A Coupled Microstripline Directional Coupler Simulated Using CST-MWS

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Abstract— Directional Coupler (DC) is a passive device which is primarily employed for monitoring purposes. It is also used in wide range of applications such as antenna feeds, balanced mixers, modulators, phase shifters, as power combiners, as reflectometers. The paper discusses the designing issues of a coupled line-microstripline directional coupler and designs a directional coupler yielding directivity of ~21 dB for the frequency 505.8 MHz. The effects of strip thickness, and substrate thickness have been studied while optimizing the design parameters in order to enhance the directivity of the coupler.

Keywords— Directional Coupler, Microstripline, 505.8MHz, CST-MWS, Coupled Lines, RF designing, Coupled lines

INTRODUCTION

Directional Coupler (DC) is essentially a four port device whose function is to tap a small portion of incident power and use it according to the application. The proportion of the amount of power extracted to incident power depends upon a factor called coupling ratio.

A directional coupler can be configured with the help of lumped elements and transmission lines. But its waveguide and coaxial versions are discussed more often. These variants are very large in size, costly to construct, and introducing changes in design of these at higher frequencies is difficult. A microstripline coupled directional coupler is made by sandwiching a dielectric slab between a conducting ground plate on one side and two conducting strips on other side. The coupling action takes place by virtue of electromagnetic interaction between the two strips placed in proximity to each other for a particular distance called coupling length. Because of these interactions coupled microstrip supports two modes of propagation viz. even mode and odd mode [2]. The configuration enjoys all the pros associated with microstripline structure and gets hampered by its cons as well. The structure enables the directional coupler to be easily integrated with other devices and allows easy troubleshooting. But because of inhomogenity of the medium, the phase velocities of the two modes differ and degrade the performance of directional coupler.

Along with coupling, characterization of devices like directional coupler is done with respect to few more parameters like isolation of undesired port; directivity, which is the difference between coupling and isolation; reflection, measure of amount of incident power reflected from input port itself; insertion loss, the measure of loss incurred when device is inserted in a transmission path. Mathematically, the ratios viz. Directivity, Coupling, Isolation can be expressed as follows (Figure 1) [11]:

$$\text{Coupling} = 10 \text{ Log } \frac{\text{Pi}}{\text{Pf}} \text{ decibels}$$

$$\text{Directivity} = 10 \text{ Log } \frac{\text{Pf}}{\text{Pb}} \text{ decibels}$$

$$\text{Isolation} = 10 \text{ Log } \frac{\text{Pi}}{\text{Pb}} \text{ decibels} = \text{Coupling (in dB)} + \text{Directivity (in dB)}$$

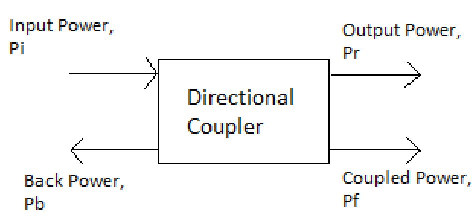

Figure 1. 4-Port Directional Coupler

Extensive research has been conducted on the design of microstrip directional couplers due to their widespread application. Akhtarzad et. al. reports design equations for the coupled microstripline in the paper [4]. Krisching and Jasen [5] also presents closed form expressions that can be implemented with the help of computers. J. H. Hinton [3] reports updated wheelers formula to yield more accurate results for wide range of width of striplines to height of substrate ratio. Erogulu [6] incorporates modifications introduced by Hinton in the design equations reported by Akhtarzad. Gupta et al [2] have given detailed analysis of microstripline structure. T. Vijayan [8] formulates the modified equations to design a directional coupler for the frequency 300 MHz using IE3D, a planar electromagnetic simulation tool.

MICROWAVE STUDIO (MWS), a Computer Simulation Technology (CST) software tool is used for three dimensional electromagnetic simulation of high frequency devices for antennas, filters and couplers etc.. Features like easy-to-use interface, parameterization and optimization capabilities, including post-processing options to increase the speed of development process.

The paper studies the considerations involved in designing a directional coupler and designs a directional coupler utilizing the various features of CST-MWS.

DESIGN EQUATIONS:

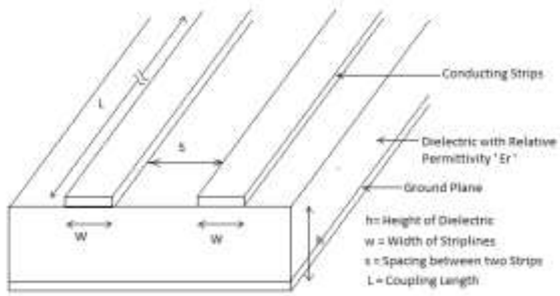

Figure 2. Schematic of Coupled microstripline directional coupler

The figure 2 introduces the various design parameters related to microstripline structure. It also shows their symbols which have been used in the text. Microstripline consists of a metallic ground plane and two strips of width 'w', separated laterally by's'. A dielectric substrate of height 'h' and relative permittivity 'Er' is sandwiched between ground and strips.

The design procedure adopted in this paper implements closed formulas given in [2, 4] which give a complete design of symmetrical two-line microstrip directional couplers, for MHz frequency range.

The coupling ratio of a directional coupler is usually given in terms of decibel. To convert it into its antilogrithmic form following equation can be used.

$$c = 10^{\frac{-Cr}{20}}$$

Where,

Cr = coupling ratio in dB

c = coupling ratio

The above ratio is then used to determine even mode and odd mode impedances Zoo and Zoe. These relations have been derived from the relation of Cr: [6, 7, 9]

$$Z_{oo} = Z_o \sqrt{\frac{1-c}{1+c}}$$

$$Z_{oo} = Z_o \sqrt{\frac{1+c}{1-c}}$$

Where,

Z_o = Characteristic Impedance in Ohms

Z_{oo} = Odd mode characteristic impedance in Ohms

Z_{oe} = Even mode characteristic impedance in Ohms

Halves of the above derived odd and even mode impedances give their counterparts for single microstriplines as: [6, 7, 9, 12]

$$Z_{oso} = \frac{Z_{oo}}{2}$$

$$Z_{ose} = \frac{Z_{oe}}{2}$$

The ratio of width of strips to height of substrate for single line is given by [1, 2]:

$$\frac{w}{h} = \begin{cases} \dfrac{8e^{A}}{e^{2A} - 2}\,, & for\ \left(\dfrac{w}{h}\right) < 2 \\ \dfrac{2}{\pi}\left[B - 1 - ln(2B-1) + \dfrac{Er-1}{Er+1}(0.23 + \dfrac{0.11}{Er})\right], & for\ \left(\dfrac{w}{h}\right) < 2 \end{cases}$$

Where,

$$A = \frac{Z_O}{60}\sqrt{\frac{Er+1}{2}} + \frac{Er-1}{Er+1}(0.23 + \frac{0.11}{Er})$$

$$B = \frac{377}{2Z_o\sqrt{Er}}$$

To determine even and odd mode single line w/h ratios Zo is replaced by Zoso and Zose in equation for single line w/h ratio. That is:

$$\frac{w}{h}_{se} = \frac{w}{h}\Big|_{Z=Zose}$$

$$\frac{w}{h}_{so} = \frac{w}{h}\Big|_{Z=Zoso}$$

Where,

$\frac{w}{h}_{se}$ = Even mode w/ h ratio for single line

$\frac{w}{h}_{so}$ = Odd mode w/h ratio for single line

Now, the above calculated even and odd mode single line w/h ratios are used to find out spacing between lines ‘ s’ as [4,9]:

$$\frac{s}{h} = \frac{2}{\pi}\cosh^{-1}\left[\frac{\cosh\left(\left(\frac{\pi}{2}\right)\left(\frac{w}{h}\right)_{se}\right)+\cosh\left(\left(\frac{\pi}{2}\right)\left(\frac{w}{h}\right)_{so}\right)-2}{\cosh\left(\left(\frac{\pi}{2}\right)\left(\frac{w}{h}\right)_{so}\right)-\cosh\left(\left(\frac{\pi}{2}\right)\left(\frac{w}{h}\right)_{se}\right)}\right]$$

As already stated the strips are placed parallel to each other for a particular distance called coupling length 'L'. This factor plays a major role in Directional couplers performance. For better coupling, L should be in accordance with the operating frequency so that it gives maximum coupling at desired frequency. For a quarter wave coupler the relation [9,6] used for L is:

$$L = \frac{\lambda}{4} = \frac{3\times 10^{8}(m/sec)}{4\times f(MHz)\times\sqrt{Eff}}$$

It is clear from the above relation that to determine the coupling length, effective permittivity is needed which, for coupled microstriplines structure, is derived in terms of even-odd mode capacitances as [9]:

$$\sqrt{Eff} = \frac{c\times C_e\times Z_{oe} + c\times C_o\times Z_{oo}}{2}$$

Where [2, 9, 6,7],

$$C_e = C_p + C_f + C'_f$$

Where,

C_e = Even mode capacitance

C_p = Parallel plate capacitance

$= E_r E_0 \frac{w}{h}$

C_f = Fringe capacitance

$= \frac{1}{2}\left(\frac{\sqrt{Ef}}{cZ_o} - C_p\right)$

Where,

The effective dielectric constant for single line directional coupler is given by [2]:

$$Ef = \frac{Er+1}{2} + \frac{Er-1}{2}F(W/h)$$

Where,

$$F\left(\frac{W}{h}\right) = \begin{cases} \frac{1}{\sqrt{1+12h/w}} + 0.04(1-w/h)^2 & (\frac{w}{h} \leq 1) \\ \frac{1}{\sqrt{(1+12h/W)}} & (\frac{w}{h} \geq 1) \end{cases}$$

Now,

$$C_f' = \frac{C_f}{1 + A(h/s)tanh(8s/h)} \sqrt{\frac{E_r}{E_{ff}}}$$

Where,

$$A = exp(-0.1exp(2.333-2.53w/h))$$

C_p is the parallel plate capacitance between the strip and the ground plane. Fringe capacitance depends on single microstrip geometry and parallel plate capacitance. $C_f^{'}$ corresponds to the effect of second line on single line fringe capacitance.

Also, the odd mode capacitance (C_O) is sum of four capacitances [2, 9, 6,7]:

$$C_O = C_p + C_f + C_{ga} + C_{gd}$$

Where,

$$C_{ga} = E_0 \frac{K(k^{'})}{K(k)}$$

Where,

$$k = \frac{s/h}{s/h + 2w/h},$$

$$k^{'} = \sqrt{1-k^2},$$

$$\frac{K(k^{'})}{K(k)} = \begin{cases} \frac{1}{\pi} \ln(2\frac{1+\sqrt{k^{'}}}{1-\sqrt{k}}), \ for 0 =< k^2 =< 0.5 \\ \frac{\pi}{\ln(2(1+\sqrt{k})/(1-\sqrt{k}))}, \ for 0.5 =< k^2 =< 1 \end{cases}$$

$$C_{gd} = \frac{E_0 E_r}{\pi} \ln\left\{\coth(\frac{\pi}{4}\frac{s}{h})\right\} + 0.65 C_f \left(\frac{0.02}{s/h}\sqrt{E_r} + 1 - E^{-2}{}_r\right)$$

C_{ga} is the capacitance through air gap. Its value is obtained from capacitance of a slot line of width 'w' with air as dielectric. K (k) and K (k`) represents elliptic function and its complement. C_{gd} is capacitance due to air dielectric interface. The first term corresponds to coupled stripline and next to it stands the relation for the coupled microstrip.

SIMULATION & RESULTS:

From the above described design equations it is clear that before starting with designing process, the designer should assign initial values to few factors like height of subsrate, thickness of metal strips, thickness of ground plane, operating frequency, coupling , permittivity of substrate used, and characteristic impedance. Since, usually type of substrate, characteristic impedance, coupling, operating frequency are system defined constraints, therefore the designer has only height of substrate and thickness of strips and ground plane in its hands, for any kind of manipulation.

The substrate here was Teflon whose permittivity is 2.1. The characteristic impedance was taken to be 50 ohms which is a very general value. Rests of the parameters were chosen arbitrarily.

The design created in CST-MWS is shown in Figure 3.

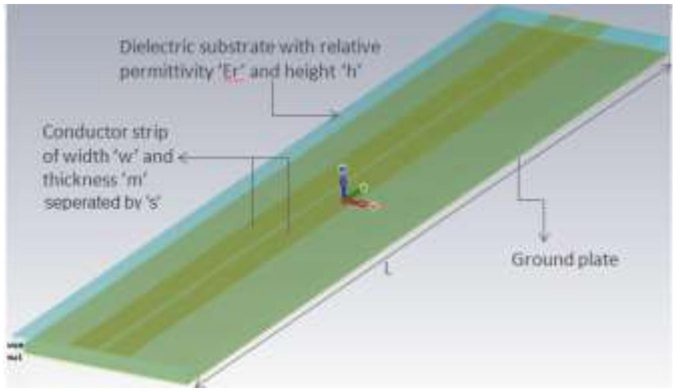

Figure 3. 3-D View of Directional Coupler in CST-MWS Design Environment

The design was created in CST-MWS design environment, implementing the equations using its wide parameterization capabilities. The results obtained after running transient solver are shown in the plot in figure 4**.** From the plot it is clear that the insertion loss is -1.17 dB, isolation is -19.769 dB, coupling is 11.27 dB, and directivity is 13.79 dB. Here the input port was numbered port 1, isolated port was port 2, output port was port 3, and coupled port was port 4

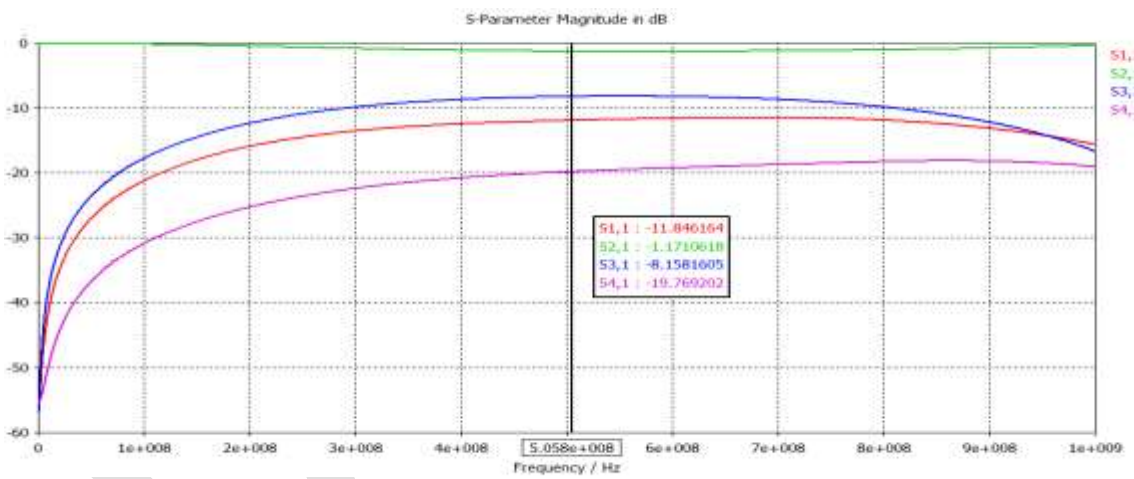

Figure 4. 1-D Plot showing S Parameters in dB

The aim was to design a 20 dB coupler but the results show that the design gave coupling of -8.15 dB and 11.61 dB directivity. Therefore, to improve directivity and achieve required coupling, further optimizations of the geometrical design parameters were done. The value of coupling came out to be -12.14 dB and directivity improved to 20.967 dB. The reflection and isolation obtained were -20.98 dB and -33.107 dB respectively. The S-Parameters chart in decibel form and the derived design parameters are shown in the figure 5 and table 1 respectively.

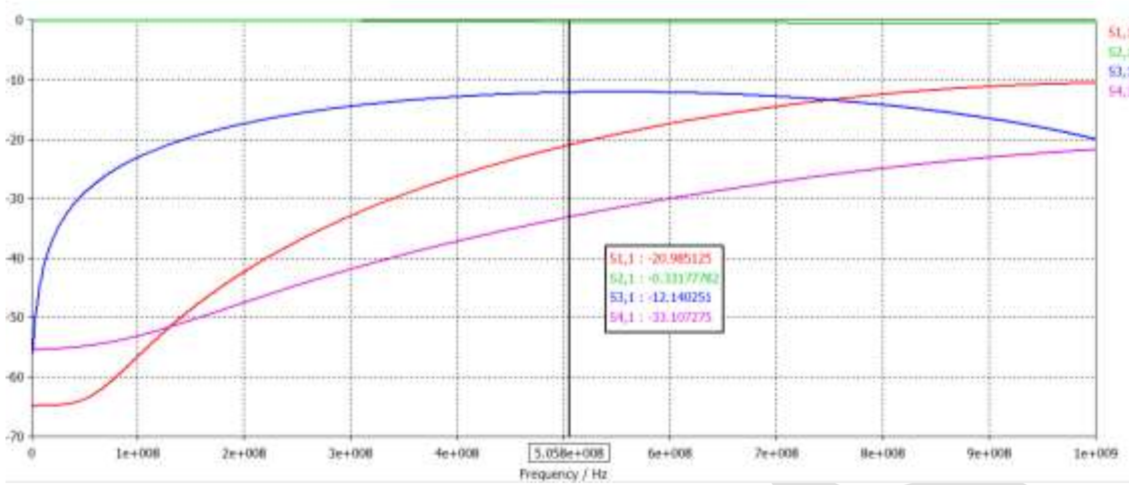

Figure 5. 1-D Plot showing final values of S Parameters in dB

The final values of parameters after optimizations, along with their symbols and description, as well as units considered, are given in table 1.

Table 1. Values of parameters

S.No.	Parameter	Description	Value
1.	Zo	Characteristic impedance of ports	50ohms
2.	Er	Relative permittivity of substrate	2.1
3.	f	Operating frequency	505.8 MHz
4.	s/h	Spacing to height of substrate ratio	0.27
5.	m	Thickness of conductor	0.2 mm
6.	Cr	Coupling ratio in dB	20 dB
7.	w/h	Width to height of substrate ratio	1.13

Now, while optimization the variations in directivity and other characterization parameters were studied with respect to changes in m and h. The associated observation tables are as follows:

Effect of strip thickness:

The values of characterization parameters of directional coupler with respect to change in strip thickness is given in table 2.

Table 2. Observation table for Strip thickness (in mm) and Directivity, coupling, isolation, reflection, insertion loss (in dB)

m(mm)	Directivity (dB)	Coupling (dB)	Isolation (dB)	Insertion loss (dB)	Reflection (dB)
0.4	-9.637	-7.365	-17	-1.56	-10.64
0.3	-10.19	-7.412	-17.6	-1.373	-11.76
0.2	-9.94	-7.449	-17.39	-1.492	-10.821
0.16	-17.04	-11.558	-28.606	-0.398	-19.47

0.15	-17.10	-11.577	-28.681	-0.395	-19.548

The best directivity and coupling, though not equal to the design value, was obtained for m= 0.15 mm therefore this value was selected.

Effect of substrate height:

After varying m, h was also varied and Directivity, coupling, isolation, reflection, insertion loss were recorded in the table 3:

Table 3. Observation table for Substrate Height (in mm) and Directivity, coupling, isolation, reflection, insertion loss (in dB).

h(mm)	Directivity (dB)	Coupling (dB)	Isolation (dB)	Insertion loss (dB)	Reflection (dB)
5	-20.566	-12.148	-32.714	-0.333	-20.923
4.5	-20.993	-12.143	-33.136	-0.331	-21.019
4.22	-21.005	-12.140	-33.145	-0.332	-20.989
4	-20.795	-12.057	-32.852	-0.337	-20.847
3	-19.506	-11.984	-31.49	-0.344	-20.619
2	-17.706	-11.663	-29.369	-0.381	-19.857

The most optimum value of h was chosen to be 4.5 mm because at this value insertion loss was the least though the difference between that obtained at 4mm, 4.5 mm and 4 mm is very minimal.

ACKNOWLEDGEMENTS

The authors would like to thank Mr. Manjeet Ahlawat, Scientific Officer/D, & Mr. R. S. Shinde, Scientific Officer/ H^+, Head, Accelerator Magnet Technology Division, Raja Ramanna Centre for Advanced Technology, India, for their motivation, guidance and support throughout the observation process carried out at Raja Ramanna Centre for Advanced Technology, India.

CONCLUSION & FUTURE SCOPE

The designed directional coupler gives a coupling of -12.14 dB, improved directivity of -20.967 dB, -20.98 dB reflection and isolation of -33.107 dB, for the frequency of 505.8 MHz. Also effect of changes in parameters like substrate height and strip thickness was observed. It was observed that the as the strip thickness is reduced and substrate height is increased, the directivity improves.

The next attempt of the author is to study the power handling capacity of the device. There are certain modifications discussed by various researchers [3, 8, and 6]. The author is attempting to implement them to achieve better coupling and directivity with reasonable values of other characterization parameters. The directivity is a factor which is very important for applications requiring accurate impedance matching. But it is equally difficult get a satisfactory value for it. Therefore, further modifications like using dielectric overlay techniques and adding delays, could be done to improve the directivity.

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