Novel Schiffman Phase Shifters

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Abstract— **In a standard Schiffman phase shifter a coupled section and a uniform transmission line are used to give a differential phase shift. In order to achieve larger bandwidth it is necessary to use tight coupled sections which are difficult to realize.**

This paper shows how different configurations of coupled lines or parallel connected coupled lines can be used together with a uniform transmission line, another coupled lines or parallel connected coupled lines in order to obtain a differential phase shifter with loose coupled lines and the same performance as for the standard case. The measurements confirm the calculated results leading to a more realizable structure.

Index Terms—**Phase shifters, Schiffman sections, coupled transmission lines.**

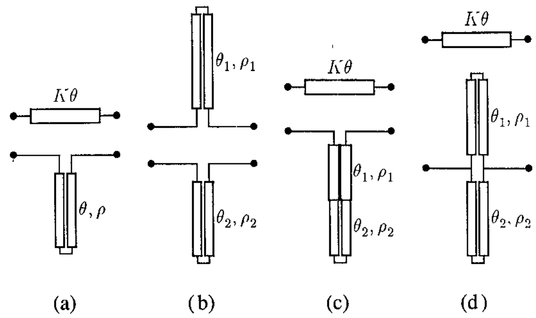

Fig. 1. Some alternatives to obtain a differential phase shifter: (a) Standard Schiffman phase shifter, (b) Double Schiffman phase shifter, (c) Schiffman phase shifter with cascaded sections, and (d) Parallel Schiffman phase shifter.

I. Introduction

A SCHIFFMAN phase shifter [1] is a differential phase shifter that consists of two transmission lines, one of them folded (coupled section) to be dispersive, Fig. 1(a). By the proper selection of the length of these lines and the degree of coupling, the phase difference between them can be made to be almost constant over a broad bandwidth.

Other method to design the phase shifter is by using two coupled sections instead, as shown in Fig. 1(b) or by using two cascaded coupled sections and a transmission line [2], [3], shown in Fig. 1(c). In this case the phase shift is determined by the choice of the length and coupling of each section.

Unfortunately, there are several cases where the phase shifter can not be realized given the desired performance, particularly in those cases when low relative dielectric constant is used. A method to reduce this problem is to design the coupled sections for higher input impedances and connect them in parallel. This alternative is presented in Fig. 1(d).

Another application of the parallel configuration is the case when the performance is poor due to the fact that the width of the transmission lines in the coupled section is too wide compared to its length.

II. A Single Coupled Section

The coupled section used in the Schiffman phase shifter consists of two parallel coupled lines of equal length connected at one end. Expressions for the characteristic impedance Z_I, and phase response for the coupled section as well as for other coupled lines were given by Jones and Bolljahn [4] in terms of the even and odd mode characteristic impedances of the lines and their lengths.

The characteristic impedance and the phase response are obtained from following equations:

$$[V] = [Z][I] \tag{1}$$

where $[Z]$ is the general impedance matrix given as [4]:

$$\left.\begin{aligned} Z_{11} = Z_{22} = Z_{33} = Z_{44} &= -\frac{j}{2}(Z_{oe} + Z_{oo})\cot\theta \\ Z_{12} = Z_{21} = Z_{34} = Z_{43} &= -\frac{j}{2}(Z_{oe} - Z_{oo})\cot\theta \\ Z_{13} = Z_{31} = Z_{24} = Z_{42} &= -\frac{j}{2}(Z_{oe} - Z_{oo})\csc\theta \\ Z_{14} = Z_{41} = Z_{23} = Z_{32} &= -\frac{j}{2}(Z_{oe} + Z_{oo})\csc\theta \end{aligned}\right\} \tag{2}$$

Using (2) in (1) for the special case when two ends of the coupled lines are interconnected, the impedance matrix expressed in terms of the even- Z_{oe}, and odd-Z_{oo},-mode impedances of the coupled lines and their lengths is obtained as

$$[Z'] = \begin{bmatrix} -\frac{j}{2}(Z_{oe}\cot\theta - Z_{oo}\tan\theta) & -\frac{j}{2}(Z_{oe}\cot\theta + Z_{oo}\tan\theta) \\ -\frac{j}{2}(Z_{oe}\cot\theta + Z_{oo}\tan\theta) & -\frac{j}{2}(Z_{oe}\cot\theta - Z_{oo}\tan\theta) \end{bmatrix} \tag{3}$$

From (3) the characteristic impedance, Z_I and the transfer constant $(\alpha + j\phi)$ are obtained [5] as

$$Z_I = \left(Z_{11}'^2 - \frac{Z_{11}' Z_{12}'^2}{Z_{22}'}\right)^{1/2} = \sqrt{Z_{oe} Z_{oo}} \tag{4}$$

and

$$\cosh(\alpha + j\phi) = \frac{(Z_{11}' Z_{22}')^{1/2}}{Z_{12}'} = \cos\phi = \frac{\rho - \tan^2\theta}{\rho + \tan^2\theta} \tag{5}$$

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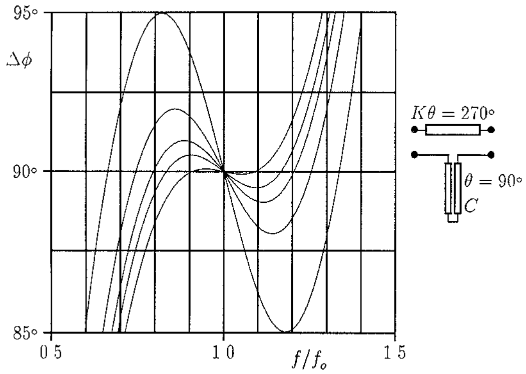
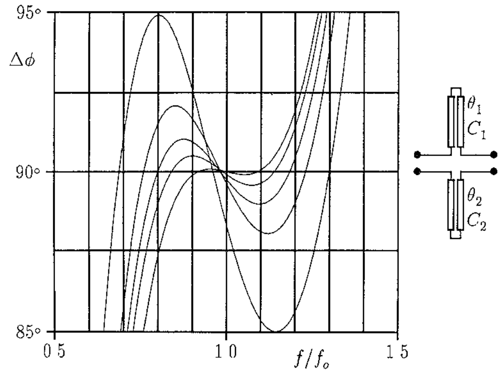


ε (°)	Z_{oe} (Ω)	Z_{oo} (Ω)	C (dB)
±5	86 9	28 77	5 98
±2	80 96	30 88	6 98
±1	78 65	31 79	7 45
± 5	77 25	32 36	7 76
± 1	75 75	33	8 11

Fig. 2. Response of 90° Schiffman phase shifters.



ε (°)	θ_1 (°)	Z_{oe1} (Ω)	Z_{oo1} (Ω)	C_1 (dB)	θ_2 (°)	Z_{oe2} (Ω)	Z_{oo2} (Ω)	C_2 (dB)
±5	158 55	69 37	36 04	10	111 33	74	33 78	8 56
±2	163 13	69 63	35 9	9.9	116 54	64 89	38.53	11 87
±1	161 42	66 83	37 41	11	114 83	64 95	38 5	11 84
± 5	160 45	65 44	38 2	11 61	113 95	64 71	38 63	11 96
± 1	166 62	67 05	37 3	10 9	121 12	57 86	43 21	16 77

Fig. 3. Response of 90° double Schiffman phase shifters.

where a lossless network ($\alpha = 0$) has been considered and

$$\rho = \frac{Z_{oe}}{Z_{oo}} \tag{6}$$

is the impedance ratio that determines the degree of coupling of the coupled section. The coupling C, in dB is defined as [6], [7]

$$C = -20 \log \left(\frac{\rho - 1}{\rho + 1} \right). \tag{7}$$

A. Schiffman Phase Shifter

As explained before, the phase shift ($\Delta\phi$) of a Schiffman phase shifter is obtained as the transmission phase difference between an uniform transmission line and a coupled section, i.e.:

$$\Delta\phi = K\theta - \cos^{-1} \left(\frac{\rho - \tan^2 \theta}{\rho + \tan^2 \theta} \right) \tag{8}$$

where θ is the electrical length of the coupled section. We assume that the length of the coupled section in the even θ_e and odd θ_o modes is equal, i.e. $\theta_e = \theta_o = \theta$ in all cases. $K\theta$ is the transmission phase of the uniform line and the transmission phase of the coupled section as given by (5).

The desired shift is obtained from (8) by the proper choice of θ, K and ρ. Also we can see that when θ is chosen to be $\pi/2$ or π at center frequency, the phase shift response is antisymmetric in respect to the center frequency and broad band characteristics are obtained for these cases [8]. In Fig. 2 the responses of 90° phase shifters are plotted when the phase deviation ϵ, is: $\epsilon = \pm 5°, \pm 2°, \pm 1°, \pm 0.5°$, and, $\pm 0.1°$.

B. Double Schiffman Phase Shifter

If instead of the uniform transmission line another coupled section is used as shown in Fig. 1(b), the differential shift ($\Delta\phi$) is obtained as

$$\Delta\phi = \cos^{-1} \left(\frac{\rho_1 - \tan^2 \theta_1}{\rho_1 + \tan^2 \theta_1} \right) - \cos^{-1} \left(\frac{\rho_2 - \tan^2 \theta_2}{\rho_2 + \tan^2 \theta_2} \right) \tag{9}$$

where $\rho_1 = Z_{oe1}/Z_{oo1}$, $\rho_2 = Z_{oe2}/Z_{oo2}$ and $Z_I = \sqrt{Z_{oe1} Z_{oo1}} = \sqrt{Z_{oe2} Z_{oo2}}$.

Any desired phase shift is obtained from (9) by choosing properly ρ_1, θ_1, ρ_2 and θ_2.

In Fig. 3 some cases giving the maximum bandwidth when the allowed phase deviation ϵ, is: $\epsilon = \pm 5°, \pm 2°, \pm 1°, \pm 0.5°$, and, $\pm 0.1°$ are shown. An unsymmetrical response is observed there since at least one of the coupled sections has $\theta \neq 90°$ at the center frequency. We see also that the double Schiffman phase shifter gives little narrower bandwidths but require considerably weaker coupling coefficients when compared to the standard Schiffman phase shifter [8].

III. Two Sections in Parallel

When two coupled sections are connected in parallel, the total four element admittance matrix $[Y_t']$ is equal to the addition of the four element admittance matrix of each section [5], i.e.;

$$[Y_t'] = [Y_1'] + [Y_2'] = \begin{bmatrix} Y_{1,11}' + Y_{2,11}' & Y_{1,12}' + Y_{2,12}' \\ Y_{1,12}' + Y_{2,12}' & Y_{1,11}' + Y_{2,11}' \end{bmatrix} = \begin{bmatrix} Y_{t,11}' & Y_{t,12}' \\ Y_{t,12}' & Y_{t,11}' \end{bmatrix}. \tag{10}$$

The four element admittance matrix for a single coupled section in terms of the even and odd mode impedances is obtained from (3) as

$$[Y'] = \begin{bmatrix} -j\frac{(Z_{oe} - Z_{oo}\tan^2\theta)\cot\theta}{2Z_{oe}Z_{oo}} & +j\frac{(Z_{oe} + Z_{oo}\tan^2\theta)\cot\theta}{2Z_{oe}Z_{oo}} \\ +j\frac{(Z_{oe} + Z_{oo}\tan^2\theta)\cot\theta}{2Z_{oe}Z_{oo}} & -j\frac{(Z_{oe} + Z_{oo}\tan^2\theta)\cot\theta}{2Z_{oe}Z_{oo}} \end{bmatrix}. \tag{11}$$

In the general case when both coupled sections are different we use (11) in (10) to get the four elements of the admittance matrix in terms of the even and odd mode impedances for the two coupled sections connected in parallel as

$$Y'_{t,11} = Y'_{t,22} = \frac{-j}{2}\left(\frac{(Z_{oe1} - Z_{oo1}\tan^2\theta_1)\cot\theta_1}{Z_{oe1}Z_{oo1}} + \frac{(Z_{oe2} - Z_{oo2}\tan^2\theta_2)\cot\theta_2}{Z_{oe2}Z_{oo2}}\right)$$

$$Y'_{t,12} = Y'_{t,21} = \frac{+j}{2}\left(\frac{(Z_{oe1} + Z_{oo1}\tan^2\theta_1)\cot\theta_1}{Z_{oe1}Z_{oo1}} + \frac{(Z_{oe2} + Z_{oo2}\tan^2\theta_2)\cot\theta_2}{Z_{oe2}Z_{oo2}}\right). \quad (12)$$

Using (12) the total characteristic impedance Z_{It} is obtained as

$$Z_{It} = \frac{1}{(Y'^2_{t,11} - Y'^2_{t,12})^{1/2}} = \frac{Z_{I1}Z_{I2}}{\left(Z_{I1}^2 + Z_{I2}^2 + Z_{oe2}Z_{oo1}\frac{\tan\theta_1}{\tan\theta_2} + Z_{oe1}Z_{oo2}\frac{\tan\theta_2}{\tan\theta_1}\right)^{1/2}} \quad (13)$$

The transfer constant is obtained when $\alpha = 0$ from (12) as

$$\cos\phi = \frac{Y'_{t,11}}{Y'_{t,12}} = \frac{\rho_{ee}(\rho_1 - \tan^2\theta_1)\cot\theta_1 + (\rho_2 - \tan^2\theta_2)\cot\theta_2}{\rho_{ee}(\rho_1 + \tan^2\theta_1)\cot\theta_1 + (\rho_2 + \tan^2\theta_2)\cot\theta_2} \quad (14)$$

where $\rho_{ee} = Z_{oe2}/Z_{oe1}$.

Equations (13) and (14) are the general expressions for design of the parallel connection of two coupled sections.

From (13) we observe that the total characteristic impedance is a function of θ_1 and θ_2 and thus the circuit is not matched for all frequencies. Since the poles produced by $\theta_1 = n\pi/2$ and $\theta_2 = n\pi/2$, $n = 1, 3, 5, \ldots$ do not cancel each other, a mismatch and a drastic change on phase exist at those frequencies. A possible solution is to place the poles outside of the bandwidth of interest but this solution gives a much narrower bandwidth than that obtained by letting the length of both coupled sections be the same ($\theta_1 = \theta_2$).

When the length of both coupled sections is the same ($\theta_1 = \theta_2$), (13) reduces to

$$Z_{It} = \frac{Z_{It}Z_{I2}}{(Z_{I1}^2 + Z_{I2}^2 + Z_{oe2}Z_{oo1} + Z_{oe1}Z_{oo2})^{1/2}}. \quad (15)$$

The phase constant given by (14) reduces in this case to

$$\cos\phi = \frac{\rho_{p1} - \tan^2\theta_1}{\rho_{p1} + \tan^2\theta_1} \quad (16)$$

where

$$\rho_{p1} = \rho_1\rho_2\frac{Z_{oo1} + Z_{oo2}}{Z_{oe1} + Z_{oe2}} \quad (17)$$

By using (15)–(17) new versions of Schiffman phase shifters can be designed.

When Z_{It}, Z_{I1}, ρ_1 and ρ_2 are known Z_{I2} is found from (15) as shown in (18) at the bottom of the page. Since (15)–(17) can be simplified under some conditions, several different alternatives have been analyzed, among others, when the differential phase shifter is made by using two parallel connected coupled sections and a uniform transmission line, a single coupled section and another two parallel connected coupled sections. In the following some cases are presented.

A. Parallel Schiffman Phase Shifter

If the single coupled section in the standard Schiffman phase shifter is replaced by two parallel connected coupled sections having the same length as shown in Fig. 1(d), then the differential shift is expressed by using (8) and (16) as

$$\Delta\phi = K\theta_1 - \cos^{-1}\left(\frac{\rho_{p1} - \tan^2\theta_1}{\rho_{p1} + \tan^2\theta_1}\right) \quad (19)$$

where ρ_{p1} is given by (17). Any desired shift is obtained by the proper choice of the parameters θ_1 and K and the performance of the shifter will depend on the coupling and the input impedance of each section. We note that (19) has the same kind of symmetry as the standard Schiffman phase shifter has (8), and so the same bandwidths are expected. In Fig. 4, some examples given the same phase deviations as those for the double Schiffman phase shifter are presented.

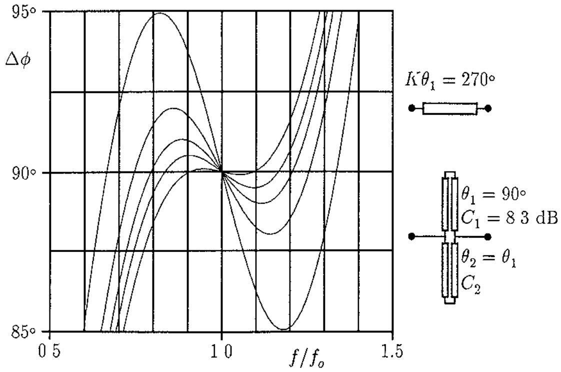
B. Parallel Double Schiffman Phase Shifter

If the uniform line in the parallel Schiffman phase shifter is replaced by a coupled section, then the differential shift is expressed as

$$\Delta\phi = \cos^{-1}\left(\frac{\rho_3 - \tan^2\theta_3}{\rho_3 + \tan^2\theta_3}\right) - \cos^{-1}\left(\frac{\rho_{p1} - \tan^2\theta_1}{\rho_{p1} + \tan^2\theta_1}\right) \quad (20)$$

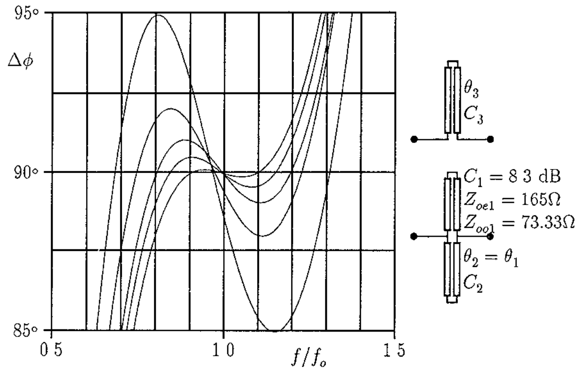
where ρ_{p1} is given by (17). The desired phase shift is obtained by proper choice of $\theta_1 = \theta_2$ and θ_3 and the performance depends on ρ_1, ρ_2 and ρ_3 and on the input impedance of each parallel connected section.

$$Z_{I2} = \frac{Z_{I1}Z_{It}^2\left(\sqrt{\frac{\rho_1}{\rho_2}} + \sqrt{\frac{\rho_2}{\rho_1}}\right) + Z_{I1}Z_{It}\sqrt{Z_{It}^2\left(\sqrt{\frac{\rho_1}{\rho_2}} + \sqrt{\frac{\rho_2}{\rho_1}}\right)^2 + 4(Z_{I1}^2 - Z_{It}^2)}}{2(Z_{I1}^2 - Z_{It}^2)}. \quad (18)$$



ε (°)	Z_{oe1} (Ω)	Z_{oo1} (Ω)	Z_{I2} (Ω)	Z_{oe2} (Ω)	Z_{oo2} (Ω)	C_2 (dB)
±5	165	73 33	93.22	183.5	47 36	4 587
±2	165	73 33	92.08	159	53 33	6 06
±1	165	73 33	91 82	150 25	56 12	6 82
± 5	165	73 33	91 73	145 25	57 93	7.34
±.1	165	73 33	91.67	140	60 03	7 96

Fig. 4. Response of 90° parallel Schiffman phase shifters.



ε (°)	θ_1, θ_2 (°)	Z_{oe2} (Ω)	Z_{oo2} (Ω)	C_2 (dB)	θ_3 (°)	Z_{oe3} (Ω)	Z_{oo3} (Ω)	C_3 (dB)
±5	103 24	157 4	53 8	6 19	150	62 1	40 26	13 42
±2	101 64	143 1	58.76	7 58	148.35	58 52	42 72	16 13
±1	100 52	134 75	62 37	8 7	146.44	58.3	42 88	16 34
± 5	100.53	131 12	64 15	9 3	146.5	57 71	43 32	16 93
± 1	100 81	125 77	67 06	10 33	146 6	57.67	43 35	16 97

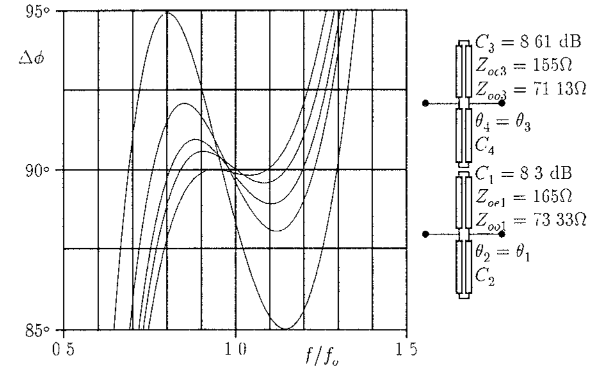
Fig. 5. Response of 90° parallel double Schiffman phase shifters.

To obtain 90° phase shift ($\Delta\phi = 90°$) the relation between the lengths of the coupled sections is found from (20) to be

$$\theta_3 = 180°n \pm \tan^{-1}\sqrt{\frac{\left(1+\sqrt{1-\left(\frac{\rho_{p1}-\tan^2\theta_1}{\rho_{p1}+\tan^2\theta_1}\right)^2}\right)\rho_3}{1-\sqrt{1-\left(\frac{\rho_{p1}-\tan^2\theta_1}{\rho_{p1}+\tan^2\theta_1}\right)^2}}}$$

$$n = 0, 1 \cdots \tag{21}$$

In Fig. 5, some cases giving maximum bandwidth when the allowed phase deviation ϵ, is: $\epsilon = \pm 5°$, $\pm 2°$, $\pm 1°$, $\pm 0.5°$, and $\pm 0.1°$ are shown. Again as with the double Schiffman phase shifter (Fig. 3) the unsymmetrical response is observed.



ε (°)	θ_1, θ_2 (°)	Z_{oe2} (Ω)	Z_{oo2} (Ω)	C_2 (dB)	θ_3, θ_4 (°)	Z_{oe4} (Ω)	Z_{oo4} (Ω)	C_4 (dB)
±5	114 9	123 2	68 6	10 91	162 12	135 5	67 29	9 46
±2	114 23	112	76 63	14 54	160 88	122	75 48	12 56
±1	112 38	110 11	78 25	15 43	158 56	115 49	80 56	14 98
± 5	111 48	109 63	78 68	15 68	157 66	110 87	84 78	17 5
± 1	111 76	107 37	80 77	16 99	158 06	107 76	87 97	19 9

Fig. 6. Response of 90° double parallel Schiffman phase shifters.

C. Double Parallel Schiffman Phase Shifter

If each coupled section in the double Schiffman phase shifter is replaced by a parallel section having the same length, then the differential shift is expressed by using (16) as

$$\Delta\phi = \cos^{-1}\left(\frac{\rho_{p2}-\tan^2\theta_3}{\rho_{p2}+\tan^2\theta_3}\right) - \cos^{-1}\left(\frac{\rho_{p1}-\tan^2\theta_1}{\rho_{p1}+\tan^2\theta_1}\right) \tag{22}$$

where ρ_{p1} is given by (17) and,

$$\rho_{p2} = \rho_3\rho_4\frac{Z_{oo3}+Z_{oo4}}{Z_{oe3}+Z_{oe4}} \tag{23}$$

The desired phase shift is obtained by proper choice of $\theta_1 = \theta_2$ and $\theta_3 = \theta_4$ and the performance depends on ρ_1, ρ_2, ρ_3 and ρ_4 and on the input impedance of each parallel connected section.

In Fig. 6, values of coupling coefficients and input impedances that give similar responses as those presented for the other cases are shown.

IV. Comparison Between Different Cases

The comparison between analyzed cases can be done as follows. The difference between the even and odd mode characteristic admittances is Y_{oc} which corresponds to the capacitance between the parallel lines. Thus we can write

$$Y_{oo} = Y_{oe} + Y_{oc}. \tag{24}$$

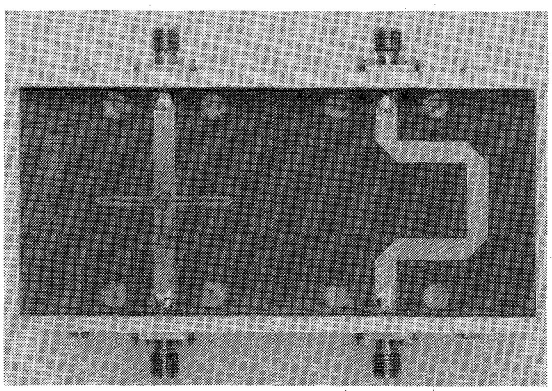
For practical reasons in a system with 50 Ω characteristic impedance we want to keep Y_{oe} above 10 mS and to have Y_{oc} as low as possible because large Y_{oo} is difficult to realize. For coupled sections with 100 Ω characteristic impedance Y_{oe} should be above 5 mS and again Y_{oc} as low as possible.

The calculated results for Y_{oe}, Y_{oo}, Y_{oc} and $\epsilon = \pm 2°$ are shown in Table I.

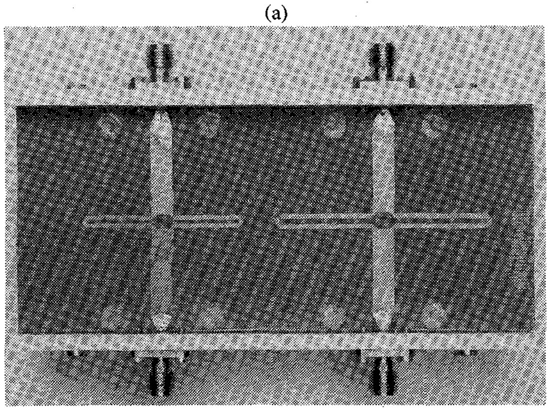
The conclusion is that all cases shown in Figs. 3–6 are considerably easier to realize than the standard case shown

TABLE I
COMPARISON OF THE DIFFERENT CONFIGURATIONS

Case (±2°)	Y_{oo} (mS)	Y_{oe} (mS)	Y_{oc} (mS)	Y_{oo} (mS)	Y_{oe} (mS)	Y_{oc} (mS)	Y_{oo} (mS)	Y_{oe} (mS)	Y_{oc} (mS)	Y_{oo} (mS)	Y_{oe} (mS)	Y_{oc} (mS)
Fig. 2	32.38	12.35	20.03									
Fig. 3	27.86	14.36	13.49	25.95	15.41	10.54						
Fig. 4	13.64	6.06	7.58	18.75	6.29	12.46						
Fig. 5	13.64	6.06	7.58	17.02	6.99	10.03	23.41	17.09	6.32			
Fig. 6	13.64	6.06	7.58	13.03	8.93	4.12	14.06	6.45	7.61	13.25	8.2	5.05



(a)



(b)

Fig. 7. Photographs for: (a) The parallel Schiffman phase shifter and (b) The double parallel Schiffman phase shifter.

in Fig. 2. In addition for the configurations in Figs. 4–6 we have the possibility to choose the coupling coefficients for different sections in such a way that Y_{oe}'s are close to each other maintaining the same phase performance.

V. MEASUREMENTS

To show the larger range of application for the proposed circuits, we have selected a parallel Schiffman phase shifter and a double parallel Schiffman phase shifter as examples. The circuits were design on Diclad 522 with $H = 1.6$ mm and $\epsilon_r = 2.5$.

Using (15)–(18) and (19) we get for the parallel Schiffman phase shifter with $\epsilon = \pm 1°$:

$$\theta_1 = \theta_2 = 90°, \quad Z_{I1} = Z_{I2} = 100\,\Omega,$$
$$\rho_1 = \rho_2 = 2.47 \quad \text{and} \quad K = 3.$$

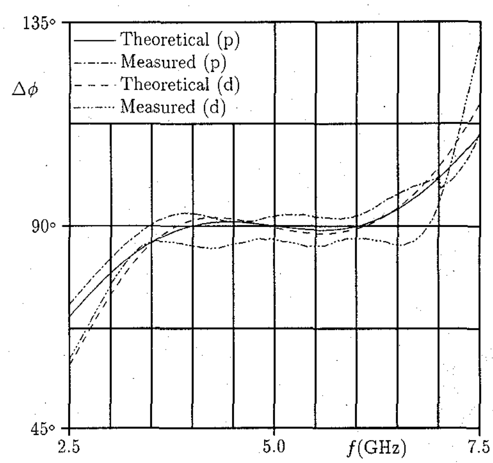


Fig. 8. Theoretical and measured responses for the parallel Schiffman phase shifter (p) and the double parallel Schiffman phase shifter (d) shown in Fig. 7.

Using (15)–(18) and (22)–(23) we get for the double parallel Schiffman phase shifter with $\epsilon = \pm 2°$:

$$\theta_1 = \theta_2 = 109.35°, \quad Z_{I1} = Z_{I2} = 100\,\Omega, \quad \rho_1 = \rho_2 = 2,$$
$$\theta_3 = \theta_4 = 156.15°, \quad Z_{I3} = Z_{I4} = 100\,\Omega,$$
$$\text{and} \quad \rho_3 = \rho_4 = 1.68$$

The photographs of the circuits are shown in Fig. 7. As a comparison the standard Schiffman phase shifter as shown in Fig. 2 can not be realized with edge coupled lines for those phase deviations on this substrate. The measured and theoretical phase responses of these circuits are presented in Fig. 8. The agreement is good.

VI. CONCLUSIONS

In this paper the theory needed to design differential phase shifters by using two coupled sections or parallel connected sections together with uniform lines, coupled sections or parallel connected sections has been presented.

The results show that the proposed differential phase shifters have larger range of the feasibility compared to the standard Schiffman phase shifter since equivalent responses are obtained with considerably weaker coupling coefficients. Moreover, since the input impedance of each parallel connected coupled section is about twice that for a single coupled section, the same coupling is even easier to realize.

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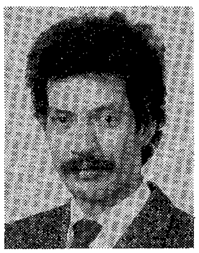

José Luis Ramos Quirarte was born in Ameca, Jalisco, México, in 1956. He received the B.S. degree in Communications and Electronic Engineering from the Universidad de Guadalajara, Guadalajara, Jalisco, México in 1980. The thesis dealt with the design of digital microwave systems of medium capacity. He received the M.S. degree in Electric Engineering Speciality in Telecommunications from the Centro de Investigación y de Estudios Avanzados del Instituto Politécnico Nacional (CINVESTAV-IPN), México D.F. in 1985. The thesis dealt with the design of a transmitter-receiver antenna for earth stations which operate according to the mexican domestic satellites.

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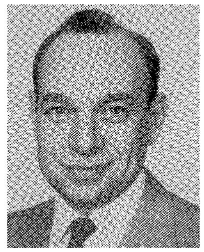

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