Design of GMR-Based Wideband Optical Reflector Using Memetic Algorithm with Fuzzy Logic Local Search

Mohammad Ali Bahar and Mehrdad Shokooh-Saremi

Abstract. Wideband, GMR-based reflector is designed employing a novel variant of memetic algorithm with fuzzy logic local search. High quality, single periodic layer reflector with SOI structure is designed with reflectance >99.50% over 1.35 µm to 1.9 µm spectral band. The proposed optimization/design method is very powerful and able to optimize complex structures with desired optical responses.

Keywords: Guided mode resonance, memetic algorithm, fuzzy logic, periodic structures, optical reflectors.

1. Introduction

Periodic dielectric structures, which can support guided mode resonance (GMR), have found applications in a variety of optical elements [1], [2]. Guided-mode (or leaky-mode) resonance is a phenomenon that takes place upon phase matching between the incident light and leaky modes of the periodic dielectric structures (like diffraction gratings). GMR manifestation is usually rapid variation in reflectance or transmittance at the corresponding resonance wavelength [3].

In this paper we design a wide-band optical reflector by determining the physical parameters of a single layer, high-contrast diffraction grating. Grating pitch (g), thickness of grating layer (t) and filling factor (f) are parameters that should be found for designing optical filter with desired spectral response. In Fig. 1 a typical grating and its physical parameters are shown.

There are powerful evolutionary algorithms that can be used as optimization methods for optical filter design [4], [5]. These algorithms can be employed to find optimal physical parameters of the optical element based on the desired response. There are several evolutionary algorithms that can be utilized to find optimal parameters of the grating structures. Particle swarm optimization (PSO) and genetic algorithm (GA) have been utilized before [6]. Here, we introduce and employ an innovative design method based on memetic algorithm that makes use of fuzzy logic for performing local search. This approach provides the conditions under which cognitive science is used in the design of optical devices.

Manuscript received February 25, 2014; revised June 7, 2014; accepted June 21, 2014.
The authers are with the Department of Electrical Engineering, Ferdowsi University of Mashhad, Iran. The corresponding author's e-mail is: m_saremi@um.ac.ir.

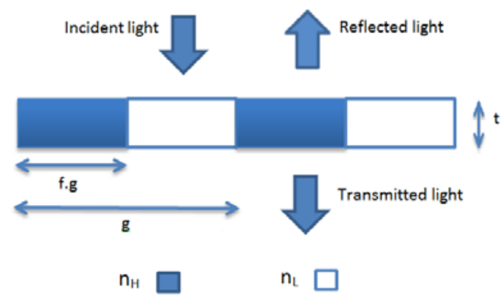


Fig.1. Single layer diffraction grating with rectangular profile and its physical parameters. Grating pitch, thickness of grating layer, filling factor, high refractive index, and low refractive index are denoted by g, t, f, n_H and n_L respectively.

The organization of this paper is as follows. In Section 1, the memetic algorithm and in Section 2, the innovative local search method using fuzzy logic are introduced. In Section 3, the principles of design are elaborated and in Section 4 the results of wideband filter design using this algorithm are reported.

2. Memetic Algorithm

2.1. Memetic Algorithm Definition

Memetic algorithm is an evolutionary algorithm which performs optimization based on genetic algorithm combined with a local search. The unit of information in memetic algorithm is called "*meme*" and the vector that includes the set of memes is called "*memeplex.*" Memeplex contains optimization parameters. Each meme is modified based on the experiences obtained by local search. Then, the memeplexes who have better experiences are selected as parents. By applying crossover and mutation on these parents, new children are produced [7]-[10].

2 2. Memeplex Generation

The memeplexis represented as a vector with *n* elements. The elements of this vector contain information about design parameters. Each of these parameters is displayed with a decimal number. For each parameter, a search range (interval) is also defined as

$$\begin{bmatrix} m_1 \\ m_2 \\ \vdots \\ m_n \end{bmatrix}; \ \forall i, m_i \in [m_{imin}, m_{imax}] \tag{1}$$

where m_i denotes i-th meme in the memeplex. m_{imin} and m_{imax} are numerical lower and upper limits of meme m_i. The space comprising of all search intervals is called search space.

2.3. Crossover

After implementation of the local search (see Section 2), the parents are selected randomly from the generated memes with good fitness. For mating, the parents must swap their information [11]. A random process determines which parameter is selected for swapping. After crossover, the generated children compete with N memeplex which have already left from previous loop execution. Then the N memeplexes with better fitness are selected and the last memplexes are eliminated.

2.4. Mutation

Mutation is an operator which changes the information of memes which are selected randomly [11]. After applying mutation operator, the generated off springs compete with N memeplexes which have already left from previous loop execution. Then the N memeplexes with better fitness are selected and the last memeplexes are eliminated.

3. The Innovative Local Search Based on Fuzzy Logic

As mentioned in Section 1, the parents gain experiences before mating and this is accomplished by a local search. In basic forms of memetic algorithm, local search is mainly accomplished based on hill climbing method or simulated annealing [5].

In this paper, we have developed a new method based on fuzzy logic to perform local search. It is described as follows: Each of the intervals that were introduced in Section 1 is divided into three equal sub-intervals. After local search and sorting the obtained results, the sub-intervals of search space are evaluated based on two criteria.

Assuming that the population number is N, the locations of N/2 memeplexes who have better fitness are evaluated. The number of these better memeplexes in each search space is calculated. The result is considered as first criterion and it is denoted by A_j for j-th search space. For j-th search space, yielding higher number for A_j indicates that the search space is more suitable for local search. Then the locations of elites are determined in the search space. The elites are memeplexes who have first, second and third locations in the sorted population. Therefore, the first elite is the global optimum.

The search space which contains elites is more suitable for local search too. Therefore, a fuzzy number (as a score) is assigned for this search space. In each iteration, the numbers 0.5, 0.3 and 0.2 are added to the scores of search spaces that contain first, second and third elites, respectively. The score of j-th search space is denoted by B_j.

A_j is normalized by dividing it over (0.5×N×iteration) and B_j is normalized by dividing it over number of iterations. A_j and B_j are considered as fuzzy numbers, and determine how the j-th search space is suitable for local search in the next loop execution. Therefore, we determine the fuzzy number which is considered as disjunction of A_j and B_j. S-norms are functions that can represent the mathematical model of logical disjunction. Similarly there are functions for modeling logical conjunction and negation which are denoted by T-norms and C (fuzzy complement), respectively [12], [13].

We use an indirect method to obtain $S(A_j, B_j)$. Regarding the set theory, the logical disjunction can be determined using Demorgan law

$$A \cup B = \sim(\sim A \cap \sim B) \tag{2}$$

where logical disjunction, logical conjunction and negation are denoted by ∪ , ∩ and ∼, respectively. The equivalent law in fuzzy logic can be considered as

$$S(A_j , B_j) = C(T(C(A_j) , C(B_j))) \tag{3}$$

There are several functions that can be used as fuzzy complement. The fuzzy complement function which is used in this paper was introduced by Sugeno [14]

$$C_\lambda(A_j) = \frac{1-A_j}{1+\lambda A_j} \lambda \in (-1 , +\infty) \tag{4}$$

As shown in Fig. 2, by increasing λ the complement operation's weight increases. Note that the value of B_j is more effective than A_j in converging of results. Hence, B_j is weighted higher than A_j. Therefore, for computing $C(A_j)$, the value of λ is considered to be equal to 2 and for $C(B_j)$ equal to 5.

Min function is the most commonly used T-norm function and in this paper it is used as follows:

$$T\left(C(A_j), C(B_j)\right) = \min\left(C_{\lambda=2}(A_j), C_{\lambda=5}(B_j)\right) \tag{5}$$

To perform complementation in Eq. (5), Sugeno function is employed. As a result, $S(A_j, B_j)$ is determined from Eq. (6)

$$S(A_j, B_j) = 1 - \min\left(C_{\lambda=2}(A_j), C_{\lambda=5}(B_j)\right) \tag{6}$$

$$R_j = S(A_j, B_j) \tag{7}$$

In Eq. (7), R_j is a fuzzy number which determines how the j-th search space is suitable for local search in the next loop execution.

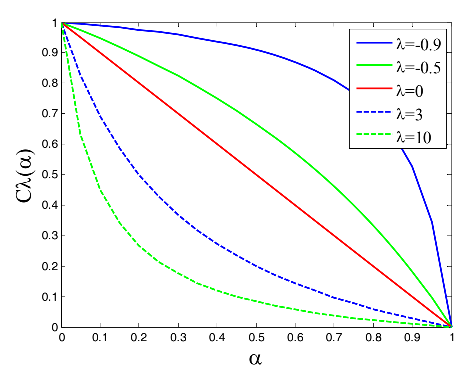


Fig. 2. Curves of Sugeno fuzzy function for different λs.

It is evident that the closer value of R_j to unity makes the j-th search space more suitable for local search. In addition, (R_j × population number) determines how many memeplexes are included in j-th search space.

4. Principles of Design

The design parameters of the periodic structure that acts as the wideband reflector are arranged in a vector with three elements according to Eq. (8). The first, second and third elements of vector denote grating pitch, thickness of grating layer and filling factor, respectively. This vector acts as a memeplex

$$memeplex: \begin{bmatrix} g \\ t \\ f \end{bmatrix} \quad (8)$$

where $g \in [g_{min}, g_{max}]$, $t \in [t_{min}, t_{max}]$, and $f \in [f_{min}, f_{max}]$.

To implement the algorithm, a set of memeplexes (each with N memes) is generated randomly. Then the fitness of each memeplex is evaluated. After that, the memeplexes are sorted according to their fitness. Sorting is done according to elitism selection [8]. In each iteration, any memeplex that has the best fitness is located on the first place and the one that has the worst fitness is located on the last place.

The diffraction efficiency of the reflected wave (reflectance) is computed by modal analysis based on transmission line theory [15]-[17]. This analysis method is very powerful and is able to analyze electromagnetic behavior of periodic multilayer structures. To evaluate the fitness of each memeplex, the reflectance of desired optical filter is compared to the computed reflectance of that memeplex over given spectral band. The desired reflectance of the optical reflector is defined as

$$R = u(\lambda - \lambda_{min}) - u(\lambda - \lambda_{max}) \quad (9)$$

where $u(.)$, λ, λ_{min} and λ_{max} are step function, wavelength, and the lower and upper bounds of the desired wavelength band, respectively. Figure 3 illustrates the desired reflectance curve of the optical wideband reflector [18].

The fitness function (FF) for evaluation of the memeplexes is defined as root-mean-square (RMS) difference between desired and computed reflectances:

$$FF = \sqrt{\frac{\sum_{n=1}^{M} \left(R_n - R'_{nj}\right)^2}{M}} \quad (10)$$

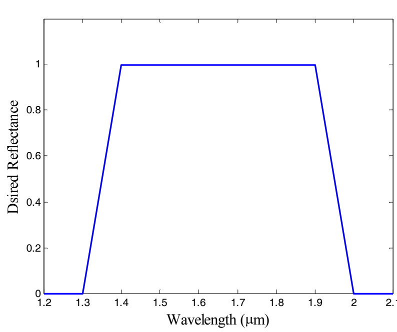


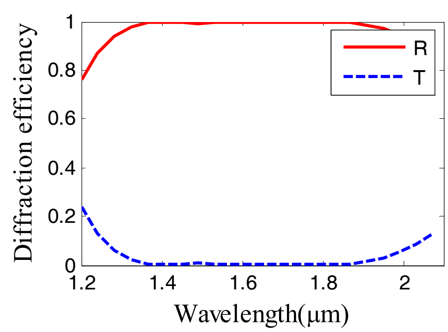
Fig. 3. Desired reflectanceof the optical wideband reflector.

where R_n is the desired reflectance and R'_{nj} denotes the reflectance of the j-th memeplex which is calculated by modal analysis based on transmission line theory. M is the number of points where the reflectance has been calculated on the curve illustrated in Fig. 3.

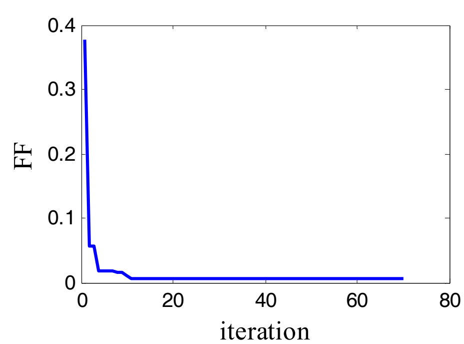
5. Results

The reflector structure is considered to be a single layer diffraction grating structure shown in Fig. 1. A TM-polarized light normally illuminates the mentioned structure. The high refractive index (n_H) is equal to 3.48 and the low refractive index (n_L) is equal to 1. The refractive indices of cover medium and substrate are 1 and 1.48, respectively. The desired wavelength range is 1.35 µm to 1.9 µm.

By optimizing the structure with the proposed design algorithm to meet the desired spectral specifications, the following optimal values are obtained: g = 0.74 µm, t = 0.46 µm, and f = 0.71. The diffraction efficiencies in reflection and transmission (reflectance and transmittance) of the optical reflector are illustrated in Fig. 4(a) where reflectance is denoted by R and transmittance is denoted by T. Figure 4(b) shows the convergence curve of the fitness function versus iteration. As seen, after 70 iterations FF reaches 0.0054. The convergence time is 462 seconds. Figure 5 presents the magnification of reflectance over 1.35 µm to 1.9 µm which is over 99.56% for every wavelength point in this band.



(a)



(b)

Fig. 4. (a) The reflectance and transmittance for the designed optical wideband reflector. (b) The fitness function (FF) versus number of iteration curve.

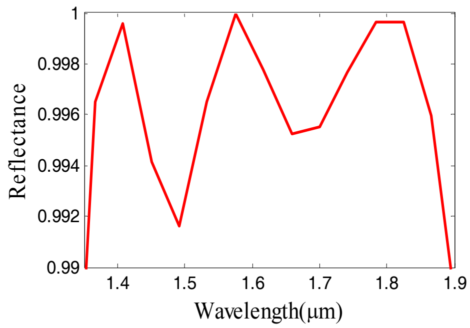


Fig. 5. Magnification of reflectance over 1.35 μm to 1.9 μm.

The proposed optimization algorithm has been implemented as a MATLAB code and it has been run on a system with 6 GB of RAM and Intel Core i5 microprocessor.

Conclusions

Design of wideband optical reflector that benefits from GMR effect in periodic dielectric structures is main target of this paper. It is generally difficult to directly and analytically determine physical parameters of GMR-based elements with desired spectral responses. Therefore, the optimization methods like evolutionary algorithms can be useful for this task. A variant of memetic algorithm is utilized here for optical wideband reflector design. Local search for the proposed memetic algorithm is realized by an innovative method based on fuzzy logic. High quality of design results and fast convergence show that the proposed method is a powerful and robust optimization algorithm.

Although one layer diffraction grating is the simplest structure that can be used and optimized for realization of GMR devices, other types of periodic structures with a variety of spectral responses can be designed using the proposed optimization method.

References

[1] S. Tibuleac and R. Magnusson, "Reflection and transmission guided-mode resonance filters," *J. Opt. Soc. Am. A*, vol. 14, no. 7, pp. 1617-1626, 1997.

[2] D. Shin , S. Tibuleac, T. A. Maldonado and R. Magnusson, "Thin-film optical filters with diffractive elements and waveguides," *Opt. Eng.*, vol. 37, no. 9, pp. 2634–2646, 1998.

[3] S. S. Wang, R. Magnusson, J. S. Bagby and M. G. Moharam, "Guided-mode resonances in planar dielectric-layer diffraction gratings," *J. Opt. Soc. Am. A*, vol. 7, no. 8, pp.1470-1474, 1990.

[4] A. Reimann, *Evolutionary Algorithms and Optimization.* Ph.D. Dissertation, Dept. Mathematics, Humboldt University, Berlin, Germany, 2001.

[5] J. Brownlee, *Clever Algorithms: Nature-Inspired Programming Recipes*, Lulu, 2011. [Online]. Available: http://www.cleveralgorithms.com.

[6] M. Shokooh-Saremi and R. Magnusson, "Particle swarm optimization and its application to the design of diffraction grating filters," *Opt. Lett.*, vol. 32 , no. 8 , pp. 894-896, 2007.

[7] R. Dawkins, *The Selfish Gene.* Oxford Univ. Press, 1989.

[8] P. Merz and B. Freisleben, "A Comparison of memetic algorithms, tabu search, and ant colonies for the quadratic assignment problem," *Proc. Congress on Evolutionary Computation, IEEE,* 1999.

[9] P. Moscato, "On evolution, search, optimization, genetic algorithms and martial arts: Towards memetic algorithms," Technical Report, California Institute of Technology, 1989.

[10] P. Moscato, A. Mendez and R. Berretta, "Benchmarking a memetic algorithm for microarray data," *Biosystems*, vol. 88, pp. 56-75, 2007.

[11] R. L. Haupt and S. E. Haupt, *Practical Genetic Algorithms.* New York: John Wiley, 2004.

[12] L. A. Zadeh , "Fuzzy sets" *Information and Control*, vol. 8, pp. 338-353, 1965.

[13] L. A. Zadeh, "Fuzzy logic," *Computer*, vol. 21, pp. 83-93, 1988.

[14] M. Sugeno , "Fuzzy measures and fuzzy integral: a survey," *in Fuzzy Automata and Decision Processes*, M. M. Gupta, G. N. Saridis, and B. R. Gains, editors, Amsterdam: North Holland, 1977, pp. 89-102.

[15] S. T. Peng, T. Tamir and H. L. Bertoni, "Theory of periodic dielectric waveguides," *IEEE Trans. Microwave Theory and Techniques*, vol. 23 , no.1, pp. 123-133, 1975.

[16] T. Tamir and S. Zhang, "Modal transmission line theory of multilayered grating structures," *J. Lightwave Technol*., vol. 14, no. 5, pp. 914-927, 1996.

[17] S. V. Savov and M. H. A. J. Herben, "Modal transmission line modeling of propagation of plane radio waves through multilayer periodic building structures," *IEEE Trans. Antennas and Propagat*., vol. 51, no. 9, pp. 2244-2251, 2003.

[18] R. Magnusson and M. Shokooh-Saremi "Physical basis for wideband resonant reflectors," *Optics Express*, vol. 16, no. 5, pp. 3456-3462, 2008.

Mohammad Ali Bahar received his B.Sc. in electrical engineering (electronics) from Sajjad University of Technology in Mashhad, Iran, in 2008. In 2013, he received his M.Sc. in electrical engineering (communications) from Ferdowsi University of Mashhad. His research interests include optical communications and design and analysis of optical periodic structures.

Mehrdad Shokooh-Saremi received his B.Sc., M.Sc. and Ph.D. in electrical engineering from Ferdowsi University of Mashhad in 1994, 1999, and 2006, respectively. He also received a Ph.D. in Science (Cotutelle) from the University of Sydney in 2007. He joined department of electrical engineering at Ferdowsi University of Mashhad in 2010, where he is now an associate professor. His research interests include design and fabrication of optical periodic structures, thin film filters, and transparent conducting oxides.