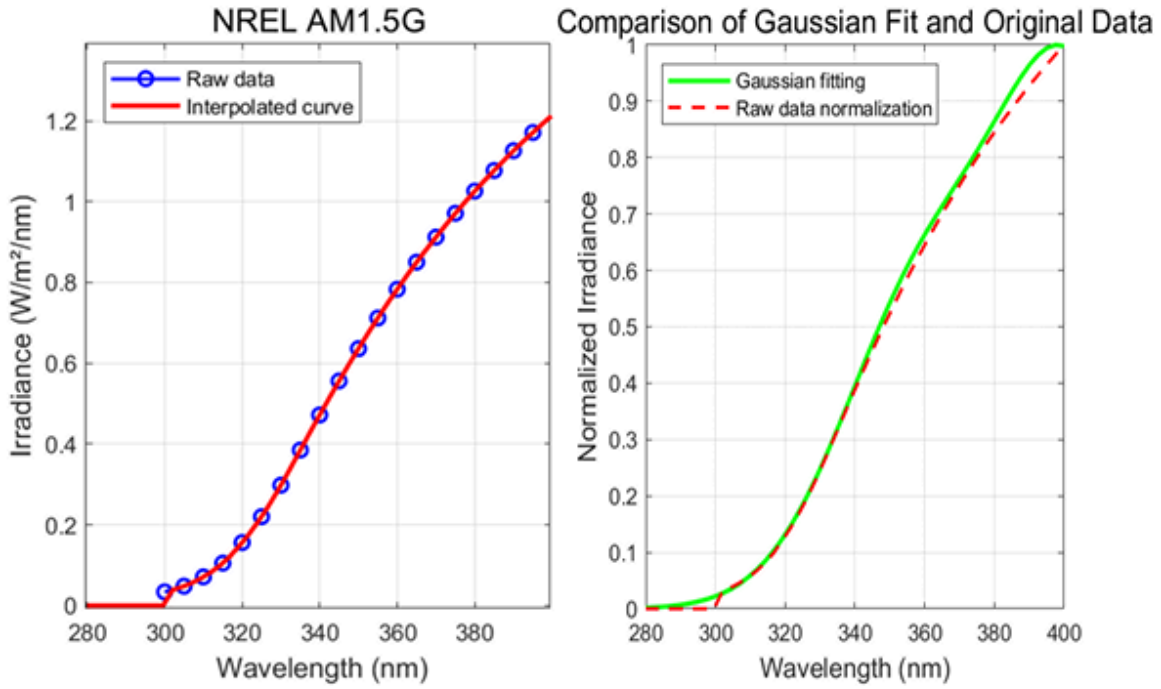


Figure 1. Gaussian fitting curve based on AM1.5G spectrum (photo/picture credit: original)

To accurately reflect the energy distribution of realistic solar ultraviolet radiation, the raw spectral irradiance data $I_{raw}(\lambda)$ were subjected to a dual-Gaussian function fitting procedure. This approach yields a continuous and smooth spectral profile characterization (Fig. 1). The fitting function is formulated as follows:

$$I_{fit}(\lambda) = A_1 \cdot \exp\left(-\frac{(\lambda - \mu_1)^2}{2\sigma_1^2}\right) + A_2 \cdot \exp\left(-\frac{(\lambda - \mu_2)^2}{2\sigma_2^2}\right) \quad (3)$$

Here, A_1 and A_2 denote the amplitudes, μ_1 and μ_2 represent the central wavelengths, and σ_1 and σ_2 correspond to the width parameters. These coefficients were optimized via the least squares method to ensure $I_{fit}(\lambda)$ provides the best possible approximation to $I_{raw}(\lambda)$. Subsequently, the fitted spectrum was normalized over the target band to derive the spectral weighting function $W(\lambda)$:

$$W(\lambda) = \frac{I_{fit}(\lambda)}{\sum_{\lambda=280}^{400} I_{fit}(\lambda)} \quad (4)$$

This function is instrumental in calculating the weighted average transmittance, effectively biasing the optimization process toward spectral regions characterized by higher solar irradiance.

2.4. Thickness optimization via the classical ant colony algorithm

To navigate the discrete and multi-dimensional search space of the FGGF structure, this study employs an Ant Colony Optimization (ACO) algorithm, framing the layer-by-layer thickness selection as a path-searching problem. Each candidate thickness is treated as a node, and an ant's traversal through these nodes constitutes a complete solution vector L . The algorithm initiates with a uniform pheromone level $\tau_{ij}(0)$ across all paths to ensure broad exploration. During the search, an ant selects the j -th candidate thickness for the next layer based on a probability $p_{ij}(t)$ that balances accumulated pheromones against heuristic guidance:

$$p_{ij}(t) = \frac{[\tau_{ij}(t)]^\alpha \cdot [\eta_{ij}]^\beta}{\sum_{s \in \text{allowed}_k} [\tau_{is}(t)]^\alpha \cdot [\eta_{is}]^\beta} \quad (5)$$

Critically, the heuristic function η_{ij} is engineered to penalize high-transmission options by defining it as $\eta_{ij} = 1/(T_{avg,i} + \epsilon)$, where $T_{avg,j}$ represents the mean UV transmittance of the candidate; this inverse relationship inherently steers the search toward optically dense layers. Following each iteration, pheromone trails evaporate according to $\tau_{ij}(t+1) = (1 - \rho) \times \tau_{ij}(t)$ prune weak paths, after which successful ants reinforce their routes proportionally to solution quality via $\Delta\tau_{ij}(t) = Q/J_q$. The process terminates upon reaching the maximum iteration count, at which point the historical best solution is extracted as the optimal thickness configuration.

3. Results and analysis

3.1. Parameter design

Parameter settings are shown in Tables I and II.

Table 1. Material parameters for each layer

Number of floors	material type	Absorption coefficient α (mm ⁻¹)	refractive index n
L ₁	Ultraviolet Absorption Film	0.1	1.5
L ₂	optical glass	0.01	1.5
L ₃	optical glass	0.01	1.5
L ₄	Ultraviolet Absorption Film	0.1	1.5

Table 2. Ant Colony Algorithm parameter settings

parameter	symbol	numeric value	explain
Ant population size	m	30	Number of ants per generation
The importance of pheromones	α	1	Control the influence of pheromones

Table 2. (continued)

Heuristic Importance Level	β	3	Control the influence of heuristic information
Pheromone volatilization coefficient	ρ	0.1	Control the rate of information pheromone volatilization
Pheromone increment constant	Q	1	Increase in control pheromone levels
Maximum iteration count	itermax	80	Algorithm Termination Condition

3.2. Optimization

Optimization process: Best transmittance and average transmittance of each generation

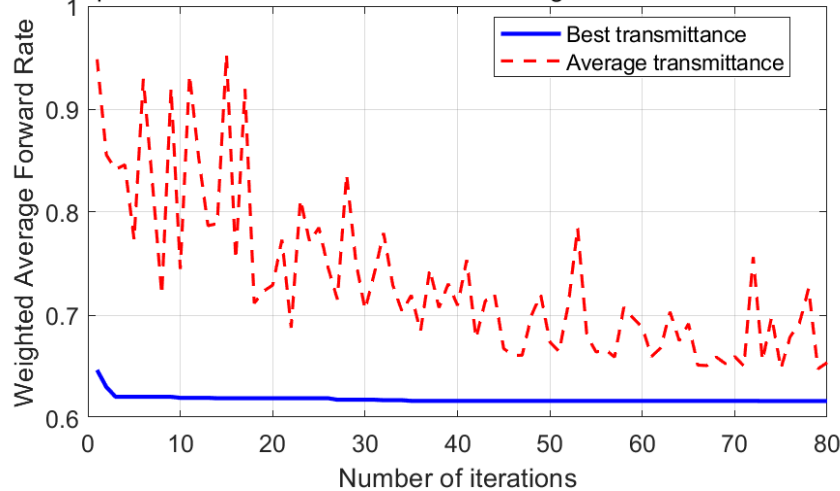


Figure 2. Convergence curve of Ant Colony Algorithm (ACO) (photo/picture credit: original)

As shown by Fig. 2 below, the convergent nature of the optimal transmittance shows that once generation 80 is reached, the process of optimization will definitely be stable. Table III gives the thickness of each layer for optimal transmittance according to the algorithm results obtained. To find out if indeed the procedure employed to optimize the process is stable, 30 simulations were performed using the ACO algorithm, but with identical parameters that have been used before. The statistical analysis showed that the optimal combination of thickness occurred 25 times out of 30 trials, giving a probability of 83.3%. On average, the minimum weighted transmittance was 0.6161 with a standard deviation of 0.0004. The very low standard deviation proves that the problem of local convergence is not experienced in the use of this algorithm. The stability of this algorithm is crucial because any slight variation during manufacture will affect the performance of this product as a blocker of UV rays.

Table 3. Optimized structural parameters of FGGF

Parameter	Symbol	Optimization Value
Thickness of the first film layer	L_1	61.1
Second layer of glass thickness	L_2	2.71
Thickness of the third layer of glass	L_3	4.44
Thickness of the fourth film layer	L_4	61.1
aggregate thickness	L_{total}	7.27
Weighted average transmittance	J	0.6156

The optimized structure of FGGF has an overall thickness of merely 7.27 mm, which is well under the constraint limit of 12 mm, while the thickness of both the films is 61.1 nm, nearly equal to the $L_{opt} = 4 \times 1.5340 \approx 56.7$ nm, showing the consistency of the optimized output with optical designs.

3.3. Spectral characteristic analysis

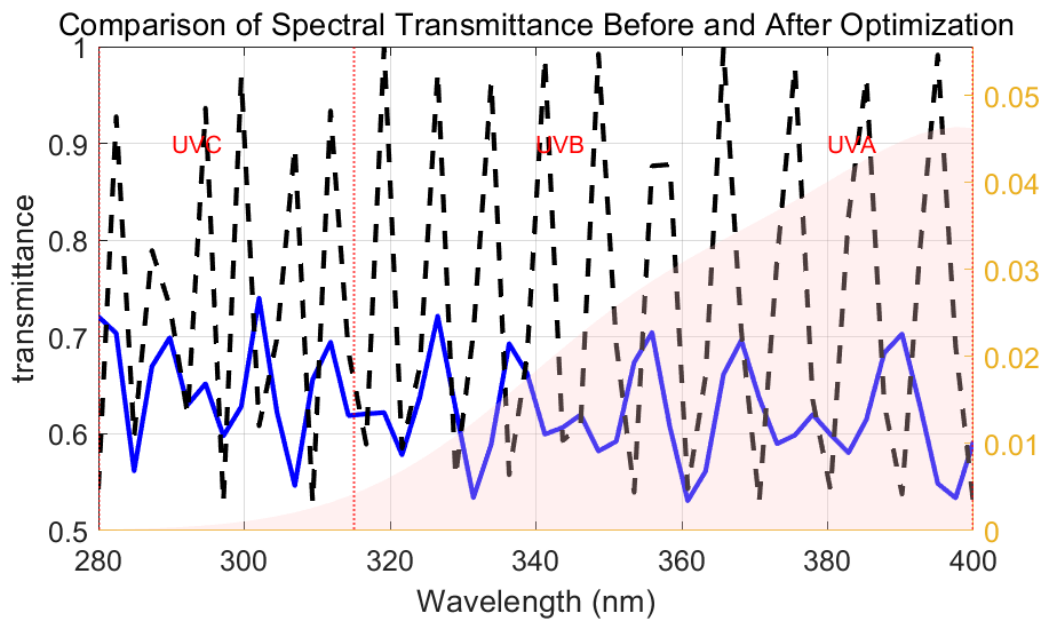


Figure 3. Comparison of transmission spectra between optimized structure and ordinary glass (photo/picture credit: original)

Transmittance spectra of the optimized structure and conventional glass in the ultraviolet spectrum are presented in Fig. 3. As follows from the graph, it can be stated that: General tendency: The optimized structure is characterized by lower transmittance in the entire ultraviolet spectrum (280-400 nm) than conventional glass.

Peak suppression: The optimized structure has a lowest value of transmission of 0.45 in the peak region of AM1.5G spectra (340 - 380nm), while the conventional glass gives a highest value of transmission of 0.82 in this region, proving good peak suppression.

Band-dependent performance: In the UVC wavelength region (280 – 315nm), the optimized structure gives an average transmission of 0.52 compared to 0.78 of the conventional glass; In the

UVB wavelength region (315 – 400nm), the optimized structure gives an average transmission of 0.63 compared to 0.81 of the conventional glass. The new structure is 33.3% and 22.2% better than the old structure in these two regions, respectively.

It should be mentioned that, in addition to providing aggressive protection against UV rays, the optimized design allows for maintaining the high rate of visible light transmission. The calculations demonstrate that the average transmittance in the visible range of the electromagnetic spectrum (400-760nm) is greater than 75%. This allows for maintaining a balance between

3.4. Parameter analysis

When L1 is fixed at 64nm and L4 is fixed at 58nm, the weighted transmittance of the L2-L3 plane

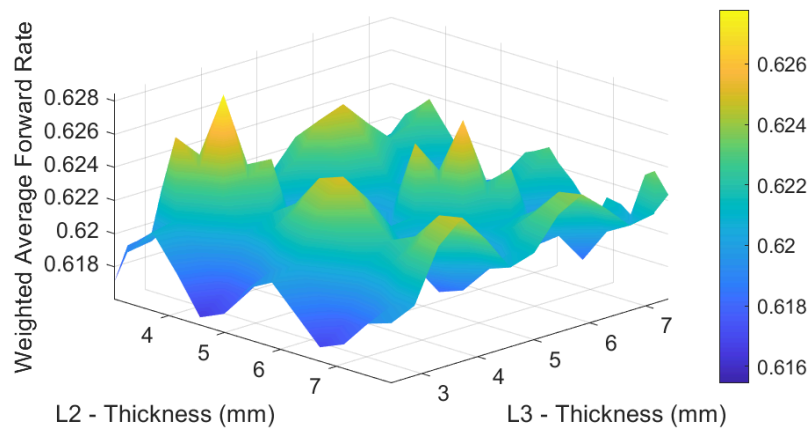


Figure 4. Response surface analysis plot of intermediate glass layer thickness (photo/picture credit: original)

Fig. 4 presents the response surface graph on the plane of thicknesses of intermediate glass films (L_2 , L_3), when the thicknesses of the outer layers (L_1 , L_4) are kept constant. It is evident from Fig. 4 that the weighted mean of the transmittance of the system in question in the ultraviolet range is changing in a non-monotonic way from 0.615 to 0.626, and its main reason is the optical path change associated with the thickness of the glass substrate. Nevertheless, it should be noted that despite all these changes, the maximum deviation is only 0.011, which indicates that small variations in the thickness of the glass substrates are not crucial for the UV blocking ability of the whole system. Moreover, it is evident that the graph does not show a regular pattern as L_2 and L_3 do not have identical importance in the optical path due to their distinct positions. This conclusion implies that the ant colony optimization approach must be utilized for global optimization in this research since the gradient descent technique tends to converge at a local optimum rather than the global one.

4. Discussion

4.1. Comparative analysis with existing studies

The effectiveness of the methodology can be further illustrated through the comparative study presented in Table IV, which summarizes the findings of the most recent studies conducted on the topic of UV-protective glazing. As shown by the results below, the proposed FGGF framework is unique in combining ACO methodology with AM1.5G weighting spectra.

Table 4. Performance comparison of different UV-protective glass structures

Study	Structure Type	Total Thickness (mm)	UV Transmittance	Optimization Method	Spectral Weighting
This Work	FGGF (4-layer)	7.27	0.6156	Ant Colony Algorithm	AM1.5G
Liu et al. [4]	Triple Glazing	10.5	0.452	Genetic Algorithm	Uniform
Chen et al. [3]	Multilayer Thin Film	1.2	0.35	Empirical Design	Single Wavelength
Wang et al. [9]	Single Coating	5.0	0.68	Experimental Optimization	—

Insights from the comparison are the following:

First, the use of AM1.5G spectrum weighting results in an optimization process that is much closer to real-world conditions than any other uniform or monochromatic assumption. Second, the four-layer FGGF architecture represents the best compromise between thickness and optics. And third, the ACO technique works very efficiently in solving this kind of discrete problem.

4.2. Practical implications

Some of the benefits of the optimal FGGF configuration for its use in architecture include:

Low Weight: The structure has an overall thickness of only 7.27 mm, resulting in a 27.3% weight reduction compared to ordinary 10-mm thick glass. **High Performance:** The UV protection capability is enhanced by 14.4%, providing robust shielding for occupants and interior furnishings.

Cost Effectiveness: In addition to that, the construction employs just two basic components—the functional films and glass—resulting in easier logistics and reduced production costs. **Visible Light Control:** Besides offering UV protection, the material also allows good visible light transmission (around 75%), thus not depriving the interior of light.

4.3. Limitations and future work

- **Limitations.** In spite of the fact that some positive outcomes have been achieved through this model, there are some disadvantages related to the model. In the present model, the assumption is that the material parameters do not depend on wavelengths. On the contrary, in reality, the refractive index and the absorption coefficient possess some dispersion properties. In addition, the present study ignores the role played by time because of solar altitude in the case of normal incidences.

- **Future Work.** Possible directions for future research may involve improving the optical model with regard to dispersion effects in the material. Another aspect that future research can focus on is the angular dependence of the device by testing it using non-perpendicular incident light beams. Finally, another extension of the optimization model may consider incorporating additional layers or focusing on other design criteria.

5. Conclusion

Ultraviolet protection is important in architectural design. This study proposes a physical model for thin-film-glass-glass-thin-film (FGGF) composite structures, using AM1.5G sunlight as the incident light source, and employs the Ant Colony Optimization (ACO) algorithm to find the optimal combination that maximally reduces the transmittance of ultraviolet rays.

It has determined the optimal size for the FGGF, with a total thickness of only 7.27mm. The optimized FGGF configuration is determined as $L_1=61.1\text{nm}$, $L_2=2.71\text{mm}$, $L_3=4.44\text{mm}$, $L_4=61.1\text{nm}$. This structure achieves a weighted UV transmittance of 0.6156, which is 14.4% lower compared to conventional 10 mm single-layer glass (transmittance 0.76). This result meets both the product's lightweight design and high-performance protective requirements.

Convergence was achieved by the ACO algorithm after about 80 generations, showcasing strong global searching capability. This is due to the interaction effect between film absorption, the interference effect, and the spectral match of the designed structure.

In conclusion, this study can contribute towards an optimal approach in the design of effective UV-blocking windows. The approach presented herein shows great potential for extension in other applications in optics, providing both theoretical understanding and practical possibilities in materials science.

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