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Evolutionary algorithm for optimization of multilayer coatings

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In this paper, a new evolutionary algorithm, the well-known imperialist competition algorithm, is proposed for optimizing the optical thin-films. In this method, the process is modeled of the competition between countries as imperialists and their colonizing of others as colonies. This algorithm could be an appropriate alternative to some of the more popular algorithms for optimizing the optical thin-films for good performance. The polarizer and edge filter for example are designed by using the imperialist competition algorithm method and the results are compared with those from two optimization high-performance methods: the genetic algorithm and differential evolutionary algorithm. Based on these results, the performance of the imperialist competition algorithm method shows that this algorithm is not sensitive to the change of its parameters and it can be an important advantage for quickly achieving a global optimal point. On the other hand the results show a better ratio of P-polarization transmittance to S-polarization transmittance in the design of a 1540-nm polarizer, which is more appropriate than the results from the other two methods. In the second design, an edge filter with a lower number of layers and more uniform bandpass spectrum than the counterparts of those methods is obtained. These results indicate that the imperialist competition algorithm is a robust method for optical thin-film designs.

Keywords: multilayers, optimization, thin-film imperialist competition algorithm

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1. Introduction

Optical thin-films today have many applications in various high-tech areas such as lasers, simulation technology, guidance technology, and so on. One of the main concerns in designing a filter is to develop a method of creating a filter with the best performance and the lowest number of layers and thickness.[1] Different methods of this design are divided into three general categories: analytical, graphical, and numerical methods.[2–4]

Numerical methods include refinement methods and synthesis methods. In designing filters, the starting point is an important issue that should be considered in the use of refinement methods, but in synthesis methods, by creating a preliminary filter design, optimization steps can be done. Synthesis methods such as the evolutionary algorithm and needle method[5–7] are much less sensitive to the point and can evolve the design for suitable results automatically.

In this paper, we propose an evolutionary algorithm as a new method of designing optical thin films. First, we explain how this algorithm works, then how it is adapted to the optimization problem of a filter, and finally, we compare its results with those from other methods. To illustrate the ability of the algorithm to optimize the filters, we consider two high-performance examples and optimize them by two efficient and powerful algorithms, the genetic algorithm (GA) and differential evolution (DE), which are used to optimize optical thin films with various applications,[8–11] and then we compare the results with those from the new algorithm. The results obtained from optimization of the polarizer at the wavelength of 1540 nm by the new method indicate a thin-film design with a higher ratio of P-polarization transmittance to S-polarization transmittance (T_p/T_s) than other methods. This polarizer is used in a laser system to obtain linear polarization for the Q switching process. On the other hand, in the second example, the results obtained in the new method represent a plan with fewer layers and less thickness.

2. ICA procedure

The imperialist competitive algorithm (ICA) is a type of evolutionary algorithm. It is a synthesis optimization method inspired by political, social, and cultural competitions between countries. For more theoretical details, see Ref. [12].

2.1. Creation of primitive empires

Like other evolutionary algorithms, the ICA algorithm begins with a random primitive population and each member of it is a country with N_{var} number of decision variables. Here p_i's are decision variables of the country, which could be some characteristics of it such as politics, culture, and so on.

$$\text{Country} = [p_1, p_2, p_3, \ldots, p_{N_{\text{var}}}].$$

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Some of the best members of the population are chosen as imperialists and others as colonies.

2.2. Assimilation

Assimilation of the colonies is done in order to approach the character of their imperialists.

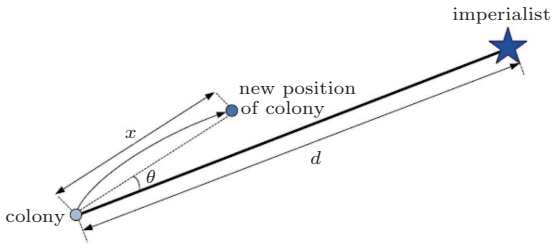


Fig. 1. (color online) General form of colony movement towards its imperialist.

According to Fig. 1 the colony country moves as far as x towards the imperialist but with angle of deviation (θ) and moves into a new position. The number of x is random with uniform distribution as

$$x : U(0, \beta \times d), \tag{1}$$

where β is a number between one and two and d is the distance between colony and imperialist. Also, θ is considered randomly and with uniform distribution:

$$\theta : U(-\gamma, \gamma). \tag{2}$$

2.3. Revolution

In the process of moving colonies to imperialists it is possible that some of the colonies achieve a better cost function than their imperialist; in this case, the colony and imperialist are replaced and the algorithm continues with the new imperialist.

2.4. Imperialist competition

The cost of empire is equal to the cost of the imperialist country plus a percentage of the total cost of its colonies and is expressed as

$$\begin{aligned} T \cdot C_n = {} & \text{Cost}(\text{imperialist}_n) \\ & + \xi \,\text{mean}\{\text{Cost}(\text{colonies of empire}_n)\}, \end{aligned} \tag{3}$$

where $T \cdot C_n$ is the total cost of the n-th empire and ξ is a positive number between zero and one. Over time, the weakest imperialist loses its power and stronger empires will take over its colonies in iteration of the algorithm. For modeling this process first we introduce the normalized total cost of the n-th empire $(N \cdot T \cdot C_n)$ as follows:

$$N \cdot T \cdot C_n = \max_i \{T \cdot C_i\} - T \cdot C_n. \tag{4}$$

Here, $\max_i \{T \cdot C_i\}$ is the maximum total cost between empires. According to Eq. (4), an empire with the least total cost has the most power. Therefore, the probability of achieving the colony by each imperialist is

$$p_{p_n} = \left| \frac{N \cdot T \cdot C_n}{\sum_{i=1}^{N_{imp}} N \cdot T \cdot C_i} \right|, \tag{5}$$

from which by using the roulette wheel mechanism the colony of competition proportional to p_{p_n} can be achieved. Empires that lose their colonies in competition with the imperialists, will be eliminated. There are several ways to terminate the algorithm. Here, the number of iteration is the end condition. The diagram of the ICA algorithm is shown in Fig. 2.

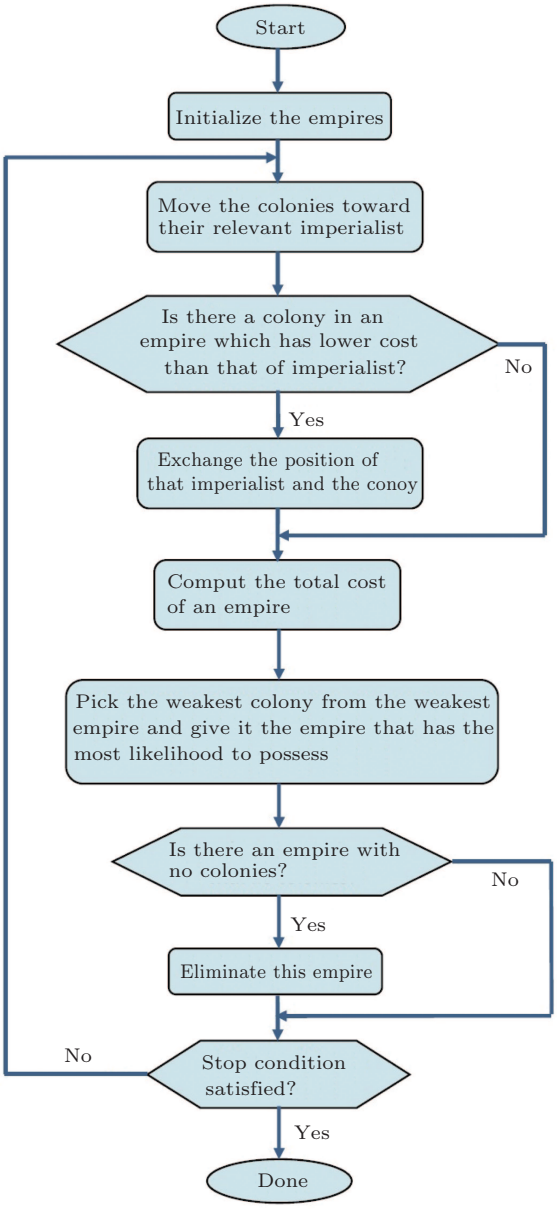


Fig. 2. (color online) General diagram of ICA algorithm.

3. Design examples and discussion

In this part, we investigate, for example, two multilayer filters using ICA, genetic algorithm, and differential evolution, and compared their results. To match the algorithm with the optimization process, each country with its total characteristics corresponds to a filter with its thickness of layers. Each characteristic of a country (p_i's) such as politics, culture, economy, etc., corresponds to the thickness of a layer of filter.

Several parameters such as thickness, materials, and number of layers are important for designing these examples. On the other hand, founding the global optimal point by selecting appropriate effective parameters of the algorithm is important. To design such filters, two materials with the highest difference between their refractive indices are required. Therefore, we consider a material with a low refractive index SiO_2, which has a high laser-induced damage threshold against laser radiation for high refractive index material TiO_2 was selected. It has transparent layers in the visible and near infrared region and also has a high laser-induced damage threshold.[13–16] These multilayer filters consist of several pairs of layers with high and low refractive index materials, which are TiO_2 and SiO_2 with refractive indices $n_H = 2.25$ and $n_L = 1.46$ respectively which are deposited on BK_7 ($n_s = 1.51$) substrate. Design is carried out by MATLAB software.

The merit function is one of the important elements in optimizing the thin-film filters. The main goal is to minimize the merit function to achieve a more satisfactory result, which is obtained by changing the layer thickness.[17,18] The merit function is the root-mean-square error between the calculated transmittance and the target value of transmittance in each iteration. A suitable merit function is defined as

$$f(\eta,d,\lambda_k)=\left\{\frac{1}{w}\sum_{k=1}^{w}\frac{[T(\eta,d,\lambda_k)-T(\lambda_k)]^2}{\delta T_k}\right\}^{1/2}, \quad (6)$$

where $T(\eta,d,\lambda_k)$ and $T(\lambda_k)$ are desired and the target transmittances at wavelength λ_k respectively. Parameters of η and d are the refractive index and thickness of a coating system respectively, and δT_k is tolerance at the wavelength λ_k. Generally, δT_k is set to be 0.01 and W is the number of points where the merit function is evaluated and is considered to be 400 (i.e., there are 400 points)

3.1. Polarizer

The first example is a Brewster polarizer[19] at a wavelength of 1540 nm, which was designed and optimized by using the ICA method. The incident ray angle is the Brewster angle of the BK_7 substrate (56°). The selection of the Brewster angle as the incident angle reduces the reflection of P-polarization and improves the performance of the polarizer.[20–22]

Table 1. Some differences among results obtained by changing algorithm parameters.

Effective parameters	Parameter value																					
Iteration	800																					
Npop[a]	300																					
Prevolution[b]	0.3												0.5									
Mu[c]	0.03			0.05			0.07			0.03			0.05			0.07					
Zeta[d]	0.2	0.4	0.2	0.4	0.2	0.4	0.2	0.4	0.2	0.4	0.2	0.4	0.2	0.4	0.2	0.4	0.2	0.4	0.2	0.4	0.2	0.4
T_P/%	96.20	96.19	96.20	96.19	96.19	96.20	96.17	96.18	96.19	96.18	96.18	96.21	96.20	96.21	96.20	96.20	96.20	96.21	96.20	96.20	96.17	
T_S/%	0.3010	0.3004	0.3010	0.3004	0.3007	0.3017	0.3001	0.3011	0.3010	0.3011	0.3008	0.3007	0.3004	0.3019	0.3004	0.3019	0.3016	0.3012				
T_P/T_S	319.60	320.20	319.60	320.20	319.89	318.86	320.46	319.43	319.57	319.43	319.75	319.85	320.27	318.65	320.27	318.65	318.96	319.29				
Physical thickness/nm	3271	3279	3271	3279	3279	3278	3270	3279	3275	3279	3277	3276	3275	3270	3275	3270	3274	3270				

[a] Number of population, [b] Revolution probability of countries, [c] Revolution rate of countries, [d] the coefficient determining the percentage of colonies participation in imperialist competition

Our target is designed to have high P-polarization (T_p) and low S-polarization (T_s) for transmittance lightwave at 1540-nm wavelength. On the other hand, our main effort is to achieve a greater value for the T_p/T_s ratio in optimizing this polarizer. The initial number of layers was chosen to be 20 and the thickness of layers was selected to be in a range from 10 nm to 300 nm. According to Ref. [23], a thin layer less than 10 nm does not have much effect on the quality of target approximation. Table 1 shows the differences among the results caused by changing the effective parameters of the algorithm. Based on it, despite changing parameters, the results are located around a global optimal point. It could be an important advantage in quickly achieving the global optimal point of the algorithm. While other algorithms have a great deal of sensitivity in determining the proper values for reaching the global optimal point.[24] This is a time consuming process because of the repetition of the algorithm to find the appropriate values of the parameters. Figure 3 demonstrates how the procedure has reached convergence. In this figure, the values of the merit function are shown in terms of the iteration. Clearly, with increasing iteration, the optimization process approaches to the lower values of the merit function. Table 2 gives some characteristics of filters, which were optimized by different methods and figures 4 and 5 show the values of S and P transmittances of the three methods.

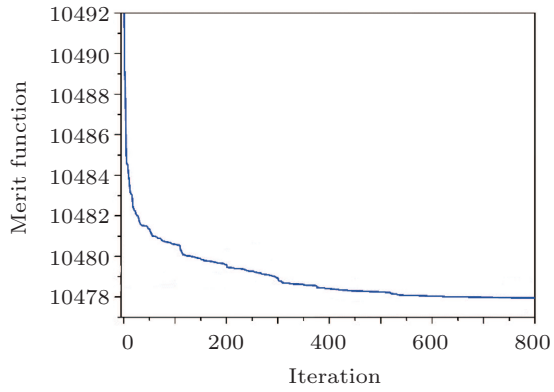


Fig. 3. (color online) Convergence curve of the algorithm.

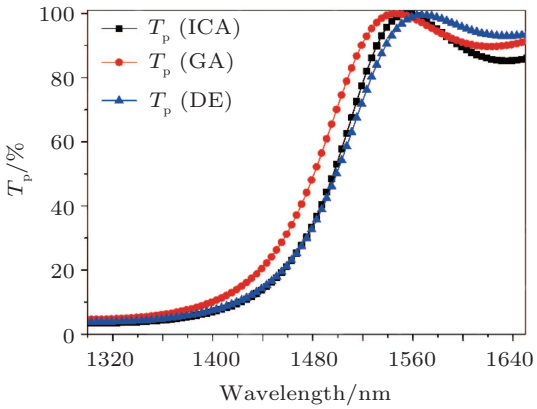


Fig. 4. (color online) P-polarization transmittance spectra from different methods.

Table 2. Characteristics of optimized polarizers.

Number of layer	Material	Physical thickness/nm		
		GA	DE	ICA
1	TiO_2^a 181.28	146.98	170.22	
2	SiO_2^b	236.63	282.24	285.86
3	TiO_2	163.81	164.76	157.23
4	SiO_2	230.91	241.75	265.68
5	TiO_2	201.18	159.74	161.25
6	SiO_2	194.73	274.58	277.21
7	TiO_2	232.57	184.31	170.31
8	SiO_2	213.50	315.82	291.09
9	TiO_2	187.35	156.72	167.13
10	SiO_2	258.49	284.51	284.09
11	TiO_2	171.43	160.84	159.70
12	SiO_2	212.85	272.46	263.52
13	TiO_2	196.05	148.69	157.03
14	SiO_2	220.24	270.23	285.13
15	TiO_2	190.59	193.76	175.15
$\sum d$/nm		3202.31	3260.39	3270.06
T_p/%		99.56	91.20	96.17
T_s/%		0.68	0.34	0.30
T_p/T_s		146	268	320

[a] $n_H = 2.18750$; [b] $n_L = 1.42157$.

According to Table 2 it seems that using the ICA method, a more appropriate value is obtained for the T_p/T_s ratio. In addition, it is noticeable in comparison with the reported results in other previous designs.[25]

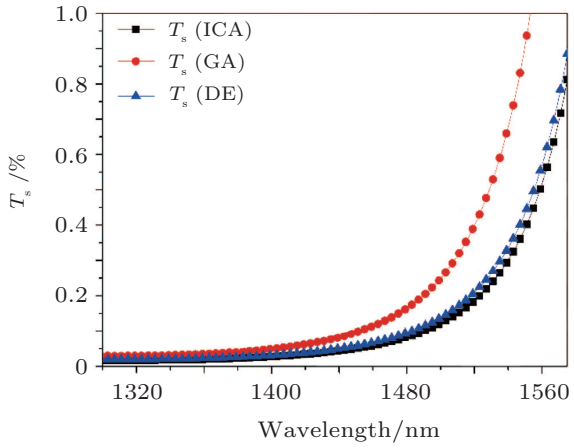


Fig. 5. (color online) S-polarization transmittance spectra from different methods.

3.2. Edge filter

The second example is an edge filter in the visible range. It is also composed of two materials TiO_2 and SiO_2 on BK_7 substrate. Our target has a high transmittance value between 400 nm and 550 nm but a low transmittance value between 550 nm and 700 nm. Table 3 shows the comparison among some parameters in three different algorithms. Figure 5 shows

the optimal transmittance spectra from three methods in the visible range. Based on Figs. 6 and 7, it seems that the optimized diagrams of the ICA method are more effective than those of the previous design models, which is more acceptable due to the number of layers and the edge width of the spectrum.[26]

Table 3. Characteristics of optimized edge filters.

Number of layer	Material	Physical thickness/nm		
		GA	DE	ICA
1	TiO_2[a]	148.90	283.61	227.32
2	SiO_2[b]	172.99	200.64	85.40
3	TiO_2	113.87	113.13	203.10
4	SiO_2	188.01	200.70	287.85
5	TiO_2	201.94	119.26	94.42
6	SiO_2	132.91	18.73	48.29
7	TiO_2	182.61	77.09	90.48
8	SiO_2	130.74	136.11	114.74
9	TiO_2	178.82	182.58	69.87
10	SiO_2	132.45	124.22	299.91
11	TiO_2	177.01	191.54	46.26
12	SiO_2	134.77	83.51	152.17
13	TiO_2	173.77	97.22	58.42
14	SiO_2	141.21	226.37	292.96
15	TiO_2	170.08	92.22	74.26
16	SiO_2	150.36	134.25	137.75
17	TiO_2	156.30	29.31	287.83
18	SiO_2	150.64	161.02	71.93
19	TiO_2	61.68	182.39	
20	SiO_2	70.39	234.34	
$\sum d$/nm		2888.24	2969.44	2642.96

[a] $n_H = 2.18750$; [b] $n_L = 1.42157$.

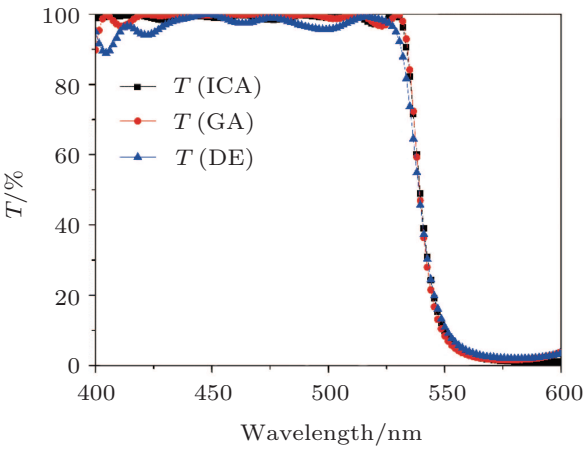


Fig. 6. (color online) Transmittance spectra of edge filter from different methods.

Figure 6 shows the transmittance spectra of the optimized edge filter by using the ICA method, which has a more acceptable edge than that by using the DE method, and on the other hand, it can be said that there are fewer ripples in the band pass than those by using the GA method. In addition, figure 7 displays the reflectance spectra of the edge filter by using the three methods. It is shown that the ripples in the ICA diagram are less than the others.

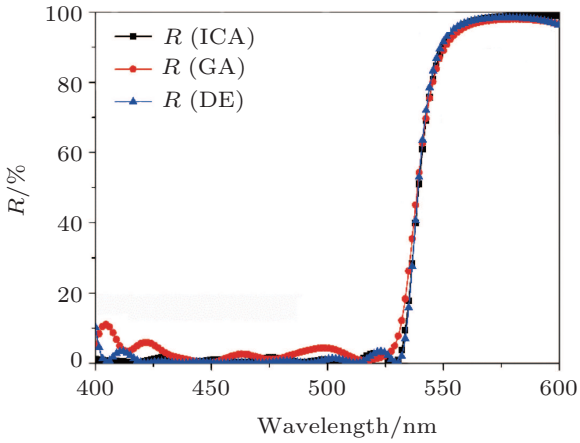


Fig. 7. (color online) Reflectance spectra of edge filter from different methods.

4. Conclusions

The ICA method of optimizing the optical thin-films is proposed. Using the ICA method, a polarization with a high T_p/T_s ratio at the desired wavelength can be obtained. In addition, an edge filter with a wide passband, close to 100%, a wide stopband, and fewer layers is available from this method. As examples indicate, the design of a polarizer and an edge filter shows that the ICA method is a very robust method. Also, due to the low sensitivity of this algorithm to the change of its parameters, it will be easier to reach a global optimal point than by other algorithms. So this evolutionary algorithm could be a suitable alternative for some algorithms such as GA and DE in the optimization of optical thin-film filters.

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