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Parametric Effects on the Coupling Performances of Directional Coupler topology

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Abstract— **This article details the design of a parallel coupled directional coupler for various coupling ratio and analysis of various factors affecting the coupling performances is presented. Both theoretical and simulation study are carried out and comparative analysis of linear and electro-magnetic simulation is performed at S-band. The concept of even and odd mode impedances as well as effect of substrate and box height on circuit performances is analyzed. Further correlation between the spacing and impedances on the coupling performance are tabulated and detailed.**

Index Terms— Directional coupler, micro-strip, coupling, parallel coupled line.

I. INTRODUCTION

Communication systems comprise of couplers, power dividers and combiners for to perform various functions. The implementation of the same in planar technology eases fabrication, implementation, and handling. Directional couplers are one of the microwave passive components that are used in array antennas, modulators, filters and power amplifiers for propose of dividing or combining the power [1]. Couplers are classified as 3-port network or 4-port network and are designed to achieve the desired coupling ratios. Three port networks are Wilkinson power divider , T-junctions, circulators whereas four port networks are hybrid coupler, directional coupler, magic-tee, having equal or unequal power division. The phase difference between the outputs can be either 90° (quadrature) or 180° (rat-race) [2-3]. The main limitation in 3-port network is to achieve simultaneously lossless, reciprocity and matched performances at all ports but in a 4-port network the same can be achieved. The main parameters of a coupler are coupling, directivity, isolation, return loss and output phase. Micro-strip parallel coupled-line topology known as backward wave coupler is widely used in microwave circuits due to its simple configuration and ease of fabrication. The main aspect of the directional coupler is the availability of input and coupled port on the same side of the plane which is different from brand line and ring based topologies. Further coupling and insertion loss are the main parameters for a parallel coupled topology rather than phase shift. There are multiple factors affecting the coupling performances in addition to frequency [4] which needs to be investigated.

This article details the concept of even and odd mode impedances, study of various parameter effecting coupling in parallel coupled topology such as substrates and box height, angular excitation along with relation of various impedances with the coupled line spacing.

II. PARALLEL COUPLED TOPOLOGY

A coupled-line coupler (CLC) is a four-port network is realized by the combination of two unshielded transmission lines (TLs) interacting with each other causing coupling between the two lines [3]. A four-port network consisting of two transmission lines coupled together and the main criteria to achieve desired coupling and directivity are:

1 .The coupled section should be a quarter-wave at center frequency

2. The product of even and odd mode impedances must be equal to Z_o^2

A parallel-line micro strip coupler is shown in figure 1 where port 1 is taken as the input port. The port that is directly coupled to port 1 is the throughput port which is one of the two output ports. The other output port is known as coupled port (Port-3) which is directly across from the input port whereas port-4 is known as isolated port. S parameters of the coupler are defined as:

S_{11} = Return Loss

S_{12} = Insertion Loss

S_{13} = Coupled Power Output

S_{14} = Isolation

(a) Parallel coupled topology (b) Cross sectional view

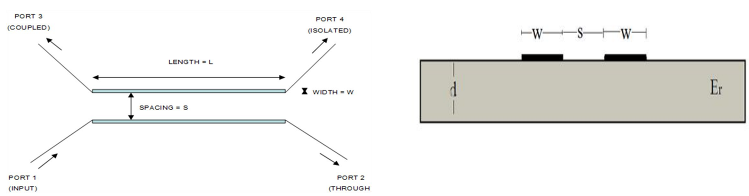

Fig 1: Parallel coupler

A. Concept of Even and Odd-mode impedances

There are two modes of current flow in parallel coupled lines where in first one current flow by displacement current between each conductor carrying the same polarity with respect to the ground that is common between them. This is termed as the even mode current and associated even mode characteristic impedance is denoted as Z_{oe}. Another one is termed as odd mode current having different polarity and associated odd mode characteristics impedance is denoted as Z_{oo}. Due to inhomogeneous nature of the micro strip lines, the odd mode phase velocity is faster than the even mode phase velocity [5]. Mathematically it can be represented as $\beta o < \beta e$. This can further be written as for the odd mode as

$$\beta o = \omega / V_0$$
$$\beta o \ell = \omega \ell / V_0$$
$$V_0 = \omega \ell / \theta_0$$
$$\theta = 2\pi f \sqrt{\varepsilon_{eff}}\, \ell / c$$

and for even mode $\beta e = \omega / V_e$

$$\beta e \ell = \omega \ell / V_e$$
$$V_e = \omega \ell / \theta_e \;; Z_{oe} = 1/(v_p C_O)$$

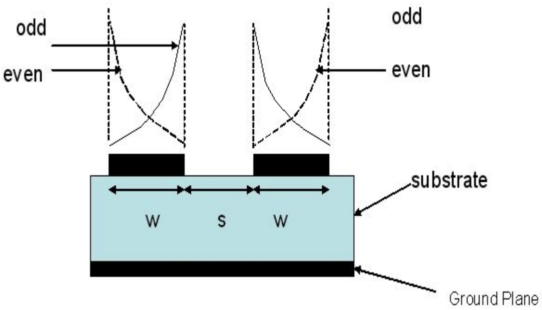

Fig 2: Concept of Even / Odd mode current distribution in the coupled line

The even and odd mode impedances are related with the characteristic impedances which are shown below:

$$Z_{oe}\, Z_{oo} = Z_o^2 \qquad (1)$$

B. Design Aspects

The design of parallel-line micro-strip couplers requires a relationship between the geometry of the device and the even- and odd-mode characteristic impedances (Z_{oe} and Z_{oo}). These values are dependent on the coupling ratio for which following equations are used [6]:

For a given coupling 'C' in dB the numeric value is calculated as

$$c = 10^{\frac{-C}{20}} \qquad (2)$$

Taking characteristic impedance Z_o as 50Ω , the required even and odd mode characteristic impedances can be derived from

$$Z_{Oe} = Z_O \sqrt{\frac{1+c}{1-c}} \qquad (3)$$

$$Z_{Oo} = Z_O \sqrt{\frac{1-c}{1+c}} \qquad (4)$$

On obtaining the impedance values, the corresponding S/H and W/H can be obtained with the standard graphs [5]. The flow chart for the coupler design is shown in Fig 3.

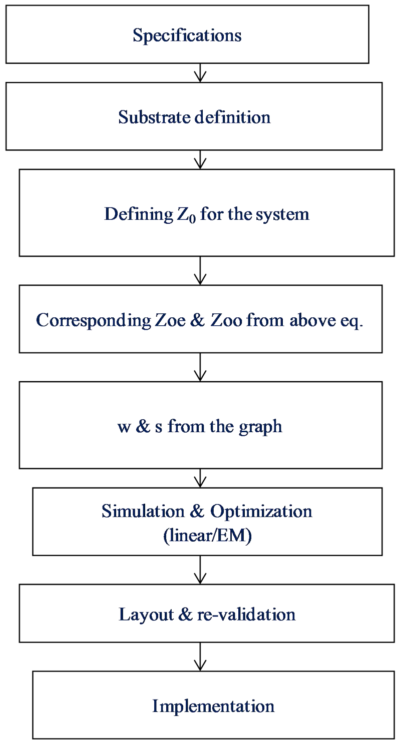

Fig 3: Flow Chart of the design of parallel coupled line coupler

III. Parametric Analysis

The design of coupler is carried out for various coupling ratios ranging from 6-dB to 25-dB using the above equations and simulation is carried out using the standard simulator [7]. The results of the theoretical and simulated data are tabulated as shown in Table-1. The below table provides the design analysis of various coupling ratios for a parallel-coupler with different coupling ratios and the difference between the theoretical and simulated values.

As evident from the table below, the percentage difference between the simulated and theoretical values increases with the coupling values. Also the dimensions for lower coupling values are unrealizable whereas at much higher coupling values the spacing is higher making it prone to interferences resulting in higher losses. So the choice for these couplers is dependent on the applications and coupling ratios. Further as the spacing goes higher the even-odd impedance differences also narrows down and approaches towards 50Ω. The role of spacing to achieve higher coupling ratios is more prominent compared to the width of the coupled line.

Coupling (dB)	Theoretical		Simulated		Z_{0e} (Ω)	Z_{0o} (Ω)	Impedance difference (Ω)	Difference in S (%)
	S/H	W/H	S/H	W/H				
6	0.055	0.60	0.0004	0.5	86.73	28.82	57.91	5.46
10	0.21	0.85	0.28	0.84	69.37	36.03	33.34	7
15	0.6	0.90	0.75	0.9	59.84	41.77	18.04	15
20	1.0	0.90	1.3	0.95	55.27	45.22	10.05	30
25	1.5	0.95	2.1	1.0	52.89	47.26	5.63	60

Table-1: Comparative analysis of various parameters for different coupling ratios

IV. DESIGN OF A 10-DB COUPLER

The above design equations are used to design a 10-dB coupler. In the present study a micro-strip coupler with center frequency of 2.2 GHz is designed on RT duroid (10 mils, 10.2) substrate. The linear and electromagnetic simulation based on Method of moments technique is performed.

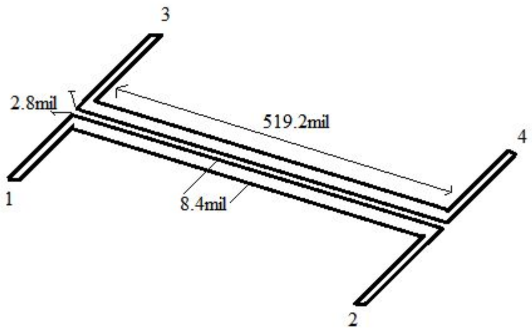

Fig 4: Layout of 10-dB coupler

The optimized width 'w' and gap of the coupler is 8.4 mils and 2.8 mils respectively and the simulated results of the same are shown in Fig 5.

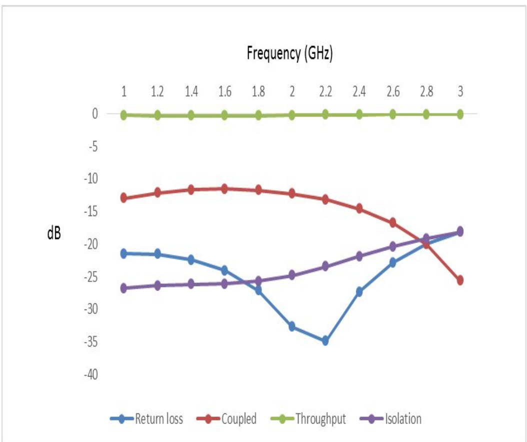

Fig 5: Simulated performance of 10dB coupler

The effect of the substrate height and enclosure effect on the coupler performance is analyzed. Table-2 shows that by increasing the substrate height the coupling reduces as the associated characteristic impedances change accordingly and reflected in the increased insertion loss. The same variation is not observed with the variation of the cover height as the radiation effect from the circuit is minimum.

Table-2: Effect of substrate and cover height on coupler performances.

Height (mils)	Effect of substrate height		Effect of box height	
	Coupling(dB)	Insertion loss(dB)	Coupling(dB)	Insertion loss(dB)
10	9.99	0.59	13.727	0.189
20	6.93	1.10	12.307	0.272
30	5.75	1.57	11.892	0.308
40	5.12	1.95	11.712	0.325
50	4.71	2.25	11.613	0.334

Generally the simulation is carried out exactly at the coupled ports without taking into consideration the location of the feeding port. In actual implementation the feeding port location is changed resulting in performance degradation.

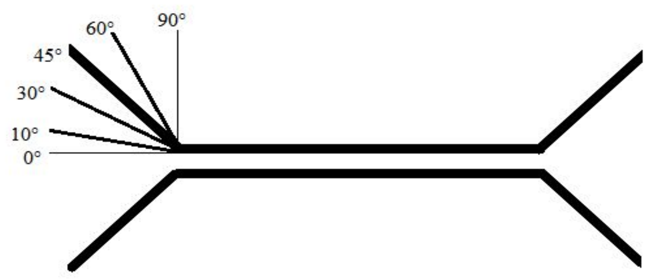

Fig 6: Schematic representation of the feeding location

In this article we studied the effect of feeding orientation on the coupler performance as shown in Fig 6 and Table-3 shows the effect of angular feeding on the coupling and insertion loss performance. Both linear and electromagnetic simulation (MOM based) are carried out for the analysis and shown in Table-3.

Table-3: Effect of feeding orientation on coupler performance

Angle(°)	Linear simulation		EM simulation	
	Coupling(dB)	Insertion loss(dB)	Coupling(dB)	Insertion loss(dB)
10	10.14	0.582	8.986	0.676
30	10.02	0.586	7.732	1.129
45	10.00	0.590	7.647	1.190
60	9.987	0.593	7.636	1.219
90	9.954	0.602	7.649	1.248

The table clearly shows that with reduce angle the feeding plane interacts and changes the coupling values. After certain angle the effect is minimized and coupler is recommended to be fed at certain angle so as to overcome the undesired coupling between the feeding planes.

Table-4 shows the overview of the effect of various parameters on the coupling.

Table 4: Various parameters effect on the coupling

Parameters	Coupling(dB)
Box height ↑	↓
Substrate height ↑	↓
Spacing b/w coupled lines ↑	↑
Width of coupled lines ↑	↑
Angle of the feeding lines ↑	↓

It is recommended to carry out the simulation at the frequency of interest before finalizing the angular position and box dimensions.

V. DISCUSSIONS

This article shows the step by step approach of designing a parallel coupled directional coupler topology. The relationship between the impedances and spacing with the coupling ratio is studied. The effect of various parameters on the coupling ratio is detailed. It is shown that higher coupling ratio is dependent on the spacing rather than the width of the transmission line. Also the effect of the angular feeding on the coupling ratio is tabulated along with the substrate and cover height.

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