4 THOMS, S., MCINTYRE, I., BEAUMONT, S. P., AL-MUDARES, M., CHEUNG, R., and WILKINSON, C. D. W.: 'Fabrication of quantum wires in GaAs/AlGaAs heterolayers', *J. Vac. Sci. Technol.*, 1988, **B6**, p. 127

5 CHEUNG, R., THOMS, S., BEAUMONT, S. P., DOUGHTY, G., LAW, V., and WILKINSON, C. D. W.: 'Reactive ion etching of GaAs using a mixture of methane and hydrogen', *Electron. Lett.*, 1987, **23**, (16), p. 857

6 PACCAGNELLA, A., CALLEGARI, A., LATTA, E., and GASSER, M.: 'Schottky diodes on hydrogen plasma treated *n*-GaAs surfaces', *Appl. Phys. Lett.*, 1989, **55**, p. 259

7 CHEUNG, R., THOMS, S., MCINTYRE, I., WILKINSON, C. D. W., and BEAUMONT, S. P.: 'Passivation of donors in electron beam lithographically defined nanostructures after methane/hydrogen reactive ion etching', *J. Vac. Sci. Technol.*, 1988, **B6**, p. 1911

MODAL CURRENT DISTRIBUTIONS ON CLOSELY COUPLED MICROSTRIP LINES: A COMPARATIVE STUDY OF THE SDA BASIS FUNCTIONS

Indexing terms: Microwave devices and components, Microstrip, Modelling

A newly proposed set of basis functions incorporated into the spectral domain approach (SDA) can efficiently and accurately model nearly true current distributions on infinitely thin and perfectly conducting coupled microstrip lines. It is validated by comparing the field solutions with those obtained by various sets of entire-domain and subdomain bases.

Introduction: The spectral domain approach (SDA) has been used extensively to determine the circuit parameters of planar or quasiplanar structures used in the microwave and millimetre wave frequency regime. The field solutions will be exact, if the current distributions on the infinitely thin and perfectly conducting strips are correctly obtained. Since the SDA formation is variational for the modal propagation constant β, an accurate modelling of the current distributions will result in the true value for the propagation constant. On the other hand, the characteristic impedance defined by the power/current definition is not variational and its accuracy strongly depends on the modelling of the current distributions on the strips. This paper presents a set of new basis functions for use in the SDA and tests it on modelling the true currents of closely coupled microstrip lines.

Formulation: Starting with a two-dimensional perfectly conducting wedge problem,[1] and the quasi-TEM approximation as described by Denlinger,[2] we derive the following bases according to the criteria reported by Jansen:[3]

$$J_{z1}(\xi) = \sum_{m=1}^{2} \sum_{n=1}^{\infty} c_{1mn} \cdot j_n(m, \xi)$$

$$J_{x1}(\xi) = \sum_{m=1}^{2} \sum_{n=1}^{\infty} d_{1mn} \cdot j_{n+2}(m, \xi)$$

$$j_n(1, \xi) = (1+\xi)^{(n-2)/2} - \sqrt{(2)} \, . \, (1+\xi)^{(n-1)/2} + \tfrac{1}{2} \, . \, (1+\xi)^{n/2}$$

$$j_n(2, \xi) = (1-\xi)^{(n-2)/2} - \sqrt{(2)} \, . \, (1-\xi)^{(n-1)/2} + \tfrac{1}{2} \, . \, (1-\xi)^{n/2}$$

$$n = 1, 2, 3, \ldots \qquad (1)$$

where c_{1mn} and d_{1mn} are unknown constants, to be determined. The normalised variables $\xi = -1$ and 1 correspond to the edges at $x = S_1$ and $S_1 + W_1$ shown in Fig. 1, respectively. The bases for other strip(s) can be obtained in a similar fashion.

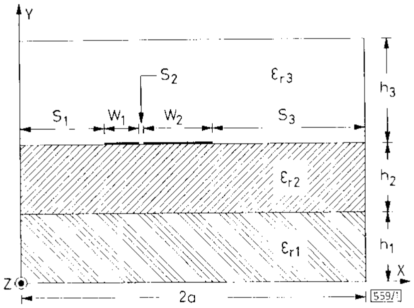

Fig. 1 *Cross-sectional view of the asymmetric coupled microstrip lines with stratified dielectric layers*

The accuracy of the modal current distributions computed on the basis of eqn. 1 is validated and compared with those obtained by the entire-domain and subdomain bases. The entire-domain bases utilise the well-known bases reported by Schmidt *et al.*[4] (the S type) and Tripathi and Lee[5] (the C type). The subdomain bases are the triangular pulse functions.[6]

Results: Table 1 lists the comparative study of the propagation characteristics of the π-mode for asymmetric coupled

Table 1 COMPARATIVE CONVERGENCE STUDY OF THE NORMALISED PROPAGATION CONSTANTS AND CHARACTERISTIC IMPEDANCES OF THE π-MODE FOR CLOSELY COUPLED ASYMMETRIC MICROSTRIP LINES

N		10^4			5×10^4		
Bases	*NB*	β/k_0	Z_{π_1}	Z_{π_2}	β/k_0	Z_{π_1}	Z_{π_2}
Proposed bases	6	1·2610138	51·8792	31·2293	1·2610501	51·9134	31·2505
	8	1·2609023	51·9049	31·2105	1·2609003	51·9386	31·2312
	10	1·2609090	51·9025	31·2118	1·2608971	51·9366	31·2324
S type	6	1·2626142	52·4952	31·3538	1·2625962	52·5170	31·3644
	8	1·2616612	52·2207	31·3002	1·2616486	52·2441	31·3123
	10	1·2612951	52·0969	31·2715	1·2612855	52·1214	31·2846
C type	6	1·2612059	52·0435	31·0846	1·2611854	52·0734	31·0995
	8	1·2609168	52·0107	31·0752	1·2609064	52·0417	31·0918
	10	1·2608705	52·0054	31·0725	1·2608641	52·0369	31·0900
Subdomain bases *M*	20	1·2609004	47·9382	27·1951	1·2608971	51·2720	30·5523
	40	1·2609011	47·9249	27·1651	1·2608972	51·2658	30·5581

N		10^5		
Subdomain bases *M*	20	1·2608967	51·6389	30·9241
	40	1·2608968	51·6387	30·9303

$2a = 2{\cdot}54$ mm; $h_1 = h_2 = 0{\cdot}245$ mm; $h_3 = 0{\cdot}762$ mm; $S_2 = 0{\cdot}0127$ mm; $S_1 : W_1 : S_2 : W_2 : S_3 = 49{\cdot}5 : 20 : 1 : 40 : 89{\cdot}5$; $\varepsilon_{r1} = \varepsilon_{r3} = 1$; $\varepsilon_{r2} = 2{\cdot}2$; $f = 150$ GHz lines with structural parameters as shown in Fig. 1. N is the number of spectral summation terms, NB is the number of entire-domain bases for modelling J_z or J_x on a strip and M is the number of equally partitioned intervals of each conducting strip when using the subdomain bases.[6] Here, the case of closely coupled asymmetric microstrip lines is employed to depict the power of the bases in eqn. 1. The aspect ratios $S_1 : W_1 : S_2 : W_2 : S_3$ are equal to 89·5 : 20 : 1 : 40 : 49·5. Notice that W_2 is nearly one third of the guided wavelength so strip 2 is electrically wide. Since S_2 is very small, the coupling between two microstrips is very strong. This makes the asymmetric microstrip lines a difficult case in which to produce convergence for the SDA program.

In Table 1, the propagation constants obtained by the proposed bases have the best agreement with those computed by the subdomain bases. The numerical data obtained by the C type and proposed bases converge faster than those obtained by the other two sets of bases as N and NB are increased. The characteristic impedances[5] obtained by the subdomain bases seem to require more than 10^5 summation terms to approach their final values. This manifests itself in the fact that the subdomain bases are often not efficient in practice to apply them.

Figs. 2 and 3 show the normalised current distributions on the microstrip lines for the particular case study. Each current component is normalised by I_1, the total current on the strip 1. NB is 10 for S and C type bases and 8 for the proposed ones. M equals 40 for the subdomain bases. The results indicate that

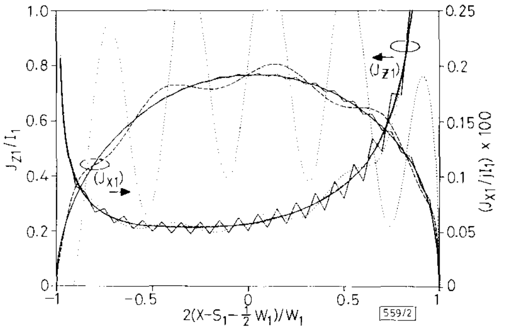

Fig. 2 *Normalised J_z and J_x on strip 1 for the π-mode obtained by the subdomain and various types of entire-domain bases*

Structural parameters as Table 1
——— proposed bases; – – – – Chebyshev (C) type;
······ sinusoidal (S) type; —-–— subdomain bases

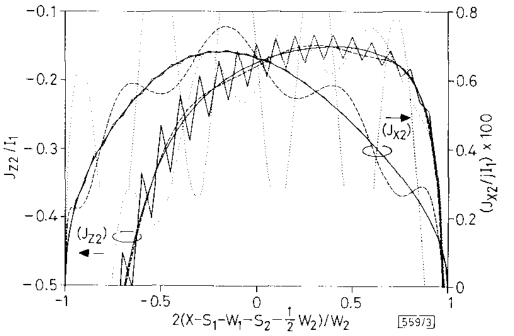

Fig. 3 *Normalised J_z and J_x on strip 2*

——— proposed bases; – – – – Chebyshev (C) type;
······ sinusoidal (S) type; —-–— subdomain bases

(i) the proposed bases have the smoothest current distributions

(ii) the entire-domain S and C type bases and the subdomain bases have current distributions fluctuating around those obtained by the proposed bases

(iii) the particular numerical investigation shows that the amplitudes of these fluctuations around the results obtained by the proposed bases get smaller as NB is changed from 6 or 8, to 10 or M from 10 or 20 to 40, and so on

(iv) each midpoint of the adjacent corners of the zigzag current distributions obtained by the proposed subdomain bases falls on the solutions obtained by the proposed bases.

By deduction, based on the discussions reported in (i) to (iv), we conclude that if M (in the case of subdomain bases) is further increased to infinity with a sufficient number of spectral terms N, the J_z and J_x obtained by the subdomain bases will have their infinite number of middle points coincide with those obtained by the proposed bases. The same conclusion applies to the field solutions of the C mode. Thus, we conclude that the values for Z_{π_1} and Z_{π_2} obtained by the proposed bases are accurate and that the proposed set of bases is capable of representing nearly true current distributions on the coupled microstrip lines and becomes a viable set of bases for the SDA analyses of planar or quasiplanar transmission lines.

C.-K. C. TZUANG
J.-T. KUO

Institute of Communication Engineering
National Chiao Tung University
75 Po Ai Street, Hsin Chu, Taiwan, Republic of China

9th January 1990

References

1 JACKSON, J. D.: 'Classical electrodynamics' (John Wiley & Sons, New York, 1975)

2 DENLINGER, E. J.: 'A frequency dependent solution for microstrip transmission lines', *IEEE Trans.*, 1971, **MTT-19**, pp. 30–39

3 JANSEN, R. H.: 'High-speed computation of single and coupled microstrip parameters including dispersion, higher modes, loss and finite thickness', *ibid.*, 1978, **MTT-26**, pp. 75–82

4 SCHMIDT, L. P., ITOH, T., and HOFMANN, H.: 'Characteristics of unilateral fin-line structures with arbitrarily located slots', *ibid.*, 1981, **MTT-29**, pp. 352–355

5 TRIPATHI, V. K., and LEE, H.: 'Spectral-domain computation of characteristic impedances and multiple ports coupled microstrip lines', *ibid.*, 1989, **MTT-37**, pp. 215–221

6 FACHÉ, N., and ZUTTER, D. D.: 'Rigorous full-wave space domain solution for dispersive microstrip lines', *ibid.*, 1988, **MTT-36**, pp. 731–737

LOW THRESHOLD HIGHLY EFFICIENT STRAINED QUANTUM WELL LASERS AT 1·5 MICROMETRE WAVELENGTH

Indexing terms: Lasers and laser applications, Quantum optics

Low threshold and high efficiency operation of strained layer multiple quantum well InGaAs/InGaAsP lasers at 1·5 micrometres wavelength is demonstrated. Current thresholds as low as 2·2 mA with threshold current densities of 440 A/cm² have been obtained. With 7·3 mA threshold current, quantum efficiency was 65%/front facet. At 20 mW CW output power the drive current was as low as 53 mA.

InGaAs/InGaAsP multiple quantum well (MQW) lasers at 1·3 to 1·5 μm wavelength have yielded several advantages over bulk lasers in the same wavelength range, such as low internal loss, high quantum efficiency, low threshold current operation and small linewidth enhancement factors.[1–4] There have been several reports predicting that further improvements are possible by employing strained layer quantum wells,[5–7] as the effective mass of holes in the heavy hole subband of quantum well layers can be significantly reduced in the plane of the wells by compressive strain. This should result in lower threshold currents and other improvements of the laser