[9] R. J. Baeten, "Analysis and characterization of microstrip PIN diode attenuators," M. S. thesis, Marquette University, Milwaukee, WI, May 1986.

[10] G. Matthaei, L. Young, and E. M. T. Jones, *Microwave Filters, Impedance-Matching Networks and Coupling Structures*. Dedham, MA: Artech House, 1980.

[11] B. A. Syrett, "A broadband element for microstrip bias or tuning circuits," *IEEE Trans Microwave Theory Tech.*, vol. MTT-28, pp. 925–927, Aug. 1980.

[12] W. J. Parris, "p-i-n variable attenuator with low phase shift," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-20, pp. 618–619, Sept. 1972.

[13] F. G. Ananaso, "A low phase shift step attenuator using p-i-n diode switches," *IEEE Trans. Microwave Theory Tech.*, vol MTT-28, pp. 774–776, July 1980.

Beam Propagation Method Applied to a Step Discontinuity in Dielectric Planar Waveguides

LOTFI RABEH GOMAA

Abstract —**The power transmission and loss at an abrupt discontinuity in planar guides are calculated numerically using the beam propagation method (BPM) for the TE modes. Discontinuities include changes in core thickness and refractive index. Symmetric and asymmetric waveguides are considered. Comparison of results with those obtained by other techniques shows a general agreement.**

I. Introduction

The power transmitted and lost at a junction between two dissimilar waveguides can be evaluated by a variational method [1] and by mode matching [2], Wiener–Hopf [3], and residue calculus [4] techniques, as well as by the Green's function [5] method. All of these techniques are relatively complicated and require the solution of an infinite set of equations, or the expansion of the field in terms of an infinite set of orthogonal functions or polynomials which are oscillatory. Hence care must be taken to guarantee the stability and the convergence of the solution. In many practical situations the reflected field can be neglected when the relative change in the refractive index is small. In such cases we can use the BPM [6], [7] to evaluate the transmitted and the scattered power at a step discontinuity. In the BPM, the total propagating electric field $E_y(x, \Delta z)$ is calculated at small intervals in the direction of propagation z using the discrete Fourier transform [6], which can be calculated by the fast Fourier transform (FFT) algorithm. An iterative calculation [6] allows an approximate evaluation of the total field at Δz, knowing the field at $z = 0$:

$$E_y(x, \Delta z) = P \cdot Q \cdot P\{E_y(x,0)\} \tag{1}$$

where P and Q are the two operators:

$$P = \exp\left[-i\frac{\Delta z}{2}\frac{\nabla_t^2}{\left(\nabla_t^2 + k_0^2 n_s^2\right)^{1/2} + k_0 n_s}\right] \tag{2}$$

and

$$Q = \exp[-i\Delta z k_0(n(x) - n_s)]. \tag{3}$$

Manuscript received July 14, 1987; revised October 14, 1987.
The author is with the Laboratoire d'Electromagnétisme Microondes et Optoélectronique, 38031 Grenoble, France.
IEEE Log Number 8719198.

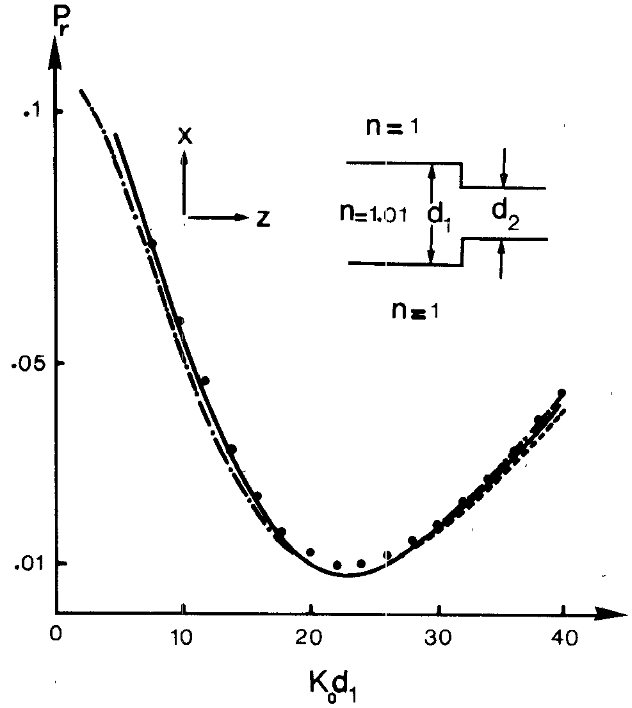

Fig. 1. Symmetric step discontinuity. —— integral equation method; –·–·–·– residue calculus technique; ---- approximate mode matching technique; ●●●● BPM.

Here, k_0 is the free-space wavenumber, n_s is the substrate index of refraction, and ∇_t^2 is the transverse Laplacian in the x direction. The error introduced in the solution (1) is of the order $(\Delta z)^3$; hence a small increment in the direction of propagation is necessary to obtain accurate results [7]. One of the main advantages of the BPM is that it gives detailed information about the total propagating field and its Fourier transform at any plane z. The discrete and the continuous parts of the spectrum of the propagating field are considered; this gives a clear insight into the evolution and the behavior of the total field at any point in any plane transverse to the direction of propagation. It is worthwhile to note that the modal content of the propagating field $E_y(x)$ is easily obtained by expanding the total field in terms of the eigenmodes of the waveguiding structure [8]:

$$E_y(x) = \sum_n t_n e_{yn}(x) + \mathscr{R} \tag{4}$$

where $e_{yn}(x)$ is the transverse field distribution of the nth guided mode and $\mathscr{R}$ is the Fourier integral representing the radiation field. The transmission coefficient t_n can be calculated by direct scalar product of (4) with the complex conjugate $e_{yn}^*(x)$:

$$t_n = \frac{\int_{-\infty}^{\infty} E_y(x) e_{yn}^*(x)\, dx}{\int_{-\infty}^{\infty} |e_{yn}(x)|^2\, dx}. \tag{5}$$

The radiated power is the difference between the guided power (knowing t_n from (5)) and the incident power.

II. Results

We consider as a first example the symmetric step shown in Fig. 1. It was studied previously by Marcuse [9] using an approximate mode matching technique; Ittipiboon *et al.* [4] studied

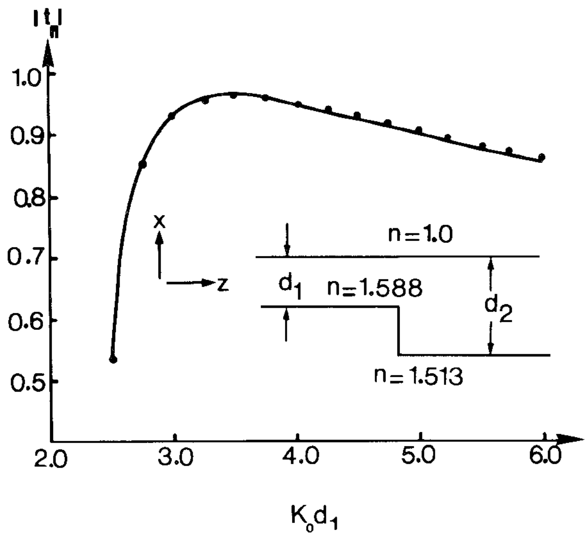

Fig. 2. Asymmetric step discontinuity. —— rigorous mode matching technique; ●●●● BPM.

the same case using the residue calculus, and recently Nishimura *et al.* [10] used an approximate integral equation to calculate the relative radiated power P_r (the ratio of the power lost by radiation to the incident power). Fig. 1 shows the results of the BPM (solid dots) presented in this letter and the three previous techniques. The variation of P_r is shown as a function of $k_0 d_1$ when the ratio d_2/d_1 is kept constant at 0.5; the field incident on the step from the right is the fundamental TE mode. As a second example we consider the asymmetric step studied rigorously by Boyd *et al.* [11] using a discretized representation of the radiation field. Fig. 2 shows the results of this method and those obtained by the BPM (solid dots) in evaluating the magnitude of the transmission coefficient $|t_n|$ as a function of $k_0 d_1$ ($d_1/d_2 = 0.5$ and the wavelength is 0.6328 μm). The comparison is fairly favorable because the relative forward radiated power is much higher than the backscattered radiated power for a step ratio $d_1/d_2 = 0.5$, as pointed out by Marcuse [9], so that the reflected field can be neglected; hence the losses are mainly due to forward scattering.

III. Conclusions

To the author's knowledge, the BPM applied to step discontinuities is presented for the first time in this paper. The applicability of this method to symmetric and asymmetric steps is checked and the results are compared with those of four other methods.

We think that the BPM is efficient for analyzing a wide class of step discontinuities, and perhaps it will be the most convenient method for dealing with step discontinuities between guides of arbitrary refractive index distribution, for example graded or buried waveguides.

Acknowledgment

The author wishes to thank Prof. P. J. R. Laybourn of Glasgow University for many helpful discussions and valuable criticism and Prof. G. H. Chartier for many constructive remarks and encouragement.

References

[1] T. E. Rozzi, "Rigorous analysis of the step discontinuity in a planar dielectric waveguide," *IEEE Trans. Microwave Theory Tech*, vol MTT-26, pp. 738–746, Oct. 1978.
[2] P. H Masterman and P. T. B Clarricoats, "Computer field-matching solution of waveguide transverse discontinuities," *Proc. Inst. Elec. Eng.*, vol. 118, no. 1, pp. 51–63, Jan. 1971.
[3] A Ittipiboon and M. Hamid, "Application of the Weiner–Hopf technique to dielectric slab waveguide discontinuities," *Proc. Inst. Elec Eng.*, vol. 128, pt.H., no. 4, pp. 188–196, Aug. 1981.
[4] A Ittipiboon and M Hamid, "Scattering of surface wave at a slab waveguide discontinuity," *Proc. Inst. Elec. Eng*, vol. 126, no. 9, pp. 798–804, Sept. 1979.
[5] P G. Cottis and N. K. Uzunoglu, "Analysis of longitudinal discontinuities in dielectric slab waveguides," *J. Opt Soc. Am.*, vol. 1, no. 2, pp. 206–215, Feb. 1984.
[6] M. D. Feit and J A. Fleck, "Light propagation in graded index optical fibers," *Appl. Opt.*, vol. 17, no. 24, pp. 3990–3998, Dec. 1978.
[7] J Van Roey, J Van der Donk, and P. E. Lagasse, "Beam-propagation method: Analysis and assessments," *J. Opt. Soc. Am.*, vol. 71, no. 7, pp. 803–810, July 1981.
[8] D. Marcuse, *Light Transmission Optics* New York: Van Nostrand Reinhold, 1972, ch 9.
[9] D. Marcuse, "Radiation losses of tapered dielectric slab waveguides," *Bell Syst Tech J.*, vol. 49, pp. 273–290, 1970.
[10] E Nishimura, N. Morita, and N. Kumagai, "An integral equation approach to electromagnetic scattering from arbitrarily shaped junction between multilayered dielectric planar waveguides," *J. Lightwave Technol.* vol. LT-3, no. 4, pp. 889–894, Aug. 1985.
[11] T J. M. Boyd, I. Moshkun and M Stephenson, "Radiation losses due to discontinuities in asymmetric three-layer optical waveguides," *Opt. Quan. Electron.*, vol. 12, pp. 143–158, 1980.

Low-Phase-Noise Gunn Diode Oscillator Design

ROBERT A. STRANGEWAY, MEMBER, IEEE, T. KORYU ISHII, SENIOR MEMBER, IEEE, AND JAMES S. HYDE

Abstract —**Low-phase-noise Gunn diode oscillators with an operating frequency of 35 GHz and an output power of 100 mW are designed, fabricated, and tested. The phase noise is −132 dBc/Hz to −125 dBc/Hz at 100 kHz offset from the center frequency. This low phase noise is obtained by closely coupling the stabilizing transmission cavity resonator and the Gunn diode oscillator coaxial line while loosely coupling the transmission cavity to the output waveguide following van der Heyden's approach.**

I. Introduction

A stable low-phase-noise microwave oscillator is always useful as a signal source for synchronized communications and scientific precision measurements. In the past, various approaches have been tried to reduce the phase noise of various types of microwave oscillators [1]–[10]. According to published references, the phase noise of a center frequency of 35 GHz ranges from −115 to −70 dBc/Hz at an offset frequency of 100 kHz from

Manuscript received August 1, 1987; revised October 15, 1987. This work was supported in part by the National Institute of Health under Grant RR01008

R. A. Strangeway is with the Department of Electrical Engineering and Computer Science, Marquette University, Milwaukee, WI. He is also with the Milwaukee School of Engineering, Milwaukee, WI

T. K. Ishii is with the Department of Electrical Engineering and Computer Science, Marquette University, Milwaukee, WI 53233.

J. S. Hyde is with the Department of Electrical Engineering and Computer Science, Marquette University, Milwaukee, WI. He is also with the Medical College of Wisconsin, Milwaukee, WI.

IEEE Log Number 8719197

0018-9480/88/0400-0792$01.00 ©1988 IEEE