GA Optimization of the Optical Directional Coupler

Pinar Ozkan-Bakbak

Department of Electronic and Communication Engineering
Yildiz Technical University, Istanbul, 34220, Turkey
pozkan@yildiz.edu.tr

Abstract **─** Optical couplers, which are passive devices, couple optic waves through optical waveguides and can be employed in many applications, including power splitters, optical switches, wavelength filters, polarization selectors, etc. In this work, a simple, fast and instant optimization design is presented for an optical directional coupler based on Genetic Algorithms (GA). This optimization design is preferred due to its favourable usage and fast convergence capability. Finally, the designed methodology has been analytically and experimentally evaluated and the results show that the GA is an advantageous method for designing an optical element where the measurable data is obtainable instead of complex formulas.

Index Terms **─** Genetic Algorithm, optical directional coupler.

I. INTRODUCTION

An optical directional coupler, which consists of two parallel optical fibers or two bent or one straight and one bent optical fibers, is a four-port circuit element and is fed by a laser or a light emitting diode at one of the ports. However the data transmission is provided through the other three ports. Due to interaction within the optical fibers, there is a periodic exchange of power between the two waveguides [1-6].

The IN 1 is the input port, OUT 1 is the output port, OUT 2 is the coupled port and IN 2 is the isolated port, as seen in Fig. 1.

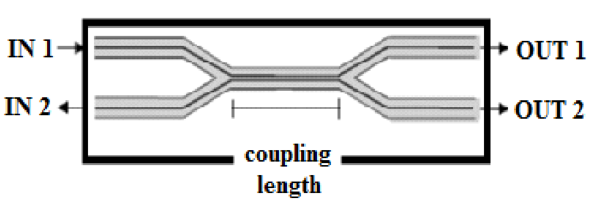

Fig. 1. The general model for directional couplers.

The concept of coupled modes at electromagnetic problems have emerged in the 1950's. The application of the coupled mode theory to optical waveguides had started by Vanclooster and Phariseau [4]. Marcuse, who worked on the interaction mechanism of parallel optical waveguides, contributed to the literature on coupled power equations [5]. The implementation of coupled mode theory to the optical waveguides can be found within Snyder and his working group studies. By increment the importance of directional couplers, especially after 1970, there are many studies in the literature on this subject [6].

A simple, fast and evolutionary structural optimization, which is based on Genetic Algorithms (GA), is described for optimization part. This optimization design is preferred due to its favourable usage and fast convergence capability [7]. The GA method can be applied by using a fitness function (FF). If the optimization is a minimization problem, the FF can be renamed as cost function (CF).

The remainder of this paper is organized as follows: In Section 2, the coupling mechanism between two optical directional coupler is analysed by using the coupled mode theory and perturbation theory. The interaction between the couplers, which consists of identical, slab, parallel, weakly guiding, lossless and uncladded optical waveguides, is analysed for a time dependent term of $\exp(jwt)$. TE even and odd, TM even and odd modes are determined in the slab and identical optic guides [1-6]. The propagation constant change is analysed to be used in the optimization as CF. In Section 3, the applicability of GA optimization in the optical directional coupler is investigated and concluded successfully. The comments on the results are explained in Section 4 and determined that the GA optimization results are compatible with the modal analysis results.

II. COUPLING ANALYSIS IN OPTICAL DIRECTIONAL COUPLER

In this study, the coupling is analyzed by using the coupled mode theory and perturbation theory. Perturbation theory is a mathematical method often used to obtain approximate solutions to equations for which no exact solution is possible, feasible or known. Detailed information about perturbation theory for solutions in optic can be found in [8]. Coupled mode theory is the

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perturbational approached analyses for the coupling of the systems [1-6, 9].

The parameters for the proposed optical directional coupler are seen in Fig. 2. The weakly guiding optical waveguides are also thought to be weakly coupled to each other and the approximate field expressions in wave guides are adopted independent of polarization. In the weak coupling analysis, process is facilitated through ignoring the modes in the opposite direction. The coupling will be investigated in space domain.

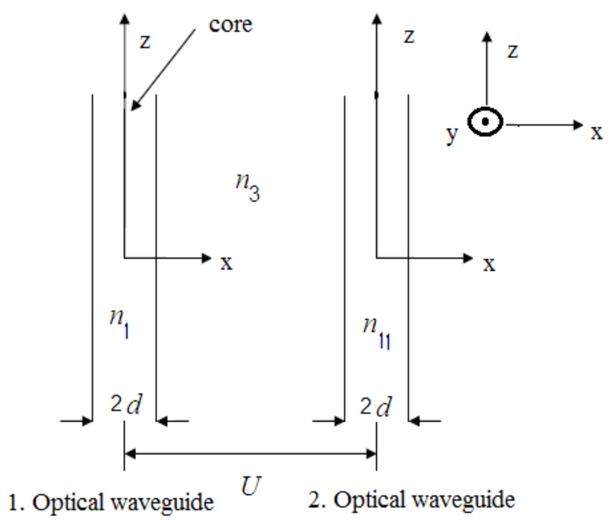

Fig. 2. The coupling between two parallel, identical, slab, weakly guiding, lossless and uncladded optical waveguides. The power reflection coefficient versus groove size.

The amplitude functions of the modes in the first and second optical waveguides are given with the propagation constants β for a time dependent term of $\exp(jwt)$ as follows:

$$a_i(z) = a_0 \exp(-j\beta_i z) \qquad i=1,2. \tag{1}$$

In lossless optic waveguides β values are real values [9] and the analyses are in space domain as follows:

$$da_i / z = -j\beta_i a_i, \tag{2}$$

where the coupling equations are:

$$da_1 / z = -j\beta_1 a_1 + c_{12} a_2, \tag{3}$$

$$da_2 / z = -j\beta_2 a_2 + c_{21} a_1. \tag{4}$$

Here c_{12} and c_{21} are the coupling coefficients. c_{12} is the effect of II optical waveguide to I optical waveguide per unit length, and c_{21} is the effect of I optical waveguide to II optical waveguide per unit length.

TE and TM modes are examined as a result of solving the Maxwell equations, Helmholtz equations and boundary conditions through optical waveguides [1-6].

TE even and odd guided field definitions in the waveguides in the core and the surrounding area respectively are as follows:

$$E_y = \begin{cases} A\begin{cases}\cos(\kappa x) \\ \sin(\kappa x)\end{cases}, & 0 \le x \le d, \\ B\exp\left(-\gamma(|x|-d)\right) & d \le x \le \infty, \end{cases} \tag{5}$$

where κ is the is the eigenvalue of core region and γ is the eigenvalue of the region surrounding the cores.

TM even and odd guided field definitions in the waveguides in the core and the surrounding area respectively are as follows:

$$H_y = \begin{cases} A\begin{cases}\cos(\kappa x) \\ \sin(\kappa x)\end{cases}, & 0 \le x \le d, \\ B\exp\left(-\gamma(|x|-d)\right) & d \le x \le \infty. \end{cases} \tag{6}$$

The propagation constant change of identical modes through identical waveguides in accordance with Maxwell's equations when the quadratic small terms are neglected:

$$\Delta\beta = \pm\frac{\omega\varepsilon_0}{4P}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}\left(n_{II}^2 - n_3^2\right)E_2^* E_1 dxdy. \tag{7}$$

P is the modes' power, n_I is the refractive index of the first waveguide, n_{II} is the refractive index of the second waveguide, n_3 is the refractive index of the region surrounding the cores. n_I and n_{II} are the equal values for providing the identicalness. The propagation constant change for TE even and odd modes is given below:

$$\Delta\beta = \frac{k_0^2}{4\gamma}\left(n_I^2 - n_3^2\right)\left[\frac{\gamma^2}{\beta^2(1+\gamma d)^2}\right]^{1/2}\begin{Bmatrix}\cos^2(\kappa d) \\ \sin^2(\kappa d)\end{Bmatrix} \tag{8}$$

$$\exp^2(\gamma d)\exp(-\gamma U),$$

and the propagation constant change for TM even and odd is given below:

$$\Delta\beta = \frac{\omega^2\varepsilon_0^2 n_I^2\left(n_I^2 - n_3^2\right)}{4\gamma}\frac{1}{\beta\left(d + \frac{n_I^2 n_3^2}{\gamma}\frac{\kappa^2+\gamma^2}{n_3^4\kappa^2 + n_I^4\gamma^2}\right)} \tag{9}$$

$$\begin{Bmatrix}\cos^2(\kappa d) \\ \sin^2(\kappa d)\end{Bmatrix}\exp^2(\gamma d)\exp(-\gamma U).$$

The modes corresponding to azimuthal mode number υ=1 are investigated for this study. V_c is the normalized frequency and the relation is given as follows:

$$(\kappa d)_c \cong V_c = \upsilon\frac{\pi}{2} \qquad \upsilon = 0,1,2,3.. \tag{10}$$

III. GA OPTIMIZATION OF THE OPTICAL DIRECTIONAL COUPLER

GA is an evolutionary algorithm that mimics the natural evolution such as inheritance, mutation, selection and crossover. The algorithm steps are simplified as:

- Randomly initialize the population and determine the fitness.
- Repeat the following steps until best individual is good enough:
  - Select the parents from the population,

- Perform the crossover on the parents creating the population,
- Perform the mutation of the population,
- Determine the fitness of the population.

GA has become a very popular optimization as it can be employed to various areas and provide global research in the solution spaces. The basic principles and applications in computer systems were presented by Holland [10] and de Jong [11] in 1975 and described in detail by Goldberg [12]. GA solver from Matlab toolbox is used in this study where we can also find multi objective GA which is concerned with the minimization of multiple objective functions.

GA solver finds the optimum results that gives the optimum propagation constant change with the relevant parameters. The CF is formulated by:

$$Cost\ Function = \min|\Delta\beta|. \tag{11}$$

Design parameter values in this coupling study are given as follows:

Operation frequency = 200 THz

$$n_{\mathrm{I}} = n_{\mathrm{II}} = 1.5, \qquad n_3 = 1.49,$$

$$U_1 = 135\mu m, \quad U_2 = 135.3\mu m, \quad U_3 = 135.8\mu m.$$

The rest parameters are equal in all simulations for good comparison.

TE and TM modes are analyzed and optimized via GA Matlab Solver in Figs. 3-6, where the compatible results of propagation constant change are figured due to the optical waveguide radius. Moreover Table 1 gives the accuracy percentage of GA results in comparison with the analytical results of each modes.

Table 1: Accuracy of GA

Accuracy of GA	Even (% Accuracy)	Odd (% Accuracy)
TE modes	99.56	99.65
TM modes	99.57	99.65
Average accuracy: % 99.60		

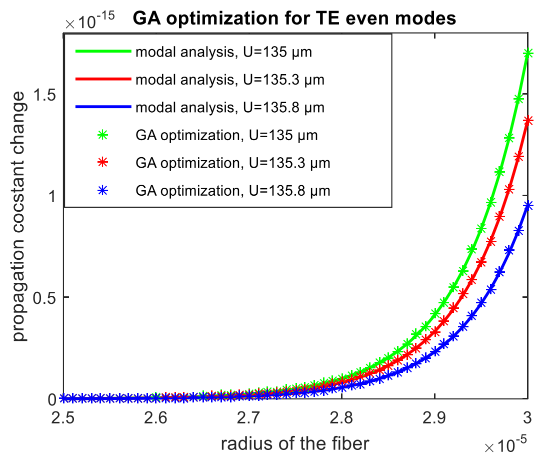

Fig. 3. GA optimization results catch the modal analysis results with high accuracy for TE even modes.

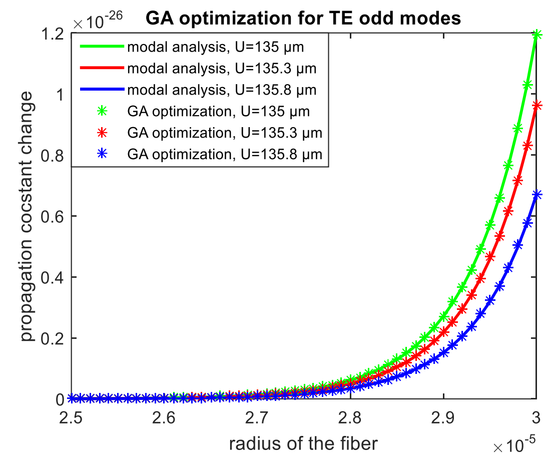

Fig. 4. GA optimization results catch the modal analysis results with high accuracy for TE odd modes.

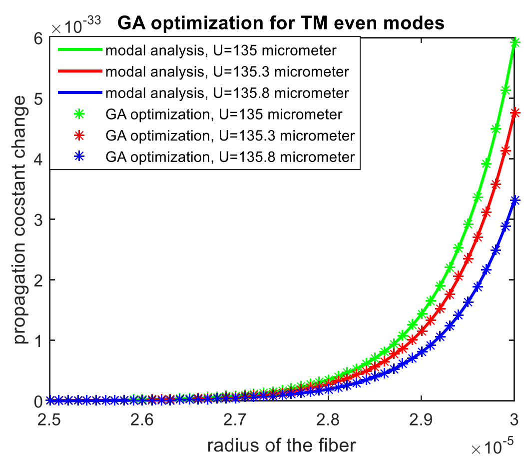

Fig. 5. GA optimization results catch the modal analysis results with high accuracy for TM even modes.

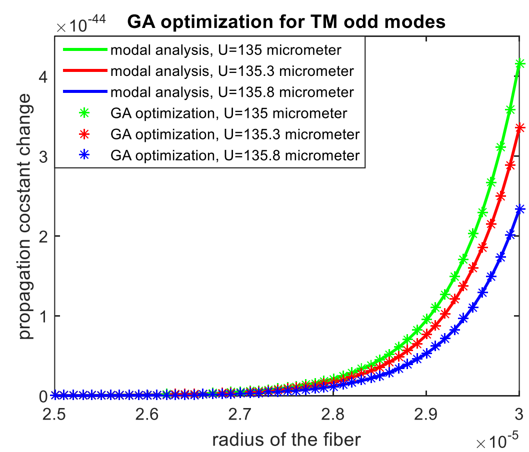

Fig. 6. GA optimization results catch the modal analysis results with high accuracy for TM odd modes.

IV. CONCLUSION

As a reminder, identical guides and equal parameters are employed to see comparative results. It is known via the modal analysis, the coupling between TE modes is more efficient than the coupling between TM modes. Moreover the coupling between even modes is more efficient than the coupling between odd modes. In addition, the propagation constant change increases with the radius of the fiber. As it is observed from the figures that GA results are in agreement with the analytical results. Thus, GA is a fast, simple, helpful and alternative method for designing a complex optical directional coupler. Consequently, GA can be enhanced in optical systems for the independent and automated processes.

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