A Novel Coplanar Slow-Wave Structure

Adnan Görür

Abstract—**A novel coplanar slow-wave structure that has the form of interdigitated-meander line is proposed in this letter for use in MMIC's. A simple analysis of this structure has been carried out by using empirical equations available in the literature and with the aid of CAD packages. A propagation velocity of about 2.8.10^7 m/s was measured. Comparisons between theoretical and experimental results show good agreements.**

I. Introduction

Recently, with the remarkable progress in monolithic microwave integrated circuit (MMIC) technology, use of lumped elements on dielectric substrates instead of distributed elements for microwave devices such as impedance matching circuits, filters and couplers has been become an attractive option for MMIC's. So far, various types of the slow-wave structures have been thoroughly investigated [1]–[3]. Propagation velocities of about $1 - 1.2.10^8$ m/s can be obtained by means of microstrip and coplanar lines with dielectric substrate such as gallium arsenide and indium phosphide [4]. However, Haydle measured propagation velocities in the range of $0.5 - 1.10^8$ m/s on the meander coplanar transmission line. But, this velocity is insufficient for MMIC applications. It is possible to decrease the transmission line length of MMIC's for example using MIS structures. However, the propagation velocity can also be decreased by means of different transmission line configurations.

The purpose of the present work is to describe a novel slow-wave structure, on which propagation velocities are up to a factor of four slower than that on normal coplanar lines. The velocity on a conventional lossless transmission line is given by $v = 1/(LC)^{0.5}$, where L and C are inductance and capacitance per unit length of the transmission line respectively. On the conventional transmission lines L and C are depend on each other and it is impossible to obtain a reduction in velocity by altering either value. A slow-wave transmission line is made simply by forming a line out of discreet inductors and capacitors, both with as large a value as possible. The size of inductors and capacitors must be much less than the minimum operating wavelength. There are many different ways of forming the required slow-wave structures. One of them has discussed in this work.

II. Analysis

It can be obtained the higher capacitance and inductance values than that of the coplanar waveguide, if the physical length of the transmission line can be increased without changing propagation length, as shown in Fig. 1. The capacitance per unit length, C can be modelled as sum of the interdigital capacitance C_1 between the parallel strips (fingers) of length l_f and the capacitance C_2 of asymmetric coplanar strips that includes the ground plane and strips of width a. Therefore, interdigital capacitance C_1 is given in [5]

$$C_1 = \frac{\pi \epsilon_0 \epsilon_{\text{eff}}}{\ln\left(\frac{8}{\pi} W_g\right)} \left(1 - \frac{A}{N}\right) \frac{N}{2} \qquad (F/m) \tag{1}$$

with

$$W_g = \frac{w_s + g}{w_s} \tag{2}$$

where ϵ_{eff} is the effective dielectric constant, g the capacitive gap, w_s the finger width, N the number of fingers and A the correction factor. ϵ_{eff} and A is given in [5]. A conformal mapping based quasi-static analysis is used to derive the line capacitance C_2 of asymmetric coplanar strip line and can be given in [6]

$$C_2 = 2\epsilon_0 \epsilon_{\text{eff}} \frac{K(k_1)}{K(k_1')} \qquad (F/m) \tag{3}$$

where $K(k_1)$ is complete elliptic integral of the first kind with module k_1 $(k_1 = (1 - k_1')^{0.5})$ and ϵ_{eff} the effective dielectric constant and are given in [6]. The substrate thickness h and the widths of asymmetric strips a and b is shown in Fig. 1. So, the capacitance per unit length of slow wave structure shown in Fig. 1 can be calculated as $C = C_1 + C_2 (F/m)$ from (1) and (3).

The inductance per unit length L is sum of the inductance of the asymmetric coplanar strips L_1 and the inductance L_2 of strip which has length l_s and width w_s. The inductance of strip with the length l_s is given in [7]. The inductance of asymmetric coplanar strips, L_1 can be obtained as

$$L_1 = 2\pi \frac{K(k_1')}{K(k_1)} 10^{-7} \qquad (H/m) \tag{4}$$

Therefore, the inductance per unit length of slow wave structure shown is given by $L = L_1 + L_2 (H/m)$.

III. Experimental Results and Discussion

In order to determine the slowing of the slow-wave structure and the effectiveness of the modelling a number of copper prototype have been constructed and tested. The slow wave structures designed in this study were constructed on 1.55 mm thick substrates that have dielectric constant of 10.2 (RT/Duroid 6010) and 2.33 (RT/Duroid 5870). Both the capacitance and the inductance for the velocity slowing have been provided by

Manuscript received November 11, 1993.
The author is with Erciyes University, Engineering Faculty, Department of Electronic Engineering, Kayseri, Turkey.
IEEE Log Number 9216031.

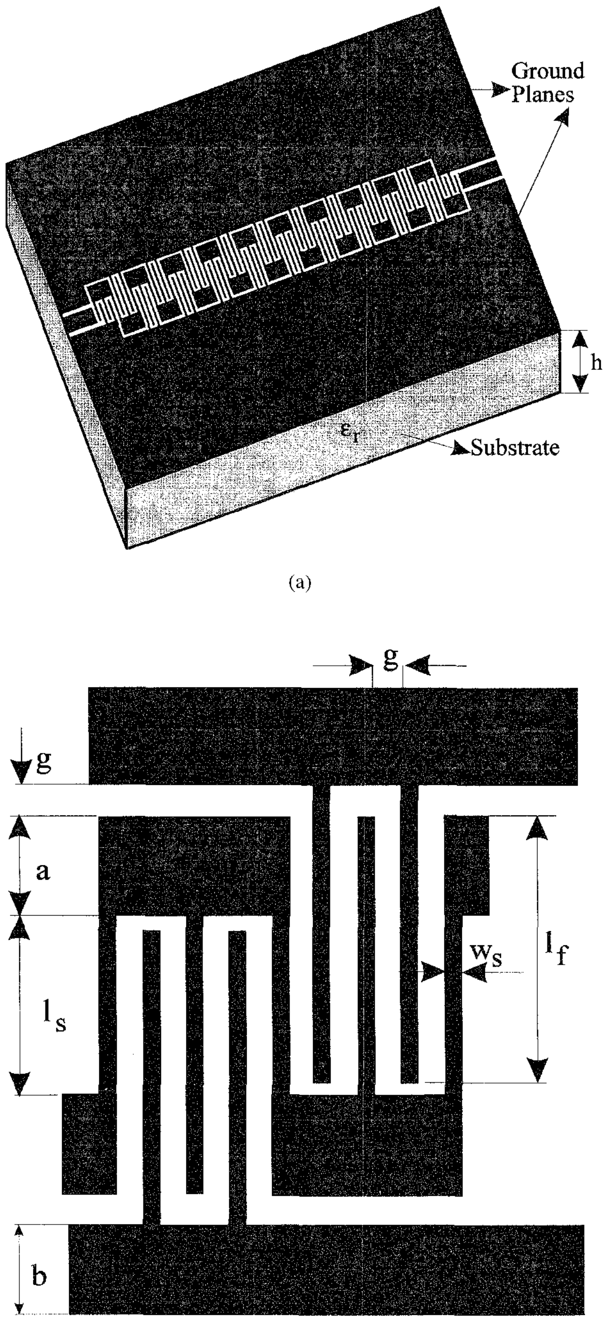

Fig. 1. (a) View of coplanar slow-wave structure, (b) a section of one period.

changing the capacitive gap g and/or the inductive length l_s. The inductance lengths are 1.6 mm, 2 mm, 2.5 mm and 3 mm and the capacitive gaps are 0.22 mm 0.28 mm, 0.32 mm and 0.38 mm. The widths of the inductive strips and the fingers are 0.18 mm for all the devices. Using the expression for ideal lossless line for the velocity, $v = 1/(LC)^{0.5}$, the values of normalized propagation velocities (v/c, where c is the light velocity in free space), were calculated. The velocity reduction factor of the devices as a function of the capacitive gap g and the inductive length l_s are shown in Figs. 2 and 3. The velocity is measured by making half a wavelength resonator out of a section of transmission line and measuring

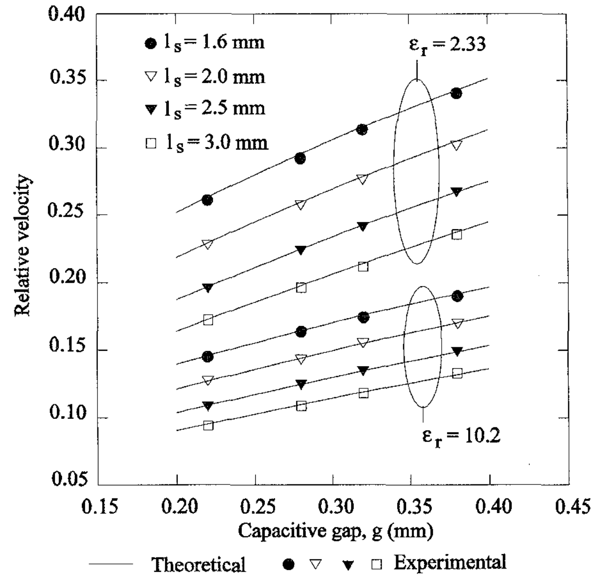

Fig. 2. Relative velocity as a function of the capacitive gap.

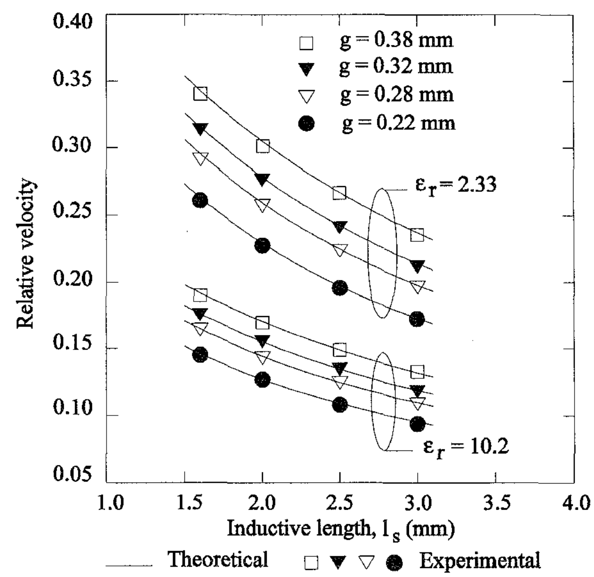

Fig. 3. Relative velocity as a function of the inductive length.

the resonant frequencies on a HP8720 network analyser. The fundamental resonant frequencies of resonators are given in Table I. The lengths of half a wavelength resonators are 32.2 mm, 37 mm, 40.2 mm and 45.2 mm for capacitive gaps of 0.22 mm, 0.28 mm, 0.32 mm and 0.38 mm, respectively. A velocity of $2.86.10^7$ m/s was obtained with a gap g of 0.22 mm and a length l_s of 3 mm. As l_s increases from 1.6 mm to 3 mm, when gap is 0.22 mm the velocity reduces from $4.38.10^7$ m/s to $2.86.10^7$ m/s. However, as g decreases from 0.38 mm to 0.22 mm, when l_s is 3 mm it reduces from $3.96.10^7$ m/s to $2.86.10^7$ m/s.

Frequency response of a resonator designed here is shown in Fig. 4. The fundamental resonant frequency of the device was 1.054 GHz. The fundamental resonant frequency of another resonator on substrate that has dielectric constant of 10.2 was 438 MHz. Ten cells have been used in the all resonators as shown in Fig. 1(a). Good frequency responses have been

TABLE I
(a) MEASURED RESONANT FREQUENCIES OF THE RESONATORS ($\epsilon_r = 2.33$). (b) MEASURED RESONANT FREQUENCIES OF THE RESONATORS ($\epsilon_r = 10.2$)

g (mm)	0.22	0.28	0.32	0.38
l_s (mm)		f_r (MHz)		
1.6	1215	1180	1169	1130
2.0	1054	1042	1030	1000
2.5	912	906	898	885
3.0	802	796	790	782

(a)

g (mm)	0.22	0.28	0.32	0.38
l_s (mm)		f_r (MHz)		
1.6	676	664	652	631
2.0	592	580	578	562
2.5	503	504	502	494
3.0	438	441	440	441

(b)

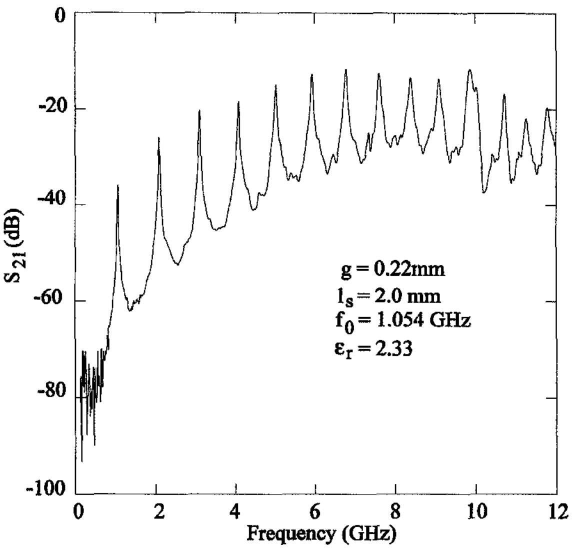

Fig. 4. Experimental frequency response of a resonator designed.

obtained in the range of the network analyser up to 10 GHz in all cases. It has been produced about ten resonances for each resonator. Above tenth resonant frequency, it has been observed that the results are not free from spurious responses and dispersive effects. As can be seen in Fig. 4, the coupling alters with frequency due to the change in reactance of the capacitive coupling gap. However, as frequency increases, it has been observed that frequency spacing between the successive resonant frequencies has been decreased. Therefore, the resonant frequencies of the resonators tested in this work are not given by $f_r = nf_0$, but $f_r = (-0.022n^2 + 1.08n - 0.088)f_0$ as shown in Fig. 5, where $n = 1, 2, 3\ldots$ and f_0 is the fundamental resonant frequency. This equation has been obtained by making use of MATHCAD for curve fitting.

IV. CONCLUSION

A new coplanar slow-wave structure that has a form of interdigitated-meander line on a duroid substrate has been described. It has been observed that the propagation velocity on these devices is a function of the capacitive gap, g and inductive length, l_s. It is obvious that as the inductive length,

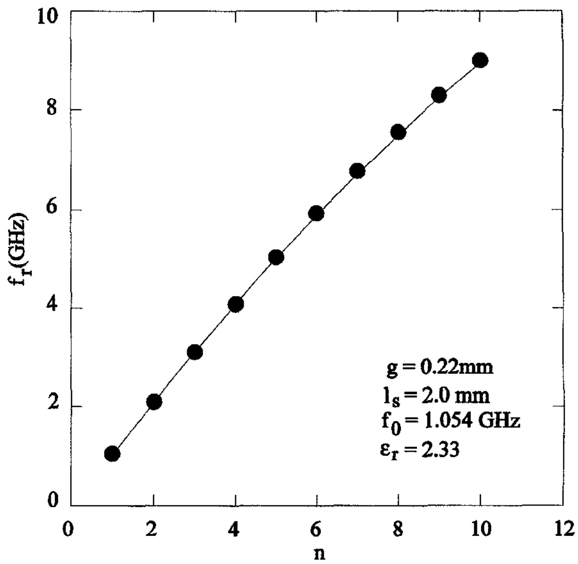

Fig. 5. Variation of resonant frequencies of the resonator of which frequency response is given in Fig. 4, with n ($n = 1, 2, 3 \ldots$.)

l_s increases, both the inductance and the capacitance per unit length increase as well. Therefore, it can be reduced the propagation velocity on this new transmission line by increasing the inductive length and decreasing the capacitive gap. As can be seen from Figs. 2 and 3, for the relative velocity values, a good agreement has been obtained between calculated and experimental results.

This device that has the form of interdigitated-meander line applicable to the miniaturization of MMIC and microwave filters on the current substrates. Also, it should be possible to significantly improve their performance. We left to design the filter using this device for future study.

ACKNOWLEDGMENT

The author acknowledges valuable discussions with Dr. M. J. Lancaster. Also, the author is thankful to all members of the Birmingham University COPS group.

REFERENCES

[1] Y. R. Kwon, V. M. Hietala, and K. S. Champlin, "Quasi-TEM analysis of slow-wave mode propagation on coplanar microstructure MIS transmission lines," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-35, pp. 545–551, June 1987.
[2] H. Ogawa and T. Itoh, "Slow-wave characteristics of ferromagnetic semiconductor microstrip line," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-34, pp. 1478–1482, Dec. 1986.
[3] Y. Fukuoka, Y. C. Shih, and T. Itoh, "Analysis of slow-wave coplanar waveguide for monolithic integrated circuits," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-31. pp. 567–573, July 1983.
[4] W. H. Haydl, "Properties of meander coplanar transmission lines," *IEEE Microwave and Guided Wave Lett.*, vol. 2, pp. 439–441, Nov. 1992.
[5] X. Y. She and Y. L. Chow, "Interdigital microstrip capacitor as a four-port network," *Inst. Elect. Eng. Proc.*, vol. 133, pt. H, pp. 191–197, June 1986.
[6] S. S. Gevorgian and I. G. Mironenko, "Asymmetric coplanar-strip transmission lines for MMIC and integrated optic applications," *Electronics Lett.*, vol. 26, pp. 1916–1917, Oct. 1990.
[7] E. Pettenpaul, H. Kapusta, A. Weisgerber, H. Mampe, J. Luginsland, and I. Wolf, "CAD models of lumped elements on GaAs up to 18 GHz," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-36, pp. 294–304, Feb. 1988.