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Optimal Design of Arrayed Waveguide Grating

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This paper describes the optimal design of an AWG spectrum to meet various specifications and improve some physical parameters. The objective function is the norm of the difference between design parameters and target values. To obtain the design parameters, the Fourier model is employed and the design variables are spacing of array waveguide, width of array waveguide, optical path difference, and focal length. The (1+1) Evolution Strategy is employed as the optimization tool. The optimization procedure is applied to a 16-channel AWG and the optimized design variables will considerably improve the system performance.

OCIS codes : 050.2770, 070.2580

I. INTRODUCTION

Arrayed-waveguide gratings (AWGs) have already proven to be critical components for many applications in wavelength division multiplexing (WDM) optical networks [1,2]. It is well known that the optical networks with cascaded AWGs require a more strict control of spectral response in each AWG. In order to allow the concatenation of many such devices and relax requirements on accurate wavelength control in a network, their spectral response must necessarily be accurately designed. Many techniques that have been introduced in order to design the spectral response of an AWG have been aimed at achieving a broadened or flattened transfer function by use of multimode output waveguides [3], two cascaded grating devices [4], multiple gratings [5], or a multimode interference coupler [6]. Some design methods using an analytic form of objective function have also proposed [7,8]. However, these techniques are sequential, that is, physical parameters are determined according to a fixed order one by one. Thus, only in single-valued optimization, they are applicable to designing desirable devices while in the multi-valued case, optimizing an objective function may fall into a local minimum, not into the global minimum.

In this paper, an optimum design method to meet several specifications of physical parameters of AWG simultaneously is presented. The spectral response of AWG is computed by using the Fourier model. The physical parameters such as 3-dB bandwidth, loss non-uniformity and insertion loss are obtained from the transmission spectrum. The (1+1) Evolution Strategy is employed as the optimization tool. The optimization method presented here is applied to the design of a 16-channel AWG. The design results show that the optimization method presented here is very useful in designing the AWG spectrum and developing some new type of AWG. This algorithm can be extended to another objective function with other weighting factors and optical parameters.

II. SPECTRAL ANALYSIS OF AWG

The Fourier optics model that was developed by Munoz [8] is employed for the calculation of the spectrum of AWG in this paper. This Fraunhofer diffraction approximation remains valid in the region of far-field diffraction, which, for the AWG case, corresponds to the condition $L_f \gg \frac{\pi W^2}{4\lambda}$ which is satisfied in general AWG where L_f is focal length, W is width of input waveguide, and λ is the optical wavelength. The frequency response of AWG incident from the pth input waveguide is calculated by the following equation:

$$t_{p,q}(\nu) = \int_{-\infty}^{\infty} f_p(x,\nu) b_o(x-qd)dx \tag{1}$$

ν is optical frequency, x is the coordinate in output plane, $f_p(x, \nu)$ is the spatial field distribution at frequencyn ν, $b_o(x)$ is the fundamental mode in the output waveguide, q is the output waveguide number, and d is the output waveguide spacing.

To check the validity of this analysis, equation (1) is applied to obtain some key parameters, such as 3-dB

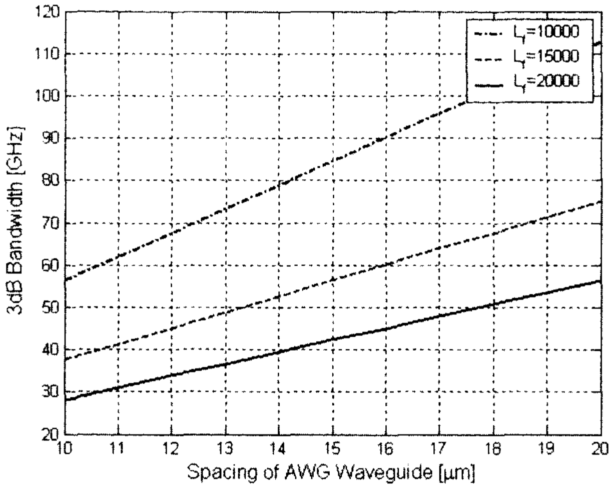


FIG. 1. The calculated bandwidth with spacing of AWG waveguide at several focal length in the slab waveguide.

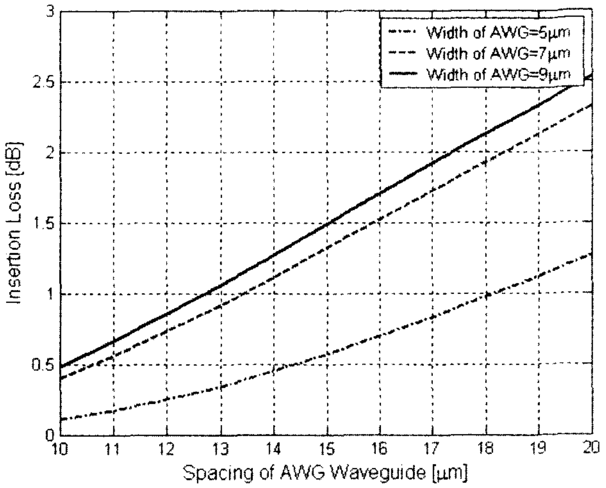


FIG. 2. The calculated insertion loss with spacing of AWG waveguide at several widths of AWG waveguide.

bandwidth, insertion loss, and loss nonuniformity.

The 3-dB bandwidth can be calculated using Eq. (1) with p=0, and q=0, that is, light transmission from center input waveguide to center output waveguide and 16 channel, 100 GHz channel spacing AWG is considered, here. The calculation results are plotted in Fig. 1 and can be interpreted as follows. The 3-dB bandwidth depends on the spacing of the AWG waveguide. If the spacing increases, the dispersion over the output plane becomes less sensitive, so the 3-dB bandwidth increases. The increase in the focal length at fixed output waveguide spacing makes the dispersion higher, yielding smaller bandwidth.

The insertion loss in (1) includes the coupling from the first FPR to the AWs and spatial diffraction to other orders on the output focal plane. The insertion loss also depends on the spacing of the AWG waveguide and the larger the spacing, the higher the insertion loss since the lower light coupling happens at the interface between the FPRs and AWs. Similarly, more coupling between the FPRs and AWs occurs in the case of the AWG with wider AWs as shown in Fig. 2.

III. OPTIMIZATION OF AWG USING (1+1) EVOLUTION STRATEGY

A. (1+1) Evolution Strategy

In this paper, (1+1) ES is employed as a main optimization tool. Among several stochastic methods, ES uses the principle of organic evolution for searching for the optimal values. The ES is widely used because it can find the global optimal solution, the algorithm is simple, and convergence speed is fast. The algorithm roughly consists of four parts: reproduction, mutation, competition, and selection [9,10].

The (1+1) ES is a simple mutation-selection scheme called two membered ES. The "population" consists of one parent only, determined by a certain parameter configuration, creating one descendant by means of adding a normally distributed random vector (mutation) to the parameter values. The 'fitter' of both individuals, obtained by evaluating the objective function, serves as the ancestor of the following iteration (selection). The step width is adjusted periodically (e.g. after 10*np function calls, where np is the number of optimization parameters) in such a way that the ratio of successful mutations over all mutations becomes p. This strategy parameter is usually set to p=0.2. In this paper, an annealing factor is set to be 0.85 and a shaking process is also considered to prevent a solution from converging to a local minimum.

B. Objective Function

The objective function of the optimal design of AWG can include any parameter if it can be calculated from the analysis equation (1). In this paper, the design variables are spacing of array waveguide, width of array waveguide, optical path difference, and focal length and 3-dB bandwidth, loss nonuniformity, as shown in Table 1 and insertion loss are chosen as design parameters, from which different choice is possible. The loss nonuniformity is defined as ratio transmissions at the central output waveguide and the outermost one.

The optimization problem and the objective function are defined as follows:

$$\text{Minimize Objective Function}=\sum_{i=1}^{3} a_i x_i$$

TABLE 1. Optimization Variables.

Variables	Meaning
d	Spacing of arrayed waveguide
w	Width of arrayed waveguide
$\triangle L$	Optical path difference
L_f	Focal length of FPR

$$x_i = \begin{cases} abs\left(\dfrac{y_i - y_{it}}{y_{it}}\right), & i = 1 \\ \dfrac{y_i - y_{it}}{y_{it}}, & \text{otherwise} \end{cases}, \quad \sum_{i=1}^{3} a_i^2 = 1 \tag{2}$$

where y_1 is 3-dB bandwidth, y_2 is loss nonuniformity, y_3 is insertion loss, y_{it} is each target value, a_i is a weighting factor. The absolute difference or differences in the objective function are determined according the following fact: The 3-dB bandwidth has a particular specification value whereas the loss nonuniformity, and the insertion loss are preferable as long as they have lower values.

C. Optimization Procedure

Fig. 3 shows the flow chart for the optimization procedure. If the design variables are determined by the optimization process, the optical parameters (y_1, y_2, and, y_3) are calculated by the Fourier method [8]. Then, the objective function is computed by (2). If the objective function is smaller than the specified value, or the relative error between present and previous optimization step is smaller than the predefined tolerance, then the optimization process is terminated.

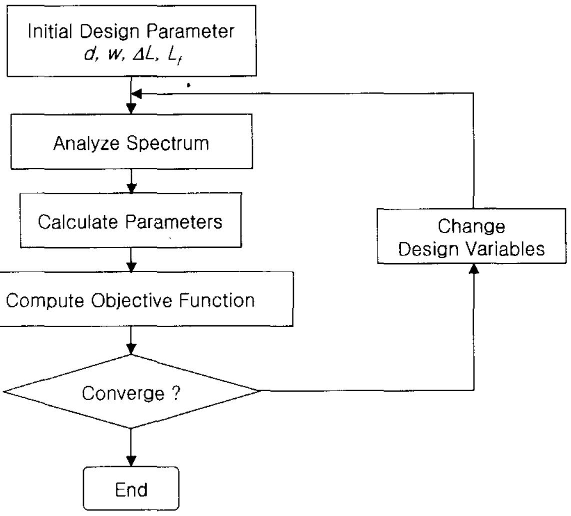


FIG. 3. Optimization procedure for AWG using (1+1) Evolution Strategy.

IV. OPTIMIZATION RESULTS AND DISCUSSIONS

The optimization method presented here is applied to the design of a 16-channel AWG with the target values 3-dB bandwidth 40 GHz, loss nonuniformity 1.5dB, and insertion loss 2 dB, as shown Table 2. The waveguide is assumed a silica-based one. Figure 4 (a), (b), (c) and (d) show the convergent objective function, 3-dB bandwidth, loss nonuniformity, and insertion loss with iteration, respectively in the case that $a_1=a_2=a_3=1/\text{sqrt}(3)$.

Figure 4 (d) shows the convergent insertion loss with iteration. But this does not represent a monotonic increasing trend because the objective function includes not only this parameter but also, 3-dB bandwidth and loss nonuniformity, that is, in range of 40-70 iterations, the process optimizes the device by improving loss nonuniformity and 3-dB bandwidth instead of insertion loss. Figure 4 (a) and Figure 4 (d) make this clear.

Figure 5 shows the transmission spectrum at the initial and final state. This shows that the insertion loss is improved and too broad bandwidth gets narrower to approach the target value 40 GHz.

Table 3 shows the transmission spectrum at upper region. The insertion loss is improved by 0.97 dB and the 3-dB bandwidth gets narrower by 9.6 GHz to the target value 40 GHz.

By changing the weighting factors, 'the importance' of the physical parameters can be further emphasized. One may enhance 'the importance' of some physical parameters by increasing their weighting factors and hence, improving the nearness from the target value. Furthermore, there are no limitations or requirements in choice of design parameters and design variables

V. CONCLUSIONS

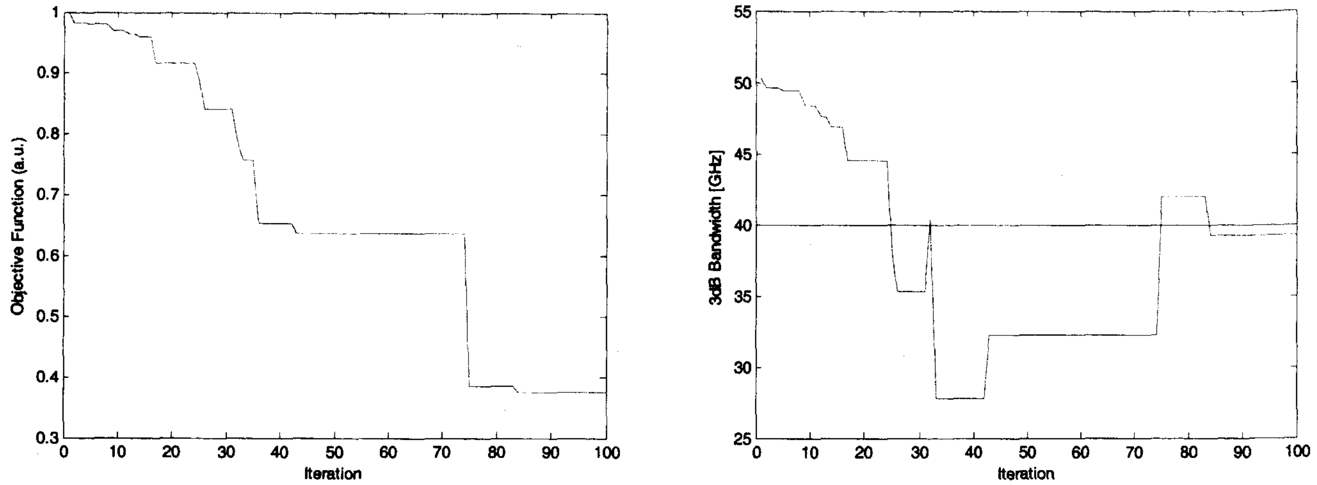
This paper presents the systematic optimum design

TABLE 2. Optimization Parameters.

Parameters	Specifications
3 dB bandwidth	50 GHz
Loss Nonuniformity	< 1.5 dB
Insertion Loss	< 2 dB

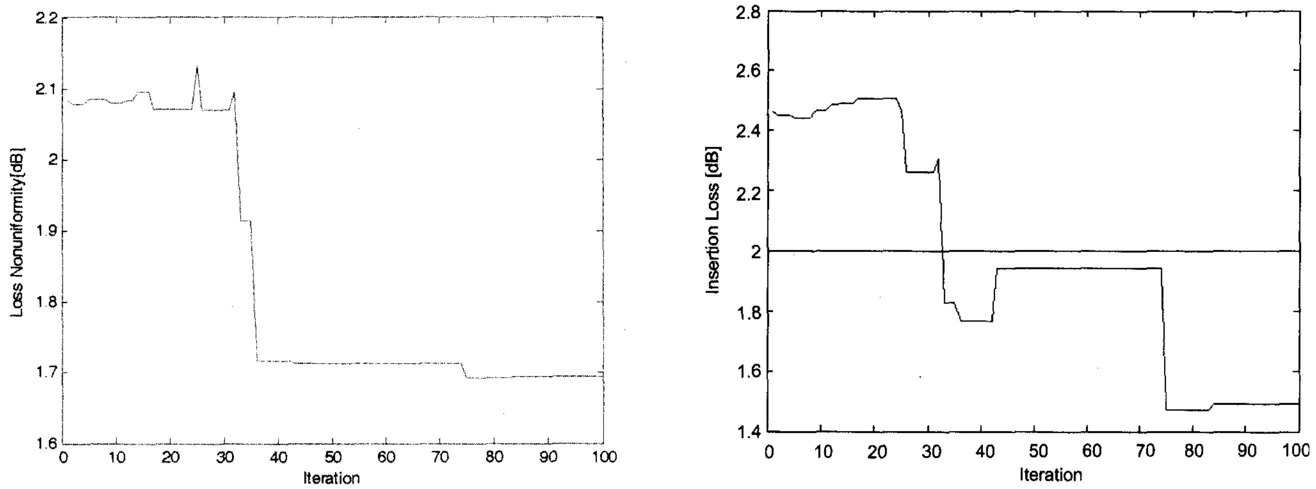
TABLE 3. Optimization Results.

Parameters	Initial	Final
3 dB bandwidth [GHz]	50.3	39.3
Loss Nonuniformity [dB]	2.08	1.69
Insertion Loss	2.46	1.49



(a) Objective function

(b) 3-dB bandwidth



(c) Loss Nonuniformity

(d) Insertion loss

FIG. 4. Iteration Procedure.

method of AWG to obtain desired values of some physical parameters including 3-dB bandwidth, loss nonuniformity, and insertion loss. The frequency response of AWG is calculated by the Fourier model and from their results the physical parameters are obtained. The (1+1) ES is employed as an optimization tool. The optimization method presented here is applied to the design of a 16-channel AWG with the target values 3-dB bandwidth 40 GHz, loss nonuniformity 1.5 dB, and insertion loss 2 dB. The optimizations are performed and convergent objective functions are obtained for some example cases. The design results show that the optimization method presented here is very useful in designing AWG spectrum and developing some new type of AWG. This algorithm can be extended to another objective function with other weighting factors and optical parameters.

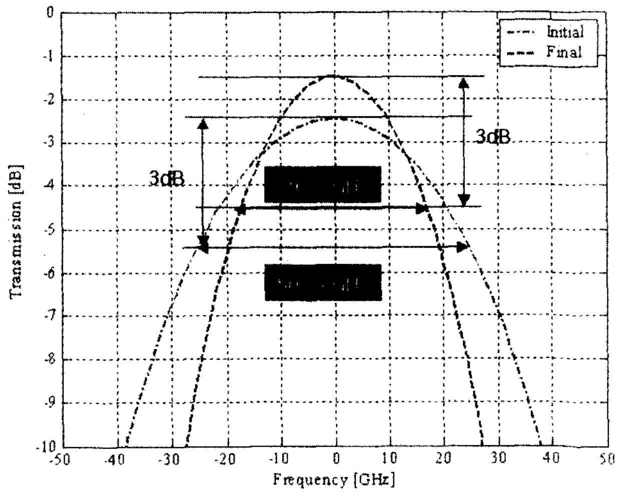


FIG. 5. Transmission spectra at Initial and final state.

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