Optics & Laser Technology 70 (2015) 94–99

Contents lists available at ScienceDirect

Optics & Laser Technology

journal homepage: www.elsevier.com/locate/optlastec

Optimization of the genetic operators and algorithm parameters for the design of a multilayer anti-reflection coating using the genetic algorithm

Sanjaykumar J. Patel, Vipul Kheraj *

Department of Applied Physics, S. V. National Institute of Technology, Surat-395007, India

ARTICLE INFO

Article history:
Received 22 October 2014
Accepted 17 December 2014
Available online 18 February 2015

Keywords:
Genetic algorithm
Optimization
Anti-reflection

ABSTRACT

This paper describes a systematic investigation on the use of the genetic algorithm (GA) to accomplish ultra-low reflective multilayer coating designs for optoelectronic device applications. The algorithm is implemented using LabVIEW as a programming tool. The effects of the genetic operators, such as the type of crossover and mutation, as well as algorithm parameters, such as population size and range of search space, on the convergence of design-solution were studied. Finally, the optimal design is obtained in terms of the thickness of each layer for the multilayer AR coating using optimized genetic operators and algorithm parameters. The program is successfully tested to design AR coating in NIR wavelength range to achieve average reflectivity (R) below 10^{-3} over the spectral bandwidth of 200 nm with different combinations of coating materials in the stack. The random-point crossover operator is found to exhibit a better convergence rate of the solution than single-point and double-point crossover. Periodically re-initializing the thickness value of a randomly selected layer from the stack effectively prevents the solution from becoming trapped in local minima and improves the convergence probability.

1. Introduction

Anti-Reflection (AR) coatings are widely used to reduce undesirable optical reflection and to increase the light transmission in many applications in the field of optics and optoelectronic devices. Generally the semiconductor materials used for optoelectronic devices exhibit high reflectivity in the range of 30–40% due to the discontinuous change in refractive index at the interface between ambient medium, usually air, and the semiconductor active layer (e.g., InP, GaAs, and Si) [1]. Conventional single-layer quarter-wave optical thickness or double-layer AR coatings can efficiently minimize the reflectivity at the interface. However, these designs are effective only over a narrow region of the optical spectrum and are more suitable for devices, such as laser diodes, which are monochromatic [2]. However, most optoelectronic devices require low-reflectivity over a wide spectral range, for example, solar cells [3–5] and superluminescent light emitting diode (SLED) [6], which necessitate AR coatings of more complex structures of thin-films with multiple layers or graded-refractive index (GRIN) [7,8]. A multilayer AR coating, which is based on the principle of optical interference in thin-films, is found to be a promising approach to minimize the interface reflectivity over a wide range of wavelengths [9–12]. However, the design of the multilayer structure is application specific and depends strongly on the requirement of the average reflectivity, the wavelength of interest and the band-width. Moreover, a multilayer AR coating requires tuning of many design variables. Therefore, an effective algorithm is required to optimize the design of a multilayer AR coating structure.

Over the years, several methods have been used for designing multilayer AR coatings. Among them, refinement methods [13] and synthesis methods [14] are two numerical methods commonly used for optical thin-film designs. The refinement method requires a starting design, from which the target design is obtained by gradually modifying the starting design. However, the quality of the solution is very sensitive to the starting design, and a good starting design is not readily available for many complex problems. In contrast, the synthesis methods generate their own starting design. The synthesis methods can also be combined with the refinement methods to improve the quality of the solutions. However, the design of a multilayer AR coating is quite complicated because it involves an extremely large and very complex search space with many local minima of the solutions. Therefore, these numerical methods may not always be adequate. Recently, advanced optimization techniques, viz. needle optimization [15], jump method [16], spiral search method [17], particle swarm optimization [18], ant colony optimization [19], and genetic algorithm (GA), have been tested in the design of multilayer AR coatings. GA, in particular, has gained considerable attention and

* Corresponding author.
E-mail address: vipulkheraj@gmail.com (V. Kheraj).

http://dx.doi.org/10.1016/j.optlastec.2014.12.022
0030-3992/

has been used for the design of a variety of optical coatings [20–25]. Although the GA has been found suitable for numerous optimization problems, the genetic operators and parameters involved in the algorithm are very specific to the particular problem [26]. Thus, a systematic study of the effects of these operators and parameters is essential to improve the efficiency of the algorithm.

In this paper, a binary-coded genetic algorithm is used to design multilayer AR coating at normal incidence in view of the specific application of the fabrication of SLEDs. The indium phosphide (InP) and air were considered as the active layer material and the ambient medium, respectively. The thickness of each layer of the multilayer stack is considered as a design variable and optimized by continuous evolution, whereas the number of layers and their sequence are assumed to be fixed with high and low refractive index materials in alternating order throughout the stack. The number of layers is chosen to be 3 for our exercise because we want to obtain the AR film design with the simplest possible multilayered structure for our application. However, the program is developed in a manner such that it can incorporate a higher number of layers to obtain more complex designs, if required. We systematically studied the effect of various genetic parameters, such as types of crossover operators (i.e., single, double, and random point crossover) and algorithm parameters, such as population size and the range of the search space, on the optimum design of AR coating. We also added an additional step in the algorithm that replaces the thickness of the randomly selected layer of the stack with a new random value generated within the specified search space with a predefined probability of occurrences, which we call the 'random re-initialization' (RIR), and the effectiveness of this step was investigated. Finally, using the optimized GA parameters and operators, an optimum design for multilayer AR coating is obtained in terms of the layer thickness along with their material sequences. The algorithm is implemented using LabVIEW (National Instruments) as a programming tool.

2. Genetic Algorithm for the design of an anti-reflection (AR) coating

GA is the stochastic global search optimization algorithm inspired by Darwin's theory of natural selection [27]. GA is capable for solving a wide range of optimization problems, even in highly nonlinear, multidimensional search spaces [28]. GA is essentially mimicking the process of natural evolution underlying the idea of 'survival of the fittest', in which the fitness of individual is improved by successive iteration through the processes of selection, crossover and mutation. There are some features of the GA that make it a very effective algorithm. For example, it does not require any knowledge of starting design and is less inclined to the trapping in local minima, even in a complex dimensional space.

2.1. Implementation of the Genetic Algorithm

The implementation of GA for the minimization of reflectivity requires an appropriate selection of various parameters. These parameters are mainly classified into two ways: (1) fixed parameters and (2) variable parameters. The scanning range of wavelengths, number of iterations (NOI), random re-initialization rate (RIR), number of layers (NOL), mutation rate, and sequence of coating materials in the stack were fixed throughout the optimization of AR coatings. The values of NOL, NOI and RIR were set to 3, 1000 and 10%, respectively, whereas the mutation rate was fixed to 0.5% during the optimization process. Here, we considered a multilayer thin-film structure in our system that is non-absorbing at the design wavelength range. The variation of the refractive index of material is alternately high (n_H) and low (n_L) in the multilayer stack. We used silicon (Si) as a high refractive index material and magnesium fluoride (MgF_2) as low refractive index material in the present study. The selection of the materials was mainly based on their high transmittance in the wavelength range of interest. The minimum thickness of layer (d_{min}) was set to 100 Å in the program, which is the minimum reproducible thickness of the layer during the deposition of the actual multilayer stack in our system. The other parameters, such as the maximum range of the layer thicknesses (d_{max}) and population size (N_{pop}), were considered as variable parameters and were systematically optimized for finding the optimum design. The prepared program is tested using different types of crossover operators, such as single point, double point and random point crossover, as well as an additional step of random re-initialization of a layer thickness. The effects of crossover operators and random re-initialization on the convergence of solution and the optimum design are studied and discussed. The thickness of an individual layer in a stack was considered as a design variable and was optimized using the GA. Table 1 presents the important GA terminology and their equivalents in the multilayer AR design problem.

The algorithm is implemented by an interactive program prepared using LabVIEW as a programming platform. The graphical user interface of the program is shown in Fig. 1. In the beginning of the optimization process, various parameters, such as the range of wavelengths, number of layers, name and sequences of the coating materials, range of the minimum and maximum thickness of layers, number of iterations, and rate of mutation and random re-initialization, are fed as input parameters into the program. The program generates an initial population (N_{pop}) of multilayer AR stacks with a fixed number of layers within the range of layer thicknesses [$d_{min,}$ d_{max}]. After the generation of the initial population, the evaluation of the performance of each individual is performed by a suitable figure of merit function, also called the 'fitness function'. In our case, the fitness function is the average reflectivity of the multilayer AR stack over the range of wavelengths, which is defined as,

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

Here, $R_{cal}(\lambda_k, T)$ is the calculated value of reflectivity at wavelength λ_k for a given set of layer thicknesses ($T = (t_1, t_2, t_3 \ldots t_n)$) using the transfer matrix method described elsewhere [29], where n represents the number of layers in a stack. $R_{desired}$ (λ_k) is the value of reflectivity at wavelength λ_k, as desired by the user as an outcome from the obtained design. For an antireflection coating, in

Table 1
Genetic Algorithm terminology in the context of multilayer AR design.

GA terms	Equivalent AR design problem term
Initial Population	Number of randomly generated stack designs for the multilayer AR coating
Individual	A particular stack, including the thickness of each layer
Search space	Range of minimum and maximum thicknesses of the layer
Fitness function	Average reflectivity of the multilayer AR stack over the wavelength range