# A NEW METHOD OF ANALYZING AND MODELING INTEGRATED OPTOELECTRONIC COMPONENTS


Nadir Dagli[1] and Clifton G. Fonstad

Department of Electrical Engineering and Computer Science
Research Laboratory of Electronics, and
Center for Materials Science and Engineering

Massachusetts Institute of Technology
77 Massachusetts Avenue, Cambridge MA 02139



## ABSTRACT

Using a mode matching technique, a modular microwave equivalent circuit incorporating both guided and continuum spectra has been developed to model integrated optoelectronic components accurately with limited computational effort. The analysis is verified with experiments on GaAs rib waveguides and directional and three guide couplers.


## INTRODUCTION

Waveguides and couplers are the most basic components of integrated optoelectronic circuits. Using them it is possible to realize switches, modulators, filters, samplers, power dividers, and combiners. In order to design and fabricate such components for integrated circuit applications, however, one must know design parameters before fabrication. Thus, although discrete components suitable for integration have been fabricated, a reliable formalism to design such components accurately and to modify existing designs to compensate for changes in process parameters, has not existed. In this paper we report a modular microwave equivalent circuit to model and analyze a wide range of integrated optical components, from arbitrarily shaped single waveguides to multiple coupled guides. The equivalent circuit representation allows powerful circuit analysis techniques to be used in the optimization of these components. The method gives accurate results without extensive calculations and the complexity of calculations increases little in going from one waveguide to a multiple coupled waveguide system. The accuracy of the technique is found to be excellent when compared with other theoretical analyses and experimental results.

## METHOD OF ANALYSIS

Rigorous analysis of open guided wave structures is difficult and requires extensive computational effort, so approximate methods are often developed (1), (2). Although these approximate methods are easy to use, they lack the accuracy desired for successful designs. In this work a modular microwave equivalent circuit is developed using a mode matching technique. The equivalent circuit representation follows the basic guidelines of well known transmission line representation of waveguides. This requires a modal expansion of fields and require the selection of a modal set. Determination of mode functions for open guided wave structures is different than for closed structures. Open structures have both discrete and continuous spectra. Continuous spectra present some difficulties and they should be discretized to result in a modular equivalent circuit. In our work this discretization is done using suitable basis function expansions, rather than by artificially bounding the structure. Uniform regions are represented as uniform transmission lines, each transmission line representing a guided or a discretized continuum mode of a particular uniform region. A set of transformers represents each discontinuity. The transformer ratios depend on the overlap integrals of the inner and outer slab modes. Since any open guided wave structure can either be represented or approximated as a cascade of uniform regions and step discontinuities, it is possible to model the whole spectrum of open guided wave structures using the models for the uniform regions and step discontinuities. For a rib guide such a treatment results in the equivalent circuit shown in Figure 1. This form of discretization results in a transmission line representation for all uniform regions, even those where there are no guided modes. Therefore, certain structures which cannot be analyzed with simple approximate techniques such as a the effective dielectric constant (EDC) method (1), can be analyzed with the present method.

The equivalent circuit is modular. Hence, once a waveguide is modeled, the analysis can very easily be extended to N coupled guides with little increase in computation by cascading the basic model. A general computer program was developed to analyze single or multiple coupled waveguides with identical or nonidentical widths and spacings. The cross sectional profile of the waveguides can be arbitrary; for example with sloped sidewalls as produced with chemical etching techniques. Applications of the method to various structures indicate that most structures can be modeled by considering only a very limited number of circuit elements. This simplifies the numerical calculations considerably. Results of this method were compared with the results of other methods including finite element methods, variational techniques and other mode matching techniques for rectangular fibers, rib guides and strip guides. Agreement is excellent and the required computational effort in most cases is substantially less than that of other techniques. For example the required CPU time to find the propogation constant of a rib guide is about 5 seconds on an IBM 4381 computer. The CPU time used to analyze the same structure on a comparable computer using a finite element method analysis is reported to vary between 60 and 300 seconds depending on the mesh size used (3). Furthermore, if one wants to calculate the propagation constant for another guide width by the present method one has simply to solve the equivalent circuit for another width value, which is very easy since only a transmission line length need to be changed. None of the circuit parameters has to be evaluated again, whereas with other techniques

[1]Present address: Department of Electrical and Computer Engineering, University of California, Santa Barbara, CA 93106.

changing the width requires repeating the full computational effort. One can easily extend the analysis to directional couplers or multiple coupled guides made from the same guide by cascading the basic model. The eigenvalues are found by solving the equivalent circuit without the need to calculate the equivalent circuit parameters again. Hence, the increase in calculations required is marginal and is substantially less than what it would be using other techniques.

## EXPERIMENTAL RESULTS

Using this program universal design curves were generated and plotted for the design of rib guides and couplers. Rib guides are the most attractive choices for integrated optoelectronic circuits, because vertical and horizontal index steps are easily controllable. Results of the theoretical analysis were verified with experiments performed on sloped side homojunction GaAs rib guides. By experimentally observing the near field profiles, the number of modes supported by waveguides of different dimensions were determined. In the fabrication, CVD grown undoped ($2 \times 10^{15}$ $cm^{-3}$ ) GaAs epilayers on $n^+$ ($10^{18}$ $cm^{-3}$ ) substrates were used. The shape and dimensions of the structures were determined by SEM observation. The index step between the epilayer and the substrate was experimentally measured to be $(5.25 \pm 1) \times 10^{-3}$ for the epilayers used in the experiment. On 7 μm thick epilayers single sloped side rib guides of various widths were fabricated by etching the epilayer 3.5 μm. All devices were tested at 1.15 μm under TE polarization. In order to see if a guide supported the second higher mode, it was excited antisymmetrically and the near field pattern was observed. In this way the guides that support the second higher order mode, i.e., the $E_{21}$ mode could be identified. For this set single guides of top width larger than 3.75 μm supported the $E_{21}$ mode as shown in Figure 2, which is consistent with theoretical predictions and verify the accuracy of the model. Based on these results it has also been verified that the effective width of a rib guide with sloped sidewalls is the width at the base of the rib, rather than the average width of the rib as is usually assumed in the literature.

In addition to single waveguides straight directional couplers and three guide couplers were also fabricated. Transfer lengths of two sets of directional couplers and three guide couplers shown in Figure 3 were also measured. Directional couplers are the most basic components of filters, switches, modulators and samplers. Three guide couplers are used as power dividers in place of rather long Y branches, as power combiners from different sources and as improved samplers (4). Near field profile and its transverse variation for a three guide coupler showing the power transfer from the center guide to the outer guides at different device lengths are shown in Figure 4. Three intensity peaks are due to the presence of three closely spaced waveguides. For three guide couplers power in the middle guide was found to vary periodically with the length of the device under all excitation conditions (5). Only when the middle guide is excited power in all guides vary periodically as the length of the device varies. Results of the experiments and theoretical calculations are summarized in Table 1. The transfer length shown for directional couplers is the length to transfer power from one guide to the other and for three guide couplers it is the length to divide the power in the center guide equally into two outer guides, which is half the length required to transfer power from one outer guide to the other. These devices were also simulated to obtain theoretical transfer lengths. In the simulations all the parameters of the structure, i.e., dimensions, sidewall angle, index step between the epilayer and the substrate, were either measured or experimentally determined. The theoretically calculated and experimentally measured transfer lengths are in very good agreement.

| | Theoretical | Experimental |
|---|---|---|
| Directional Coupler 1 | L=5.6 mm | L=5.0 mm |
| Directional Coupler 2 | L=3.0 mm | L=2.8 mm |
| Three Guide Coupler 1 | L=3.42 mm | L=3.8 mm |
| Three Guide Coupler 2 | L=1.87 mm | L=1.9 mm |

Table I

Summary of the results of experimental and theoretical transfer lengths of directional and three guide couplers.

## CONCLUSIONS

In this work a modular microwave equivalent circuit was developed to model integrated optoelectronic components. The technique gives accurate results with limited computational effort. Experimental results indicate that the present method of analysis is very accurate and powerful and is applicable to a very broad range of problems. As such, it is an important contribution to the design and realization of high performance integrated optoelectronic components.

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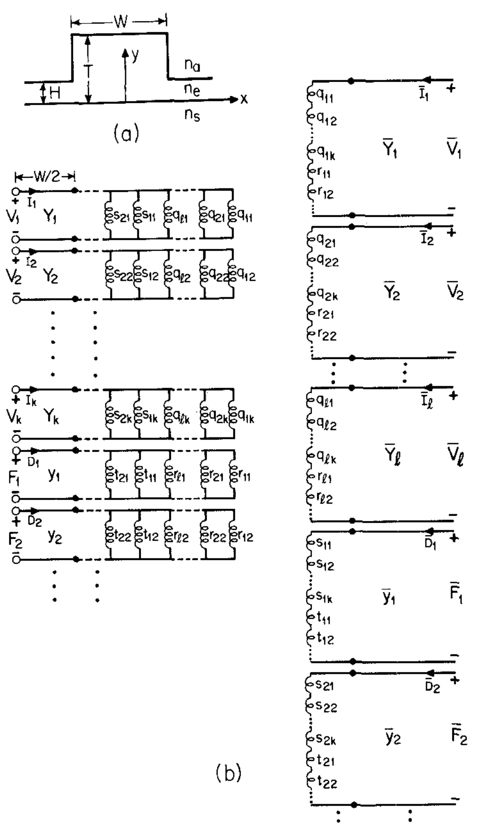
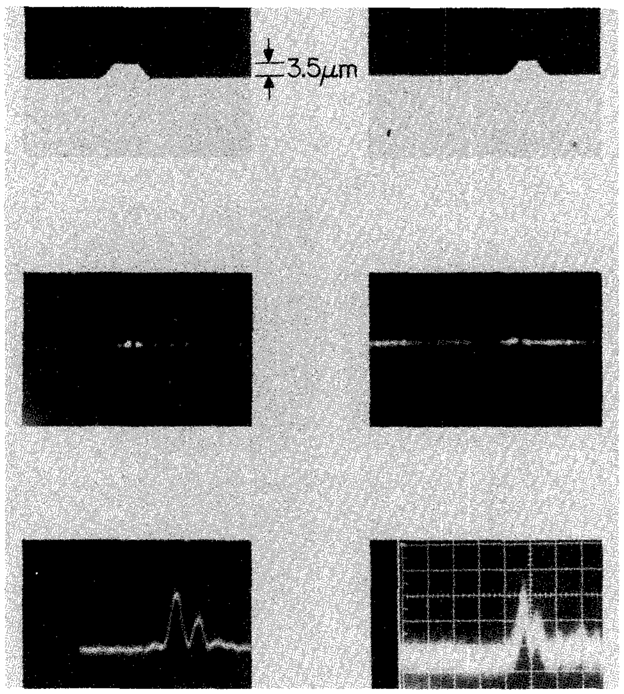
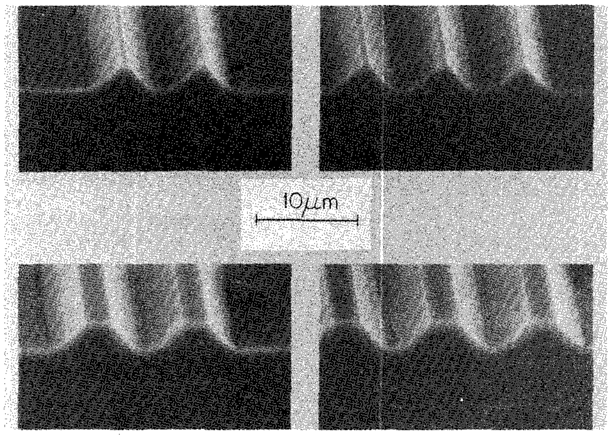



1. (a) A rib waveguide

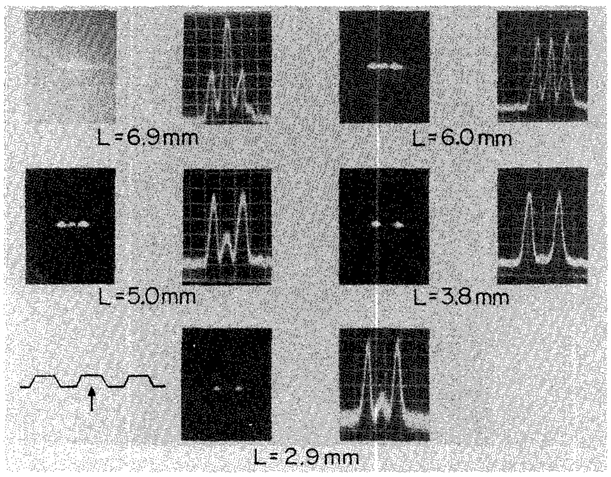
(b) Its microwave equivalent circuit.




2. Near field profiles and their scans showing the guides supporting $E_{21}$ mode fabricated on 7μm thick epilayers.




3. SEM pictures of the directional couplers and three-guide couplers used in this work.




4. Near field profiles and their scans for a three-guide coupler showing the power transfer from the center guide to the outer guides at different device lengths.