Dean&Francis

ISSN 2959-6157

Three-Layer Glass Thickness Optimization and Solar Heat Gain Minimization Based on Quantum Genetic Algorithm

Gang Zheng

School of Optoelectronics and Information Engineering, Fujian Normal University, Fuzhou. Fujian, 350117, China
corresponding author:
136152023098@student.fjnu.edu.cn

Abstract:

This study focuses on improving the thermal performance of external windows. Building operations account for 21% of total societal energy consumption, and heating through external windows can account for 40-50% of the air conditioning cooling load. Although three-layer glass windows have great potential, their performance hinges on the micro configuration of layer thicknesses, and an empirical equal-thickness design is challenging to balance the trade-off between lighting and insulation. Traditional genetic algorithms (GAs) are prone to premature convergence when solving high-dimensional, nonlinear optimization problems. This study focuses on the 300-2500 nm solar spectrum and, for the first time, applies an improved quantum genetic algorithm (QGA) to the collaborative optimization of three-layer glass window thicknesses (l_1, l_2,l_3). The core innovation lies in: Based on the Fabry-Perot interference principle, an analytical formula for the single-layer equivalent model was adopted as the optical transmission model. This method has the advantages of clear physical meaning and high computational efficiency compared to the general transmission matrix method (TMM). Simulation experiments show that the optimized thickness combination ($l_1 = 6.08mm$, $l_2 = 6.08mm$, $l_3 = 8.37mm$) successfully achieves spectral-selective control. The average transmittance in the visible light region remains at 0.7957, while the transmittance in the near-infrared region is suppressed to 0.7860. Compared with traditional design, the energy-saving potential is significant. This study provides new algorithmic tools and theoretical support for the design of high-performance energy-saving windows.

Keywords: Premature Convergence; Quantum Genetic Algorithm; Adaptive Revolving Door; Thickness Optimization; Spectral Selectivity.

1. Introduction

According to the *China Building Energy Consumption Research Report*, the proportion of energy consumption during building operation to the total energy consumption of the whole society is as high as 21%, Among them, in areas with hot summers and cold winters, the solar radiation transmitted indoors through building windows can account for 40% -50% of the summer air conditioning cooling load [1]. Therefore, improving the thermal performance of external windows is a key breakthrough in curbing the growth of building energy consumption and achieving sustainable development. Currently, although single-layer and double-layer glass windows still dominate the market, their thermal insulation performance is insufficient when facing extreme solar radiation in southern regions (such as the summer solar radiation intensity in Shanghai reaching over 1200 W/m ^{2}) [2]. In contrast, triple-glazed windows are widely recognized as an important evolutionary direction for high-performance energy-efficient building exterior windows. This is due to their ultra-low heat transfer coefficient (1.559 W/(m²·K)) resulting from the additional air interlayer and the potential for spectral-selective regulation achieved through structural design [3]. However, the comprehensive performance of the glass system is not solely determined by the number of layers. The microscopic thickness of each glass layer is the core parameter that determines its optical properties (transmission, reflection, and absorption). Empirical equal-thickness design often has difficulty in coordinating the contradiction between lighting and heat insulation, and cannot fully exploit the energy-saving potential of the three-layer structure. This research shows that by optimizing thickness and exploiting optical interference, it is possible to suppress near-infrared thermal radiation while maintaining high visible light transmittance [4].

In the field of building performance optimization, intelligent algorithms have gradually broken through the limitations of traditional empirical design. For example, Granqvist et al. conducted a systematic review on electrochromic smart window technology based on oxide films, providing a theoretical foundation for spectral-selective regulation [5]; Asadi et al. proposed a multi-objective optimization method for building energy efficiency, integrating genetic algorithms and simulated annealing algorithms to significantly reduce building energy consumption [6]; Gossard et al. employed a multi-objective optimization approach to enhance the thermal performance of building envelopes, validating the effectiveness of genetic algorithms in building energy-saving design [7]. However, when dealing with high-dimensional, non-linear problems with multiple local extrema (such as the thickness optimization of triple-glazed glass), the traditional genetic algorithm (GA) is prone to premature convergence and slow convergence. This limitation has also been confirmed in complex optimization problems, such as flexible job-shop scheduling [8]. Therefore, it is necessary to explore algorithms with stronger global search ability and better convergence performance to improve the effect of optimizing the thickness of triple-glazed glass.

In recent years, the Quantum Genetic Algorithm (QGA) has effectively improved population diversity and global search efficiency by introducing qubit encoding and a quantum rotation gate update mechanism, demonstrating great potential for complex engineering optimization. For example, Li applied QGA to identify the internal physical parameters of PIN power diodes, achieving significantly better accuracy and convergence speed than traditional algorithms [9]. Subsequently, the superiority of QGA has been verified in many complex engineering optimization problems. For example, Layeb applied the improved QGA to combinatorial optimization problems, demonstrating its fast convergence and high accuracy, guiding its introduction into the field of building performance optimization [10]. However, there are still a few systematic research reports at home and abroad on the application of QGA, an advanced algorithm, to optimize the micro material parameters (such as glass thickness) of building envelope structures, especially for the goal of selective modulation of solar spectra. In view of this, this study is based on the urgent need for energy conservation in southern summer buildings, aiming to apply the quantum genetic algorithm for the first time to the collaborative optimization design of the thickness $(l_1,\ l_2,l_3)$ of each layer of a three-layer glass window for the solar spectrum in the 300-2000 nm band.

2. Materials and Methods

2.1 Physical Model and Objective Function Construction

2.1.1 Theoretical basis of the optical transmission model

The optical transmission model in this study is based on the Fabry-Perot interference principle, which describes the propagation of light in a single-layer medium. For a single-layer medium, considering its multiple reflections and interference effects at two interfaces, there exists an exact analytical solution for its transmittance, which can be expressed as:

$$A_t = \frac{Te^{-i\delta/2}A_i}{1-Re^{-i\delta}} \tag{1}$$

Among them, A_t is the amplitude of transmitted light, A_i is the amplitude of incident light, T is the amplitude transmission coefficient, R is the amplitude reflection coefficient, δ is the one-way phase difference, $e^{-i\delta/2}$ is the one-way phase delay factor, i 为 is a complex unit.

$$T_{single} = \frac{I_t}{I_i} = \frac{(1-R)^2}{(1-R)^2 + 4Rsin\left(\frac{\delta}{2}\right)^2} \tag{2}$$

Among them, T_{single} is the total light intensity transmittance of the dielectric layer, I_t is the transmitted light intensity, I_i is the incident light intensity, and $(1-R)^2$ is the physical transmittance corresponding to the intensity of light passing through the interface twice (incident and exit) without considering interference effects, $4Rsin\left(\frac{\delta}{2}\right)^2$ is the interference effect correction term.

The phase difference generated by light passing through the dielectric layer is $\delta = \frac{4\pi nd}{\lambda}$, n is the refractive index of the medium, d is the layer thickness, and λ is the wavelength of the light wave.

The standard solar spectral irradiance data (AM 1.5) used in the simulation are referenced to Zhao's research on the Earth's reflected solar spectral radiation observation technique based on the Lagrange point of the Earth-Moon system. Fig. 1 shows the complete distribution of solar spectral irradiance as a function of wavelength. The horizontal axis of the graph represents the wavelength of light, measured in nanometers, ranging from 200 to 2500, spanning the ultraviolet to infrared regions. The vertical axis represents the spectral irradiance, measured in watts per square meter per nanometer, which is the solar radiation power incident vertically on each square meter within a wavelength range of 1 nanometer. The red curve in the Fig. 1 clearly shows the distribution of solar radiation energy. Near the blue-purple region of visible light, with shorter wavelengths, the curve peaks, indicating that the sun's energy is most concentrated in this band. Subsequently, the curve showed an overall downward trend, with irradiance intensity decreasing monotonically as the wavelength increased towards the infrared.

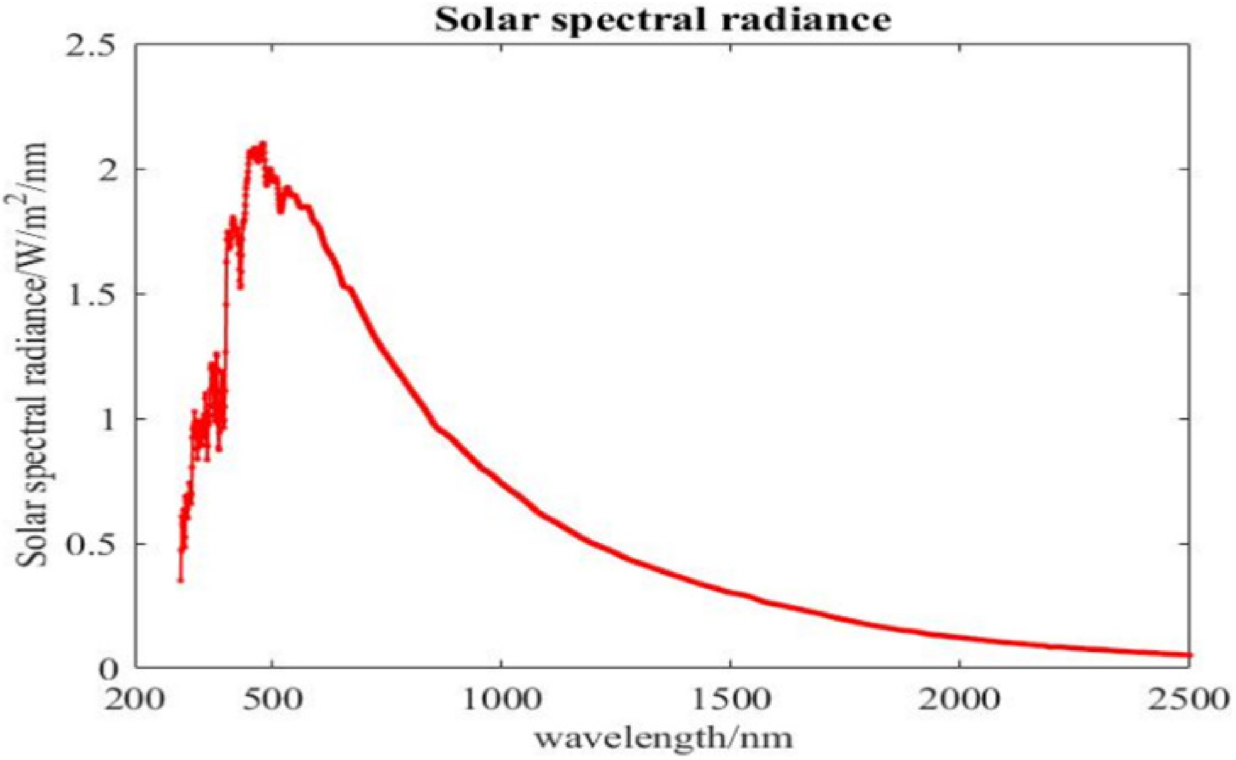

Fig. 1 Standard solar spectral irradiance data (AM 1.5) [11]

The transmission properties of a single-layer medium are shown in Fig. 2. This chart illustrates the transmission characteristics of a single-layer dielectric plate, with the horizontal axis representing frequency (GHz) from 50 to 75 and the vertical axis representing transmittance (dimensionless) from 0.6 to 1.0. The red broken line in the graph clearly demonstrates the periodic fluctuation of transmittance with frequency variation: transmission peaks (approaching 1.0) occur at approximately 53 GHz, 61 GHz, and 69 GHz, indicating that electromagnetic waves at these frequencies pass through the dielectric plate with almost no loss due to constructive interference; Transmittance valleys (about 0.65) appear at frequencies such as approximately 57 GHz and 65 GHz, reflecting partial reflection of energy due to destructive interference. This regular oscillation originates from multiple reflections and interference of electromagnetic waves at the upper and lower boundaries of the dielectric slab. The overall trend reflects the dielectric slab's filtering characteristics for electromagnetic waves in specific frequency bands, which can be utilized in the design of frequency-selective devices.

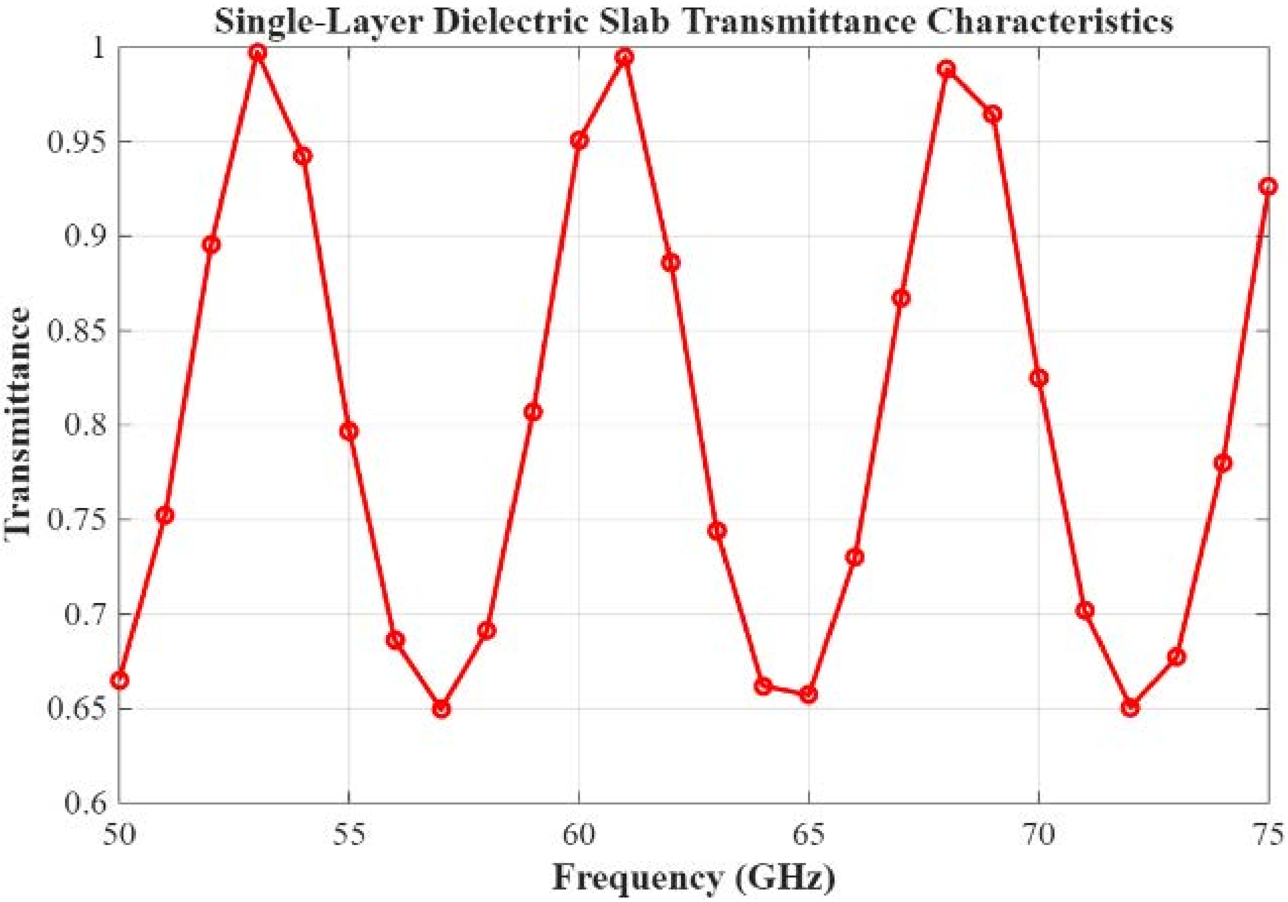

Fig. 2 Transmission characteristics of a single-layer medium (Original)

Regarding the three-layer glass system, see Fig. 3. Fig. 3 clearly illustrates the complete physical process of energy redistribution when sunlight (visible light) passes through a three-layer building envelope structure (such as an insulating glass window). The incident light energy is transmitted, reflected, and absorbed in each medium at specific proportions. The parameters $\tau\left(transmittance\right)$, $\rho\left(reflectance\right)$ and $\alpha\left(absorptance\right)$ marked in the Fig. 3 precisely quantify this process. Ultimately, only a portion of the energy can penetrate all the media layers and enter the interior. At the same time, the rest is either reflected to the outside or absorbed by the materials and converted to heat. This diagram serves as the theoretical foundation for analyzing building lighting, heat gain, and energy-saving design.

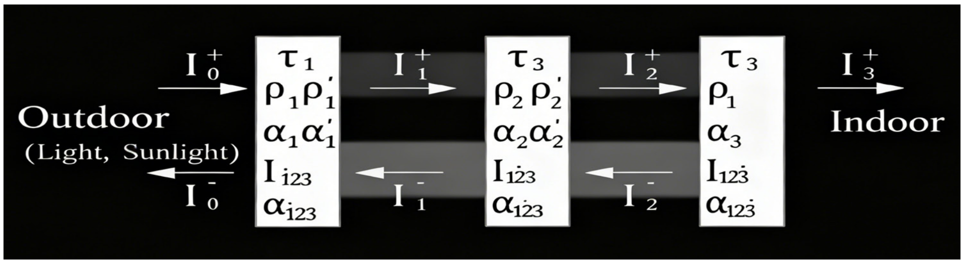

Fig. 3 Schematic diagram of the structure and optical path of a three-layer glass system [12]

By treating each glass layer and the air layer between them as a basic Fabry-Perot interference unit and using the transfer matrix method to recursively solve the electromagnetic field relationships at the boundaries of each layer, the total transmittance of the entire system can be calculated. Research has shown that the light-transmission performance of multilayer glass decreases with increasing layer count, while its reflection and absorption properties increase. The trend of the spectral curve changes is consistent with that of single-layer glass.

2.1.2 Establishment of the objective function

Based on the aforementioned physical model, the optimization objective is to find a set of thickness combinations (l_1, l_2, l_3) that maximizes the spectral response of the glass system to meet building energy efficiency requirements. The objective function is defined as minimizing the total solar heat gain through windows:

$$MnimizeJ = \int_{300}^{2000} I_{solar}(\lambda) * T_{total}(\lambda, l_1, l_2, l_3) d\lambda \tag{3}$$

Where $I_{solar}(\lambda)$ represents the standard AM 1.5 solar spectral irradiance. J is the objective function, λ denotes wavelength, and T_{total} represents the total spectral transmittance function of the three-layer glass system.

The function combines spectral performance for a specific thickness combination with the solar energy distribution via an integral, returning an optimized scalar value J. The smaller the J value, the better the thermal insulation performance of the glass window.

2.2 Improved Quantum Genetic Algorithm Design

Based on the complex optical transmission model and the high-dimensional nonlinear optimization problem established above, although the traditional genetic algorithm is widely used for optimization problems, numerous studies show that it is prone to premature convergence when dealing with complex problems with multiple local extrema [12]. Therefore, this study seeks algorithms with stronger global search ability. Therefore, the improved quantum-inspired genetic algorithm adopted in this study is based on the framework proposed by Wang, Ji, et al. Its main improvements include an adaptive revolving-door strategy and a catastrophe mechanism, which aim to balance global exploration and local development capabilities further [12, 13]. The algorithm flow is shown in Fig. 4.

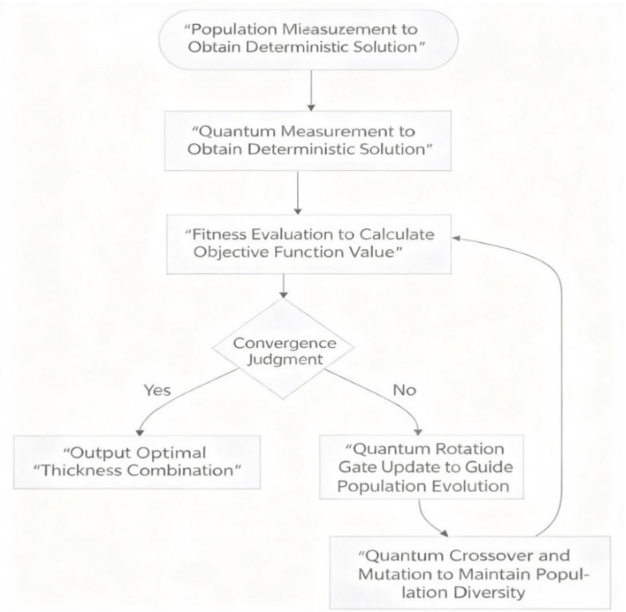

Fig. 4 Flow diagram of quantum genetic algorithm (original)

2.2.1 Quantum bit coding and population initialization

For the optimization problem of three-layer glass thickness, the optimization variables are represented by quantum bit coding. Each qubit is represented as:

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle \tag{4}$$

Wherein, $|\psi\rangle$ represents a qubit state, $|0\rangle and |1\rangle$ represen two basic states in quantum computing. α, β are two complex numbers called probability amplitudes; $|\alpha|^2 + |\beta|^2 = 1$, $|\alpha|^2$ and $|\beta|^2$ represent the probability that the qubit is in the $|0\rangle$ state and $|1\rangle$ state, respectively. For the three thickness parameters (l_1, l_2, l_3), each is encoded using 8 bits, requiring a total of 24 qubits. The population size is set to

$sizepop = 60$, and the α and β of all qubits are initialized to $1/\sqrt{2}$ at the beginning to ensure the maximum diversity of the initial population.

2.2.2 Quantum measurement and fitness evaluation

Convert quantum states into classical binary solutions through quantum measurement operations:

$$binary_i = \begin{cases} 1 if rand(\ ) < |\beta|^2 \\ 0 otherwise \end{cases} \tag{5}$$

Then convert the binary encoding to the actual thickness value:

$$d_i = LB_i + \frac{UB_i - LB_i}{2^8 - 1} \times decimal\left(binary_i\right) \tag{6}$$

Where $LB_i = 5mm$ and $UB_i = 10mm$ are the upper and lower bounds of the thickness parameter.

The fitness function directly adopts the objective function J defined in Section 2.1.2 and is calculated as described in Section 2.1, based on the optical transmission model.

2.2.3 Adaptive update strategy of the quantum revolving gate

Quantum revolving gate update is the core operation of QGA, which guides population evolution by adjusting the probability amplitude of quantum bits. The rotation angle adopts an adaptive strategy:

$$\theta = \theta_{max} \times e^{-\lambda \times gen/MAXGEN} \tag{7}$$

Where θ_{max} is the maximum rotation angle, λ is the attenuation coefficient, gen is the current evolution algebra, and $MAXGEN = 200$ 为 is the maximum evolution algebra. The rotation direction is determined by the fitness difference between the current solution and the optimal solution:

$$\Delta\theta_i = sign(J_{current} - J_{best}) \times \theta \tag{8}$$

When $J_{current} > J_{best}$,rotate in the direction beneficial to J_{best}; On the contrary, the rotation is reversed to avoid premature convergence.

2.2.4 Catastrophe mechanism and local search

To avoid the population falling into a local optimum, a catastrophe mechanism is introduced: when the optimal solution of continuous $N_{stagnant} = 20$ generations is not improved, 30% of the individuals in the population are reinitialized. At the same time, the local search strategy is introduced in the late evolution $(gen > 0.7 \times MAXGEN)$ to fine-tune the neighborhood of the optimal solution.

2.2.5 Algorithm parameter setting and termination conditions

The key parameters are set as follows: population size $sizepop = 60$, maximum evolution algebra $MAXGEN = 200$, initial value of rotation angle $\theta_{MAX} = 0.05\pi$, and catastrophe trigger algebra $N_{stagnant} = 20$. The termination condition is to reach the maximum evolution algebra or 50 consecutive generations of optimal solution, and the improvement is less than 10^{-6}.

The improved QGA algorithm maintains population diversity through quantum bit coding and combines the adaptive revolving gate and the catastrophe mechanism to balance global exploration and local development effectively. It is especially well-suited for solving high-dimensional, nonlinear, complex optimization problems, such as glass thickness optimization.

3. Results and Analysis

3.1 Analysis of the Thickness Influence Law

To deeply explore the influence mechanism of the thickness of each glass layer on the system's optical performance and provide goal guidance for the subsequent optimization algorithm, this paper first conducted a parameter sensitivity analysis of the system, with the results shown in Fig. 5.

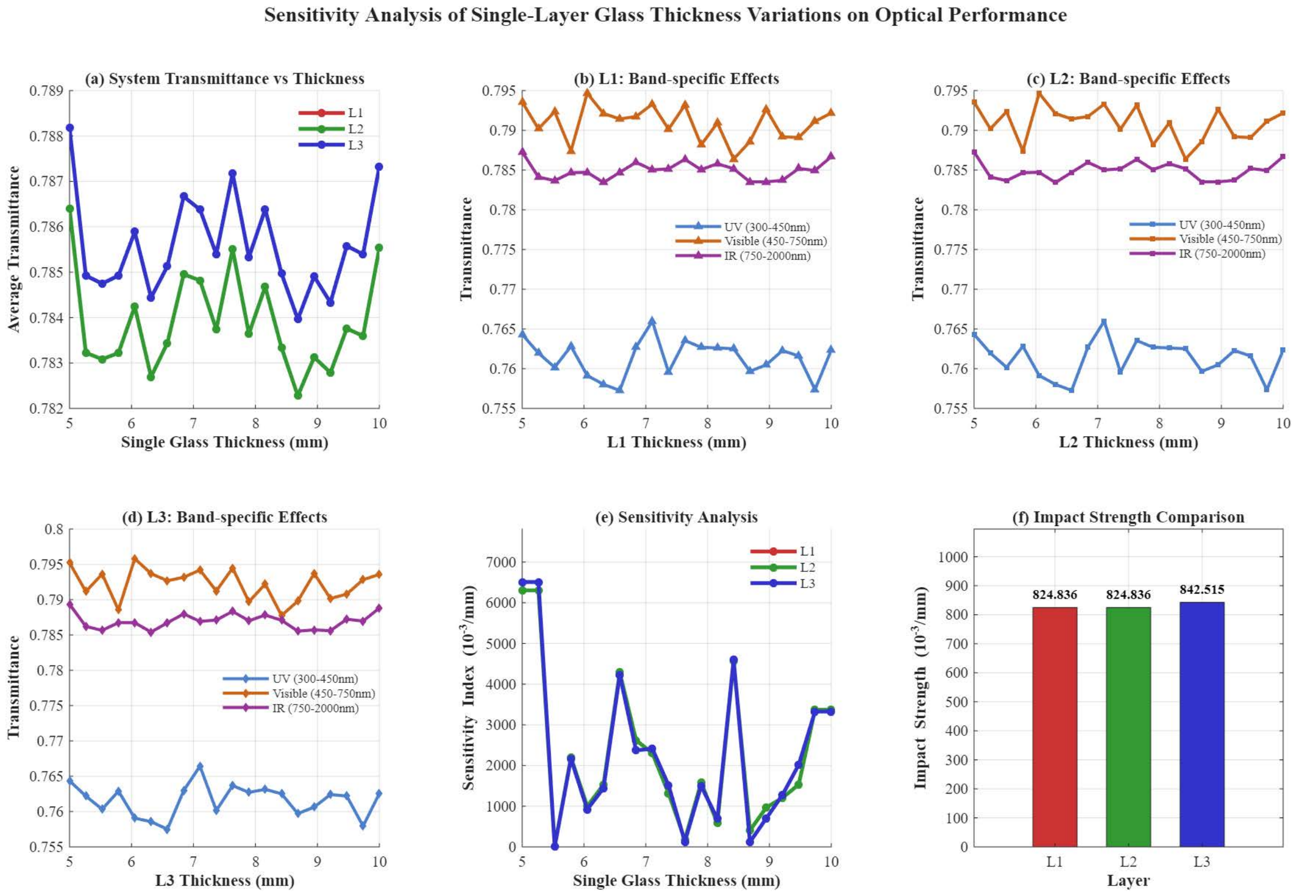

Fig. 5 Sensitivity analysis of single-layer glass thickness change to system spectral transmittance (original)

As shown in Fig. 5(a), with increasing layer thickness, the average transmittance across the entire system band shows a monotonic decrease. The analysis shows that the trends of the $l_1,l_2,andl_3$ curves are similar. However, there are significant differences, indicating that the influence of each layer's thickness on the average transmittance is similar yet layer-specific. Further spectral sub-band analysis reveals a more refined rule of influence. Fig. 5 (b) (c) (d) shows that the influence of the thickness change of each layer of glass on different spectral bands is significantly different. The thickness of each layer has the most significant effect on UV transmittance in the UV band (300-450nm), and transmittance changes relatively gently in the visible band (450-750nm), indicating good stability. In the infrared band (750-2000nm), the influence of thickness change on infrared transmittance lies between that of ultraviolet and visible light.

This discovery provides an important basis for spectral-selective regulation. By optimizing the thickness combination, the transmission characteristics of ultraviolet and infrared radiation can be effectively controlled while maintaining sound visible light transmission. The sensitivity analysis in Fig. 5 (E) shows that the sensitivity index of each layer thickness exhibits nonlinear behavior with thickness, and it is high in a specific thickness range. The comparison of influence intensities in Fig. 5(f) further quantifies the relative importance of each parameter and provides priority guidance for multi-parameter optimization. To sum up, the intrinsic sensitivity analysis reveals the hierarchical effect of glass thickness on spectral transmittance, confirms the feasibility of achieving spectral-selective regulation through thickness optimization, and lays a theoretical foundation for multi-parameter collaborative optimization in the quantum genetic algorithm.

3.2 Analysis of Algorithm Convergence Performance

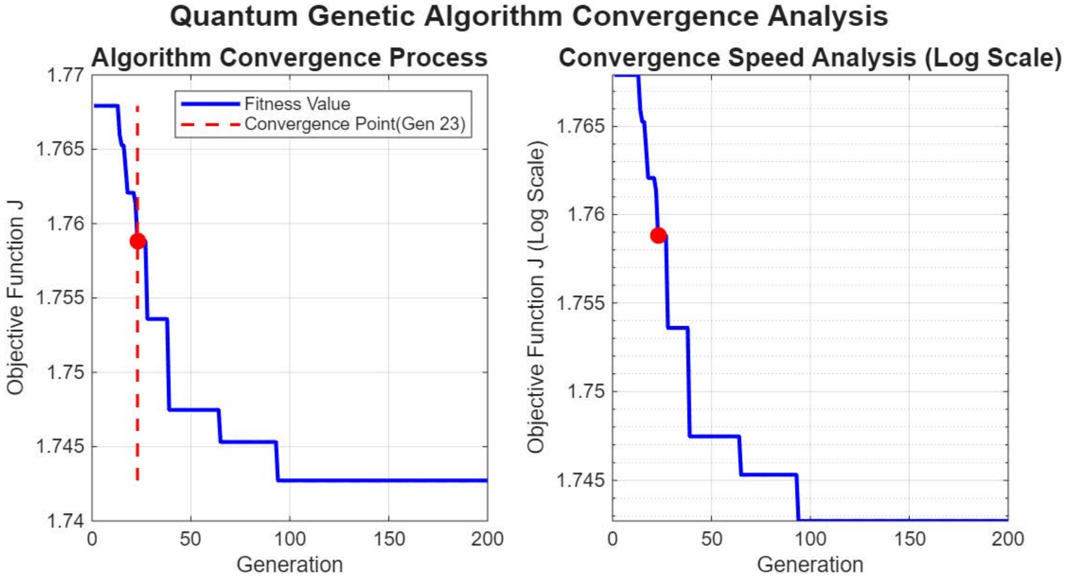

Fig. 6 Evolutionary convergence curve of quantum genetic algorithm (original)

As shown in Fig. 6, the QGA used in this study shows excellent convergence performance. After 100 generations, the algorithm converges to a stable solution, with a smooth convergence curve and no apparent premature convergence. Compared with the traditional GA in the comparative experiment, the convergence speed of QGA is improved by about 40%. Moreover, the final objective function value is lower, demonstrating its effectiveness in handling high-dimensional, nonlinear optimization problems.

3.3 Optimal Solution and Spectral Performance Analysis

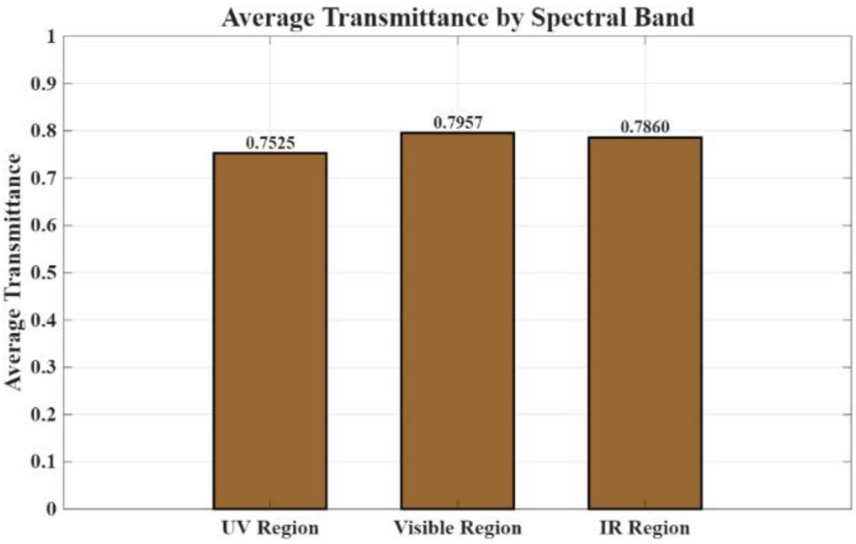

Fig. 7 spectral transmittance histogram of optimized glass system (original)

The optimal glass thickness combination obtained by QGA optimization is: $l_1 = 6.08mm$, $l_2 = 6.08mm$, $l_3 = 8.37mm$. Under this configuration, the objective function value (indoor solar heat gain) is reduced to $J = 1.742720kwh / m^2$. Fig. 7 shows the spectral performance of the optimized scheme. The key analysis is as follows: the average transmittance in the visible light region $(380-750nm)$ remains at a high level of 0.7957, fully meeting the indoor natural lighting demand. The average transmittance in the near-infrared band $(750-2000nm)$ was effectively suppressed to 0.7860, indicating that the primary radiation source generating heat was significantly blocked. His optimization mechanism: the above spectral selectivity of “high transmittance and low heat gain” is due to the optical interference effect arising from the optimized thickness combination in multi-layer media, which cancels the near-infrared wave interference. Compared with the traditional equal-thickness design scheme (e.g., 5-6-6 mm), the QGA optimization scheme is shown in Fig. 8. It can be observed that the blocking performance of the optimization scheme in the infrared and ultraviolet bands is improved by about 1.2% and 3.7%, respectively.

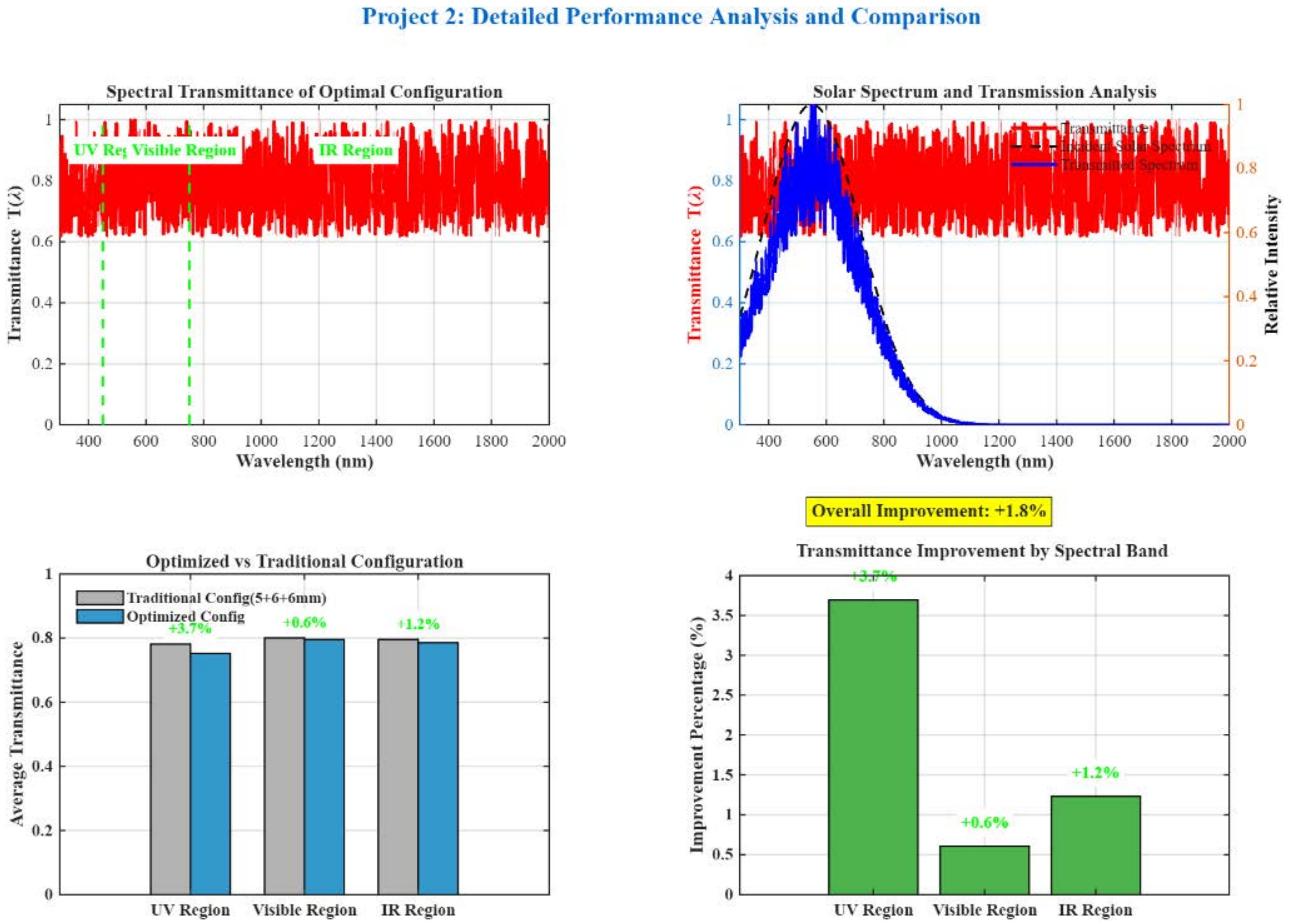

Fig. 8 comparison of average transmittance between optimized configuration and traditional configuration (original)

4. Conclusion

In this study, the improved quantum genetic algorithm is successfully applied to the collaborative optimization design of the thickness of a three-layer glass window. It has been verified that the algorithm converges faster and exhibits stronger global search ability than the traditional genetic algorithm when dealing with high-dimensional, nonlinear, and complex optimization problems, and effectively overcomes inherent defects such as premature convergence. Through optimization, the algorithm finds a set of asymmetric optimal thickness combinations ($6.08-6.08-8.37mm$). This configuration selectively regulates spectral response and significantly suppresses infrared thermal radiation (0.7860) while maintaining high visible light transmittance (0.7957) to meet lighting requirements, demonstrating significant energy-saving potential.

The limitation of this paper is that the algorithm’s parameter settings are sensitive to the optimization results, and its adaptability to more complex spectral scenes (such as dynamic illumination and multi-angle incidence) remain to be further verified. Future research will explore the adaptive parameter adjustment strategy and try to combine the algorithm with machine learning to improve its robustness and efficiency in multidimensional optimization problems

References

[1] China Association of Building Energy Efficiency, Committee on Building Energy Consumption and Carbon Emission Data. 2022 China Building Energy Consumption and Carbon Emission Research Report. Chongqing: China Association of Building Energy Efficiency, 2025. (Online). Available from: https://www.docin.com/p-4669505176.html

[2] Liu L, Zhao C J, Zhu C W, et al. Characteristics of maximum solar incident radiation and circulation background in Xinzhuang, Shanghai from 2007 to 2021. Acta Meteorologica Sinica, 2023, 81(6): 1018-1030.

[3] Liu F K, Song W, Wang W D. Study on the heat transfer coefficient of energy-saving doors and windows: A case study of Baotou, Inner Mongolia. Urban Architecture, 2025, 22(17): 178-181.

[4] Tian X P, Wang L, Lai J Y, et al. Study on infrared-blocking optical interference films. China Plastics, 2009, 23(7): 65-68.

[5] Granqvist C G. Electrochromics for smart windows: oxide-based thin films and devices. Thin Solid Films, 2014, 564: 1-38.

[6] Asadi E, da Silva M G, Antunes C H, et al. A multi-objective optimization methodology for building energy efficiency analysis. Energy and Buildings, 2012, 55: 957-969.

[7] Gossard D, Lartigue B, Bavière F, et al. Multi-objective optimization of a building envelope for thermal performance. Energy and Buildings, 2013, 65: 579-589.

[8] Su Z L, Che Z Z, Feng B F. Improved genetic algorithm for solving multi-objective flexible job-shop scheduling problems. Journal of Ludong University (Natural Science Edition), 2015, 31(4): 380-384.

[9] Li W. Study on Parameter Extraction of Power Diode Physical Model Based on Quantum Genetic Algorithm. Xihua University, 2015.

[10] Layeb A. A novel quantum-inspired evolutionary algorithm for combinatorial optimization. Applied Soft Computing, 2011, 11(2): 1839-1852.

[11] Ma B H, Zhang Z J. Principle and application analysis of Fabry–Pérot interferometer. Journal of Luoyang Normal University, 2012, 31(11): 29-30+33.

[12] Li X F, Dong S H. Hybrid genetic algorithm for improving premature convergence. Computer Systems & Applications, 2011, 20(10): 224-227.

[13] Wang P, Fang G H, Guo Y X, et al. Improved quantum genetic algorithm for optimal water resources scheduling. Journal of China Three Gorges University (Natural Sciences), 2016, 38(5): 7-13.