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Design of Multilayer Anti-Reflection Coating using Jaya Algorithm

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Abstract

In this present research study, a novel and efficient optimization approach for designing multilayer anti-reflection coatings (ARCs) with ultra-low reflectivity. Such coatings found a promising application in the field of optoelectronic device. Designing such coatings is challenging because of the complex, nonlinear search space, which often includes multiple local minima. To address this, we propose a simple, reliable, and effective optimization method, the Jaya algorithm, for the design of broadband multilayer thin-film structures. An interactive simulation programme was developed in LabVIEW based on the Jaya algorithm to facilitate the design process. A systematic study was conducted to determine suitable values for key algorithm parameters, including the search space range, number of iterations, and population size. The algorithm iteratively adjusts the thickness of each layer in the AR stack, using algorithm's built-in search mechanism to converge on optimal values. Results show that the Jaya algorithm consistently converges to reliable layer thickness values. The developed program demonstrates successful optimization of AR coatings with ultra-low reflectivity across a broad wavelength range. Validation in the near-infrared (NIR) region confirms that the method can achieve average reflectivity (R) below 10^{-3} over a 200 nm bandwidth, using various material combinations within the multilayer stack.

Keywords— Thin-Films, Anti-Reflection Coating, Jaya algorithm, LabVIEW.

I. INTRODUCTION

Anti-Reflective (AR) coatings are widely applied to eliminate the undesired surface reflections from the materials. Anti-reflective coatings are used in a wide range of applications where it is desirable to have low loss or low reflection of light as it passes through an optical surface. While advantageous in mirrors or filters, light reflection is an unfavorable phenomenon in many optical equipment, including eyewear, lenses, and sensors. To reduce its reflectivity from Fresnel reflections among certain wavelength range to an optical surface having a dielectric thin film coating known as an anti-reflection coating. By employing various techniques, such as etching techniques or patterning the surface with an antireflective (AR) coating film to reduce reflectance and increase transmittance, researchers are trying to decrease this undesired light. Due to the abrupt change in refractive index at the interface between the ambient medium, often air, and the semiconductor active layer, semiconductor materials used in optoelectronic devices display high reflectivity in the range of 30–40%. This high reflectivity arises primarily from the refractive index mismatch between the semiconductor (the device's active layer) and the surrounding medium, usually air [1]. To address this, single- or double-layer AR coatings with quarter-wavelength optical thicknesses of dielectric materials are commonly employed. However, these coatings perform optimally only at specific angles of incidence and within narrow spectral ranges, making them most suitable for monochromatic or highly coherent sources, such as laser diodes [2]. However, many optoelectronic devices, such as solar cells [3] and photodetectors [4] require ultra-low reflectivity over a broad spectral bandwidth at both normal and oblique incidences to enhance photon collection. Similarly, devices like light-emitting diodes (LEDs) [5] and superluminescent LEDs [6] benefit from improved photon-extraction efficiency under such conditions. Achieving consistently low reflectivity across a wide spectral range typically demands more complex multilayer AR coating structures.

II. LITERATURE REVIEW

The design of multilayer AR coatings is particularly challenging due to the highly nonlinear, multidimensional nature of the search space, which often contains numerous local minima. Additionally, the process involves tuning a large number of design variables, including layer thicknesses and material indices. Therefore, a robust and efficient optimization algorithm is essential to achieve the desired optical performance in multilayer AR coating designs.

Over the past decade, advanced optimization techniques such as simulated annealing (SA) [7], gravity search algorithm (GSA) [8], genetic algorithm (GA) [9], artificial immune algorithm [10], differential evolution (DE) [11], ant colony optimization (ACO) [12], particle swarm optimization (PSO) [13], and artificial neural networks (ANN) [14] have been successfully applied to the design of multilayer antireflection (AR) coatings, addressing the limitations of traditional numerical methods.

Aforesaid all optimization methods are robust and stochastic in nature and generally do not rely on specific initial conditions. However, they require careful tuning of algorithm-specific control parameters to effectively search for global optima. For instance, GA depends on crossover and mutation rates; PSO requires parameters such as velocity, inertia weight, and cognitive and social coefficients; ACO uses factors like the number of ants, pheromone evaporation rate, and pheromone intensity; and DE requires parameters such as population size (NP), differential weight (F), and various mutation and crossover strategies. Improper selection of these parameters can lead to increased computational cost or convergence to local, rather than global, optima.

To overcome burden of the selection of an appropriate algorithm specific parameter in case of existing global optimization algorithm, Rao et al. [15] recently introduced a novel global optimization approach namely Jaya algorithm. The JAYA algorithm has been developed by Sir R.V. Rao in 2016. The word "victory" is a Sanskrit term that is used by JAYA. The characteristics of evolutionary algorithms and swarm-based intelligence are combined in this population-based metaheuristic algorithm. JAYA algorithm is a population-based algorithm. Jaya algorithm (JAYA) is a new metaheuristic algorithm, which has a very simple structure and only requires population size and terminal condition for optimization. Given the two features, JAYA algorithm has been widely used to solve various types of optimization problems. The detailed description of Jaya algorithm is discussed elsewhere in the literature [15].

To the best of our knowledge, this is the first application of the Jaya algorithm for the design of multilayer AR coatings in optoelectronic devices. In this study, the Jaya algorithm is implemented to design AR coatings for normal incidence, specifically for superluminescent light-emitting diode (SLED) applications. Indium phosphide (InP), commonly used as the active layer in SLEDs, is chosen as the substrate, with air as the ambient medium. The multilayer AR structure consists of alternating layers of materials with high and low refractive indices. The number and sequence of layers are kept fixed for this design, although the program can be extended to accommodate more complex configurations.

To estimate the effectiveness of the Jaya algorithm, we conducted a systematic study on the impact of population size on convergence behavior and the variation of the fitness function, i.e. defined as the average reflectivity over the specified wavelength range, was analyzed across iterations. Based on the optimal population size and number of iterations, the final multilayer AR coating design was obtained, specifying the layer thicknesses and material sequence. The algorithm was implemented using LabVIEW as the programming platform.

III. Implementation of Jaya algorithm for the design of multilayer anti-reflection (AR) coating.

Before implementing the Jaya algorithm for anti-reflection (AR) coating design, it is essential to carefully select key algorithmic parameters such as the population size (N), the number of iterations (NOI), and the minimum and maximum allowable layer thicknesses in the AR stack. These parameters are essential for achieving minimized average reflectivity over a user-defined wavelength range.

Several design-specific parameters were fixed throughout the design process. These include the scanning range and step size of the design wavelengths, angle of incidence, total number of layers, and the material types and sequence used in the stack. The material sequence alternates between layers of high refractive index (nH) and low refractive index (nL) materials. For this study, non-absorbing materials were selected within the design wavelength range, although the developed program is flexible and can accommodate any coating material to design various AR structures. Specifically, silicon (Si) was chosen as the high-index material, and magnesium fluoride (MgF_2) as the low-index material, based on their excellent transmittance characteristics within the target wavelength range.

The minimum layer thickness (d_{min}) was set to 100 Å, representing the smallest reproducible thickness achievable with the deposition system used. The maximum layer thickness (d_{max}) was fixed at 4000 Å. In this work, the thickness of each individual layer in the AR stack was treated as a design variable and optimized through a continuous iterative process using the Jaya algorithm. Table 1 outlines the terminology of the Jaya algorithm and its equivalent terms in the context of multilayer AR design problems. A flowchart detailing the complete process of the program developed for multilayer AR coating design based on the Jaya algorithm is shown in Fig. 1.

The algorithm was implemented via an interactive numerical simulation program developed using in LabVIEW as the programming tool. The graphical user interface was created to facilitate the AR coating design process based on the Jaya algorithm as shown in Fig. 2. Initially, the program reads various design-specific parameters and algorithm parameters, including the scanning range of wavelengths, number of layers, sequence of coating materials, range of minimum and maximum layer thicknesses, and the number of iterations.

$$R_{averaged} = \frac{\left\{ \sum_{k=1}^{p} [R_{cal}(\lambda_k, T) - R_{desired}(\lambda_k)] \right\}}{p} \qquad (1)$$

Here, Rcal (λ_k, T) is the calculated reflectivity at wavelength λ_k for a given set of layer thicknesses ($T=Ti(t_1,\ t_2,\ t_3 \ldots t_n)$) using transfer matrix method described in detail elsewhere [16], where n indicates the number of layers in the stack. Rdesired (λ_k) is the value of reflectivity at wavelength λ_k as desired by the user as an outcome from the optimized design.

JAYA terms	Equivalent AR design problem terms
Population size	Number of sets of multilayer Anti-Reflection designs
Individual	A particular set of multilayer AR stack
Best solution	Minimum value of fitness function
Worst solution	Maximum value of fitness function
$U_{m,i,best}$ $U_{m,i,worst}$	Value of the unknown variable from the best and worst solutions exists in the population with the minimum and maximum value of the fitness function
Search space	Minimum and maximum layer thicknesses within a certain range
Fitness function	Average Reflectivity of multilayer Anti-Reflection Coating stack over wavelength range

Table 1: JAYA algorithm terminology in the context of multilayer AR design.

This iterative optimization continues until the stopping criteria are met, leading to a multilayer AR design with optimized average reflectivity over the wavelength range of interest. For AR coating design, the objective is to achieve the lowest possible reflectivity across the entire wavelength range of interest. Therefore, in this study, the desired reflectivity ($R_{desired}$) to be 0 for all defined wavelength range. The p is the total number of wavelength steps in the wavelength range of interest. After evaluating the fitness of the initially generated multilayer AR stacks, the fitness of each multilayer AR stack is improved based on best multilayer AR stack and worst multilayer AR stack in the entire population using Eqn. (1).

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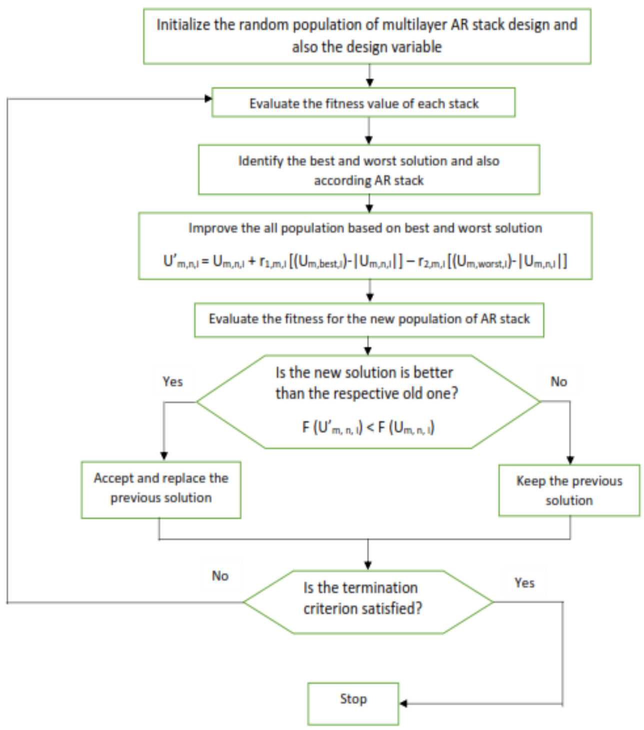

Fig. 1. Flowchart of Jaya algorithm for reflectivity minimization.

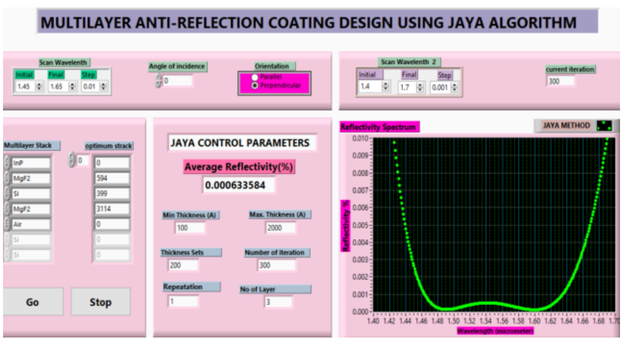

Fig. 2. Graphical user interface of self-developed numerical simulation program based on Jaya algorithm for multilayer AR coating design.

IV. RESULTS AND DISCUSSION

On the convergence of the best design, the effects of different algorithmic factors, such as population size and the range of the maximum layer thickness, were studied and optimized. The variation in fitness function for different population sizes is examined over the entire iteration process in case of JAYA algorithm.

Effects of population size

In any population-based optimization algorithms, the population size is one of the key parameters that directly impacts on performance of the algorithm. [17] Due to incorrect population size selection, several of these algorithms suffer parameter convergence. The global optimum value does not guarantee that solution converges in a lower population size. While, a large population size that have better solution than it makes search space exploration rigorous.

We systematically examined how varying the search space (i.e., the minimum and maximum allowable layer thicknesses) affected convergence. Our results showed that when the maximum layer thickness was set to 4000 Å, the solution converged successfully in all 100 trials. For the present problem, the minimum and maximum layer thicknesses were fixed at 100 Å and 4000 Å, respectively. Additionally, the number of layers and iterations were set to 3 and 150, respectively.

Fig. 3 provides information of the average of the best fitness with respect to population size for different search space range. From the graph, it is clearly observed that the average of the best fitness is gradually decreasing with increasing population size as shown in Fig. 3. From the study, it is observed that maximum thickness range is enhanced from 3000 Å to 4000 Å, the average of the best fitness almost reached to the global value with much lower population size. In addition to this, there is not noticeable change in the average of the best in case of the population size 100 and 120. Hence, in this study, we keep 100 is the optimal value of the population size.

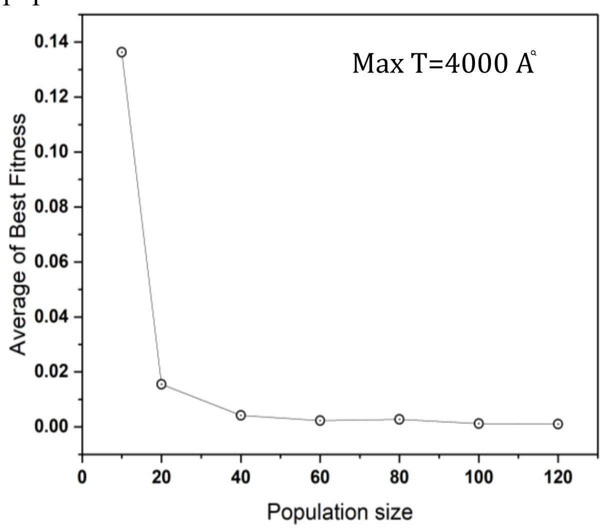

Fig. 3. Population size vs Average of best fitness graphs for different search space.

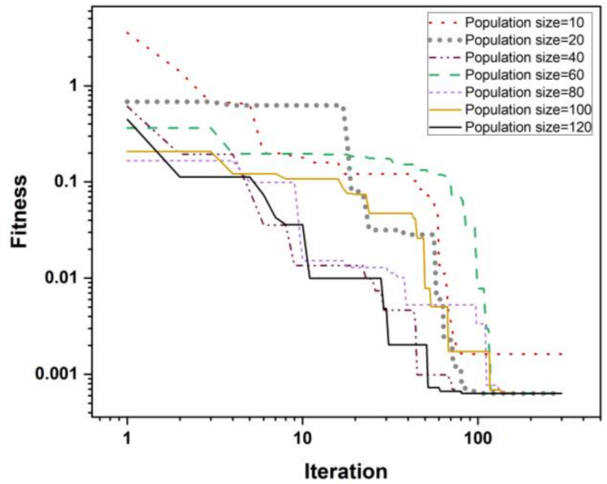

Fig. 4. Fitness evolution with the iterations in the case of different population sizes.

Fig. 4 shows the evolution of the fitness as the iteration progresses for different population sizes. In this case, maximum thickness range and number of iterations were fixed 4000 Å and 150. As shown in the figure, for the population size of 80 and below, the rate of improvement in the solution over the iterations is quite low and it never reaches the global minimum in the stipulated number of iterations. The improvement of the fitness is more or less the same in the case of population sizes of 100 and 120, except in the initial iterations, when the improvement in the solution with population size of 100 is relatively faster than that with a population size of 120. However, eventually, they saturate at similar values, and there is no significant difference in the final solutions. Therefore, we require a population size of at least 100 to achieve the global optimum AR design in the present research study.

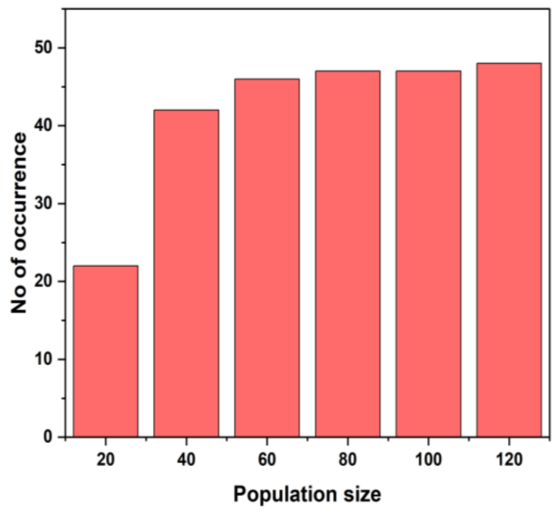

Fig. 5 Comparison of different population sizes in terms of reaching global optimum at maximum thickness at maximum 4000Å

Fig. 5 depicts the number of occurrences that converged to the optimal AR design with increasing population size. From the figure, it is clear that the occurrence of an event that the solution (fitness value) converged to the global optimum in case of the population size 20 is less than 25 out of 50 trials. Increasing the population size from 20 to 80 improves this number significantly. In case of population size of 100 and 120, the number of occurrences of the global optimum was found around 49 in 100 trails. The population size of 120 led to the 100 occurrences of global optimum solution out of 100 trials for AR design problem. However, there is no significant difference in the obtained values of AR designs for the case of population size 100 and 120. In addition to this, more population size increases computation efforts. Thus, we fixed the population size 100 and number of iterations 150 in our program to design the desired AR coating structures.

V. MULTILAYER AR COATING DESIGN

Based on the study mentioned above, the best AR design solution is obtained by finding and fixing the optimal values of input parameters into the self-developed programme, such as population size, number of iterations, number of layers and selection and sequence of the materials in the AR stack etc. Using these values in the self-developed program, we designed a three-layer AR coating for the near-infrared wavelength range, utilizing magnesium fluoride (MgF2) and silicon (Si) as the low and high refractive index materials, respectively. The optimized thickness of each layer, along with their material sequence, over the wavelength range of 1450-1650 nm is summarized in Table 2. From the table, it is clear that the Jaya algorithm successfully minimizes reflectivity over a wide range of wavelengths with a minimal number of layers.

Layers	**Materials stack**	**Thickness in Å**
Substrate	**InP**	**Massive**
1	MgF2	594
2	Si	399
3	MgF2	3114
Incident medium	Air	---
physical thickness (Å)		4107
Average Reflectivity (%)	0.00063358	
Reflectivity (%) at Centre wavelength (1550 nm)	0.00049370	

Table.2. Three-layer AR coating design over the 1450-1650 nm wavelength range.

The simulated reflectivity spectra of the Vis and NIR AR designs are depicted in Fig. 6. It is evident from obtained design that JAYA successfully minimize reflectivity over a broad range of wavelengths with a small number of layers utilizing only two material systems.

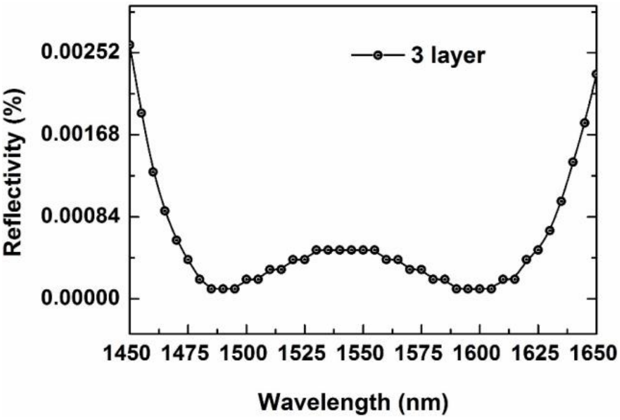

Fig. 6. Reflectivity spectrum for the evolved design with three layers.

VI. CONCLUSION

We successfully demonstrated the use of Jaya algorithm to the design of multilayer anti reflection (AR) coatings, aimed at achieving ultra-low reflectivity over the wavelength range of 1450–1650 nm at normal incidence. We systematically investigated the effect of population size on the AR coating design using the Jaya algorithm. In addition, we examined how population size affects the evolution of the best fitness value over successive iterations.

Our findings indicate that the Jaya algorithm achieves optimal AR coating designs with a significantly smaller population size which demonstrates faster convergence rate, thereby reducing computational time. With optimized parameters for population size and iteration count, the Jaya algorithm consistently achieved 100% reliability in identifying the optimal solution. Using these optimized conditions, we successfully designed a three-layer ultra-low reflective coating operating over the 1450–1650 nm range.

Analysis of the variation in the average best fitness with population size for Jaya algorithm exhibits superior consistency in converging toward the global optimum AR design, requiring fewer iterations and a smaller population size. Overall, the Jaya algorithm proves to be an effective and efficient optimization technique for AR coating design and similar optoelectronic applications, offering distinct advantages in computational efficiency, reliability, and reproducibility. We conclude that the Jaya algorithm is a highly efficient, straightforward, and rapid method for solving complex optimization problems such as broadband AR coating design.

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