# 應用演化式演算法設計光學光學多層薄膜之塗抹問題

# Optical Thin Film Coatings Using an Evolutionary Algorithm

**計畫編號：NSC 88-2215-E-002-003**

**執行期限：87 年 8 月 1 日至 88 年 7 月 31 日**

**主持人：高成炎　　國立台灣大學資訊工程學系**

**一、中文摘要**

**光學薄膜塗抹有許多廣泛的重要應用領域，如科學儀器之製造、光學、醫學和太空設備等,此技術也可應用在構造、汽車工業、通信和電腦及顯示設備上,同時一些非光學上的問題亦可應用此方法。近幾來光學薄膜塗抹已被應用於電子光學設備上,如光纖通信、液晶顯示器、雷射二極體、發光二極體和所有形式的雷射應用。設計光學塗抹的問題可被表示成整體最佳化之問題,因此可用電腦程式來解,但此整體最佳化之形式有許多的區域最小值(local minimum),因此非常困難。在此計劃中,我們將發展一個新的演化式演算法解光學薄膜塗抹的問題,此演化式演算法可達成三個目標：1). 自動產生起始設計點無需光學的特定知識，藉以縮短發展時間和成本。2). 實驗結果證明光學塗層厚度和最佳反射值間的理論關係，同時也說明此演算的有效性。3). 應用此演算法到二種實際的光學薄膜塗抹問題上。**

**關鍵詞：演化式計算、遺傳演算法、演化式策略、光學多層塗抹**

**英文摘要**

Optical thin films coatings have numerous remarkable applications in many branch of science and technology, such as scientific instrument manufacturing, spectroscope, medicine, and astronomy. They also have been used in architecture, the automotive industry, communication, computer and display devices; and have used for non-optical applications of thin films. In recent year, thin film optical coatings are applied to optoelectronic devices, for examples, fiber communication, liquid crystal display, laser diodes, light-emitting, and all types of lasers and laser application. To design an optical coating problem can be formulated as a global minimization optimization problem solved by computer program. Nevertheless, the formulated problem is extremely difficult because of the large number of local minimum in the merit function, and so it is hard to find feasible solutions efficiently no matter what methods are applied. In the project of this year, we will develop an evolutionary algorithm to synthesize a multilayer coating system to promote the performance. The algorithm will aim at three purposes. First it automatically generated a start design to reduce the time and cost. And then it is able to confirm the theoretical consideration that predicates a relationship between the optical thickness and the best achievable mean reflectance of a multilayer optical coating. Finally it is applied to two thin-film problems to demonstrate the benefit of our proposed evolutionary algorithm.

**Keywords:** Evolutionary Computation, Genetic Algorithm, Evolution Strategies, Optical Multilayer Coating

## 二、計畫緣由與目的

The optical thin film coating is importance to all modern optics and is stated as follows [14] [7] broadly: any device or material is deliberately used to change the spectral intensity distribution or the state of polarization of the electromagnetic radiation incident on it in order to satisfy performance specification and some constraints. The thickness of thin films is the order of the wave-length of light and is infinite small as it compares to extent of films. Thin-film multilayer systems can be widely used to in the infrared, visible and ultraviolet regions of spectrum. Optical thin-film coatings have numerous remarkable applications in many branches of science and technology, such as scientific instrument manufacturing, spectroscope, medicine, and astronomy. They also have used in architecture, the automotive industry, energy conversion, computer and display devices, and communication [8]. In recent year, thin-film optical coatings are applied to optoelectronic devices, for instance, fiber communication, liquid crystal display, laser diodes, and light-emitting.

To design an optical coating problem can be formulated as a global minimization problem and this approach becomes the most widely used technique for designing optical thin-film coatings. Nevertheless, the formulated problem is extremely difficult because of the large number of local minimum in the merit function, and so it is hard to find feasible solutions efficiently no matter what methods are applied. Whichever of these approach is used, the objective is to find the thickness, refractive indices, and layers of a thin film system whose performance closely matches the specified performance. These numerical approaches can be classified into refinement methods [1], [6], [9] and synthesis methods [5], [13], [16], [18], [19].

In recent years, there has been a growing effort on applying evolutionary algorithms, including genetic algorithms [10], [15] and evolution strategies [3], [12] to synthesize multilayer thin-film systems. These articles demonstrate that evolutionary algorithms are robust and obtain competitive results with others synthesis methods.

The main focus of this project is to develop a new evolutionary algorithm, called Family Competition Evolutionary Algorithm (FCEA), to synthesize multilayer thin-film systems. The approach integrates self-adaptive Gaussian mutation, self-adaptive Cauchy mutation, decreasing-based Gaussian mutation, and family competition. In order to illustrate the power of our approach, we considered three different thin-film design problems that were widely used as benchmarks for various optimizing approaches. These experimental results indicate that FCEA is a powerful and robust optimization technique.

## 三、結果與討論

FCEA is a multi-operator approach which integrates decreasing-based Gaussian mutation, self-adaptive Caychy, and self-adaptive Gaussian mutation, and their performance heavily depends on the same factor, called step size, that decides the perturbation size. It is the core philosophy of FCEA to design operators by using the adaptive rules and family competition for cooperating each other in order to achieve good performance.

FCEA differs from previous evolutionary approaches on several aspects. 1) In one generation, FCEA sequentially uses each mutation operator with probability 1 as shown in Fig. 1. This strategy is unlike previous multi-operator approaches which applied each operator with different probabilities adapted according to their performance. 2) Operators in FCEA are designed to compensate for disadvantages of each other in order to balance the global search and local search ability via the following three mechanisms: i) the family competition and adaptive rules are used to adapt the step sizes of the two mutation operators for creating the relationship between them; ii) the decreasing-based mutation is closer to a global search operator than the self-adaptive mutation by setting larger initial step sizes; and iii) the self-adaptive mutation is closer to a local search operator by the nature of self-adaptive approaches.

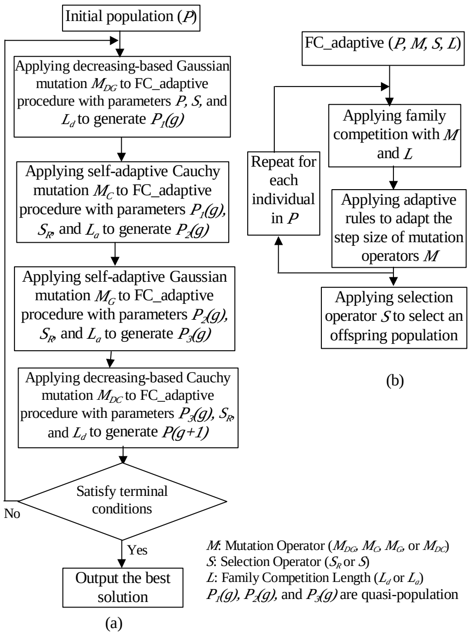


Fig. 1. The outline of family competition evolutionary algorithm.

## A. Infrared Antireflection Coating: two-material periodic coating problem

This problem was first proposed by Aguilera et al [1] and its interesting wavelength is infrared region. The goal is to reduce the reflectance to zero at 0.1 $\mu$ m wavelength increments between 7.7 and 12.3 $\mu$ m; therefore, the number of wavelength value is 47. The incident medium is air and the substrate refractive index is $n_s$ = 4.0. The only used coating materials are Ge ($n_h$ = 4.2) and ZnS ($n_l$ = 2.2). At least 57 different solutions, obtained from over 20 non-evolutionary approaches [1] [6] [8] and from over three evolutionary approaches [3] [15] have been published for this problem since 1988. Above all, many predicated solutions and theoretical approaches on this coating problem have been published. Any application of an evolutionary approach should focus on a comparison to solutions obtained by well-known approaches; therefore, this problem is a good benchmark problem. therefore, this problem is a good benchmark problem. We used the two-materials periodic structure, i.e. $(n_h n_l)^M$ or $(n_l n_h)^M$ where M is the number of layer, to synthesize this problem. Initially, the step sizes of $\pm^{\omega}$, $\nu^{\omega}$, and $\cdot^{\omega}$ are set to 0.08, 0.02, and 0.02, respectively. The initial thickness of each layer was uniformly selected from the region between 0.2 and 1.0.

FCEA was totally executed 100 times for various total optical thickness and various layer numbers. Fig. 2(a) shows spectral profile of typical evolutionary intermediate solutions obtained by FCEA and Fig. 2(b) presents refractive-index profile of the last solution. The merit function (MF) value is 61.07% while function evaluations is 100. MF is promoted to 1.01%, 0.7%, and 0.63% while function evaluations are 50,000, 150,000 and 300,000, respectively. After FCEA executes 650,000 function evaluations, the last solution quality is 0.60 whose layer number 23 and thickness is 38.61 µm. From our experimental results, we observed that the solution quality was improved quickly in the early search time.

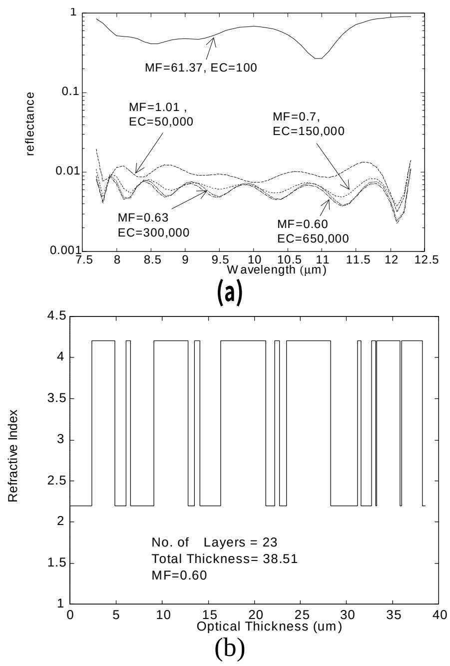


Fig. 2. Typical evolutionary intermediate solutions obtained by our FCEA in the synthesis of the infrared antireflection problem. (a) is the spectral reflection profiles of solutions where EC denotes function evolutionary times and MF represents the merit function value .(b) is the refractive-index profile of the last solution whose MF is 0.60% and thickness is 38.61 µm.

FCEA obtained two observed results that consisted with parallel ES [12] according to Fig 3. First, Willey's predicated optimal values [20] were overestimated as the total thickness is lower than 30 µm. Second, we also observed the "Bermuda triangle" when the optical thickness range 11and 17 µm. However, Fig 3 shows that FCEA outperformed parallel ES [21] as the optical thickness is beyond 30 µm. We considered that the RMS predicated optimum may be the best approximated solutions.

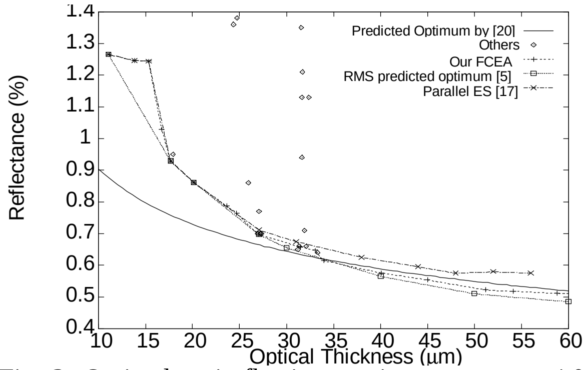


Fig. 3. Optimal antireflective coatings on a $n_s$ = 4.0 substrate based on the refractive index pair 2.2 and 4.2 for different overall optical thickness of the system.

## B. Narrow-Band Rejection Filter: Inhomogeneous coating problem

This problem is a narrow-band rejection filter [4, 15]. The target is that the reflectance value is 90% between 0.58 and 0.62 «m and zero outside this band in the visible region between 0.5 and 0.7 «m. The incident medium is air and the substrate is glass ($n_s$=1.52). The merit function was calculated at 48 wavelengths which are 16 equidistant wavelengths for three wavelength range: 0.5-0575 «m, 0.585-0.61-«m, and 0.625-0.70 «m. The feasible refractive indices region is between 1.35 and 2.20 «m, so this problem is an inhomogeneous optical coating problem.

FCEA was executed 50 runs on this problem with the maximum total thickness 20 µm and maximum EC is 250,000 to fairer compare performance with other approaches. The average performance was 1.72% and the average thickness was 17.9 µm. We extended the EC to 850,000 and we obtained best solution was 0.541% with thickness 18.54 µm. The required time was about 1.5 hour when our program ran on Intel-pentium 166 Mhz. Fig. 4 shows the spectral reflection profile and refractive-index profile of the best solution obtained by our FCEA.

Here we compared our performance with inverse Fourier transform method [4] and hybrid approach that combined genetic algorithm and gradient method [15]. The average reflectance of hybrid method [15] was 0.3% for 0.5-0.575 µm, 90.07% for 0.585-0.615 µm, and 0.26% for 0.625-0.700 µm. The hybrid method must assign the total thickness to 20 µm and the layer number to 40. On the other hand, the average reflectance of our best solution whose layer number is 31 and thickness is 18.54 µm in this paper, was 0.3% for 0.5-0.575 µm, 90.02% for 0.585-0.615 µm, and 0.30% for 0.625-0.700 µm. Our approach can optimize the merit function value and the layer number at the same time. They [16] stated that their results were competitive with inverse Fourier transform method. Therefore, our approach was competitive with these two methods and our approach was more flexible.

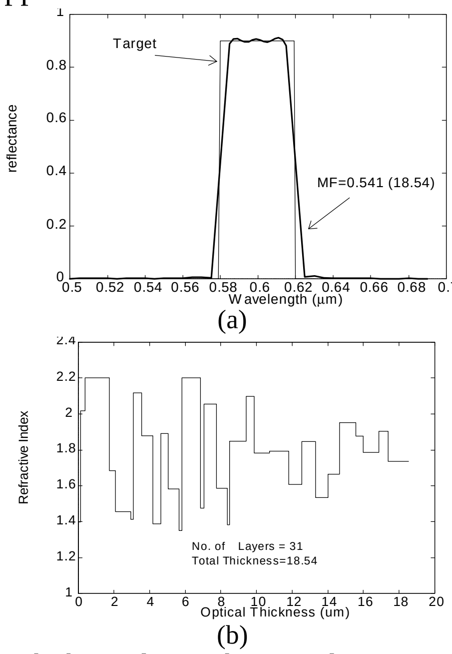


Fig. 4. The best solution, the MF value was 0.541 and the total thickness is 18.54, of rejection filter found by FCEA: (a). Spectral reflections profile of the best rejection filter. (b) refractive-index profile of the best solution.

This study has demonstrated that FCEA is a robust approach for global optimization. Our experience suggests that a global optimization method should consist of both global and local search strategies. For FCEA, decreasing-based mutations with a large initial step size is a global search strategy; self-adaptive mutations with family competition procedure and replacement selection are local search strategies. These mutation operators can closely cooperate with one another.

Experiments on two problems verify that the proposed approach is very competitive with other algorithms, including genetic algorithms and evolution strategies. We believe that the flexibility and robustness of FCEA make it a highly effective global optimization tool.

## 四、參考文獻


[1] J. A. Aguilera, et al., “Antireflection coatings for germanium IR optics: a comparison of numerical design methods,” *Applied Optics 27(14*), pp. 2832-2840, 1988.

[2] T. Bäck, *Evolutionary Algorithms in Theory and Practices*, Oxford,1995.

[3] T. Bäck and M. Schutz, "Evolution strategies for mix-integer optimization of optical multilayer systems,” *in Proc. of Fourth Ann. Conf. on Evolutionary Programming*, 1995, pp. 33-51.

[4] B. G. Bovard, “Derivation of a matrix describing a rugate dielectric thin film,” *Applied Optics 27(10),* pp. 1998-2005, 1988.

[5] J. A. Dobrowolski, “Comparison of the Fourier transform and flip-flop thin-film synthesis methods,” *Applied Optics 25(12*), pp. 1966-1972, 1986.

[6] J. A. Dobrowolski and R. A. Kemp, “Refinement of optical multilayer systems with different optimization procedures,” *Applied Optics 29(19*), pp. 2876-2893, 1990.

[7] J. A. Dobrowolski, “ Optical properties of films and coatings,” *Handbook of Optics, M. Bass ed.* ,McGraw-Hill, New York, 42.1-42.130, 1995.

[8] J. A. Dobrowolski, “Numerical methods for optical thin films,” *Optics and Photonics News 8(6)*, pp. 24-33, Jun, 1997.

[9] J. Druessel and J. Grantham, “Optimal phase modulation for gradient-index optical filters,” *Optics Letters 18(19*), pp. 1583-1585, 1993.

[10] T. Eisenhammer, et al., “ Optimization of interference filters with genetic algorithms applied to silver-based heat mirrors,” *Applied Optics 32(31*), pp. 6310-6315, 1993.

[11] D. E. Goldberg *Genetic Algorithms in search, Optimization & Machine Learning*, Reading. MA: Addison-Welsley, 1989.

[12] H. Greniner, “Robust optical coating design with evolutionary strategies,” *Applied Optics 35(28),* pp. 5477-5482, 1996.

[13] L. Li and J. A. Dobrowolski, “Computation speeds of different optical thin-film synthesis methods,” *Applied Optics 31(19*), pp. 3790-3799, 1992.

[14] H. A. Macleod, *Thin film optical filters*, McGraw-Hill, New York, 1986.

[15] S. Martin, J. Rivory, and M. Schoeanauer, “Synthesis of optical multilayer systems using genetic algorithms,” *Applied Optics 34(13),* pp. 2247-2254, 1995.

[16] A. V. Tikhonravov, M. K. Trubetsko, and G. W. Debell, “Application of the needle optimization technique to design of optical coatings,” *Applied Optics 35(28),* pp. 5493-5508, 1996.

[17] A. V. Tikhonravov, “Some theoretical aspects of thin-film optics and their applications,” *Applied Optics 32(28),* pp. 5417-5426, 1993.

[18] P. G. Verly , A. V. Tikhonravov, and M. K. Trubetsko, “Efficient refinement algorithm for the synthesis of inhomogeneous optical coatings,” *Applied Optics 36(7*), pp. 1487-1495, 1997.

[19] W. J. Wild and H. Buhay, “Thin film multilayer design optimization using Monte Carlo approach,” *Optics Letters 11(1*), pp. 745-747, 1986

[20] J. M. Yang, C. Y. Kao and J. T. Horng, “A continuous genetic algorithm for global optimization.” In *Proceeding of the Seventh Intl. Conference on Genetic Algorithm* 1997, 230-237.

[21] M. Schutz and J. Sprave, "Application of parallel mixed-integer evolutionary strategies with mutation rate pooling,” *in Proc. of Fifth Ann. Conf. on Evolutionary Programming*, 1996, pp. 345-354.

[22] J. M. Yang and C.Y. Kao, "An Eevolutionary Algorithm for Synthesizing Optical Thin-Film Designs," to appear in Parallel Problem Solving from Nature- PPSN V, 1998, pp. 947-958.