Sustainable Engineering and Innovation ISSN 2712-0562
Vol. 2, No. 1, June 2020, pp.26-33

30 dB microstrip coupler with high directivity

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Abstract
Due to inhomogeneous structure of a microstrip directional couplers, i.e. partly dielectric substrate, partly air, they mostly present property of poor directivity and low coupling level. High directivity is achieved by a capacitive compensation by gap coupling of open stub formed in sub-coupled line. Nevertheless, these couplers have advantage of easy fabrication, lightweight and incorporation with other microwave devices and are validated via design using Sonnet software. The main goal was to obtain coupling around -30 dB, meaning that almost all power is passed to the output, with a wide band; from around 3.5GHz to nearly 9GHz. Desired values have been obtained, including isolation and input match reaching -70 dB.

Keywords: Capacitive Compensation; Directional Coupler; Directivity; Microstrip; Sonnet Software.

1. Introduction

Directional couplers with parallel-coupled microstrip transmission lines are easily fabricated, which makes them widely used for various RF and microwave applications because they can be easily incorporated into and implemented with other circuits: designs of various balanced power amplifiers, mixers, modulators, measurement systems, circularly polarized antennas, beam-forming array antennas, etc. [1]-[2]. Recently, the concept of Substrate Integrated Waveguide (SIW) studied widely has already been applied to the design of microwave components with the virtues of high integrity, low loss and less cost [3]-[4]. In practical applications, the coupling level of microstrip coupled-line coupler is mainly limited by the narrow separation between two parallel edge-coupled transmission lines, usually 0.1 mm, in the printed circuit board (PCB) fabrication. However, due to inhomogeneous dielectric - partly dielectric substrate, partly air - odd phase velocities are unequal (the odd-mode phase velocity commonly faster), which is cause of coupler's poor directivity (and the design theory for TEM transmission-line couplers is based on an assumption of the same phase velocities of even and odd propagation mode). In this case, the odd mode has more fringing electric field in the air region rather than the even mode with electrical field concentrating mostly in the substrate underneath the microstrip lines. As a result, the effective dielectric permittivity in the latter case is higher, thus indicating a smaller phase velocity for the even mode. Consequently, it is required to apply the phase velocity compensation techniques to improve the coupler directivity that decreases with increasing frequency. Poor directivity also can be caused by increase in dielectric permittivity [5]. Therefore, the main limitations of the traditional coupled-line couplers are low coupling level and poor directivity in microstrip implementation.

In addition, it is difficult to achieve tight coupling owing to impractical spacing between the coupled lines in conventional edge coupled microstrip couplers. These are reasons for using the broad-side stripline configuration for tight coupling and high directivity, which needs more fabrication cost and efforts than a conventional microstrip line coupler. However, due to suitability of microstrip integration with other microwave circuits, it became very attractive to use simple ideas and means to improve them.

Several techniques are available to equalize or compensate for the inequality in the each mode velocity of the coupled microstrip line. Theoretically, equalising the even- and odd-mode phase velocities of the symmetric coupled microstriplines or equalising inductive and capacitive coupling coefficients of the asymmetric ones can achieve ideal isolations. The wiggly-line coupler first proposed by Podell suffers from a lack of pertinent design information [6]. Dielectric overlays on the top of the coupled lines have also been used to equalize the mode phase velocities by increasing the odd mode effective dielectric constant [7]. The capacitively and inductively compensated directional couplers with high directivity were used to equalize the phase velocities [8]. Re-entrant mode coupler was proposed by S. B. Cohn to obtain tight coupling [9]. A capacitive or inductive compensation method by lumped elements, described by M. Dydyk [10], D. Kajfez [11] and [12], originally has been used to resolve the phase difference problems. However, Kajfez's analysis is only approximate. The developed equations for the capacitance determination are nearly true for tight coupling; however, the center frequency prediction is lower than desired. But Dydyk's method [13] overcomes these shortcomings and provides a closed-form solution for the compensating lumped capacitance and new odd-mode characteristic impedance necessary to realize an ideal microstrip directional coupler. With a few lumped capacitors placed on the coupled section and coupled inductors replaced by ground inductors, Andrews and Aitchison [14] introduced a quadrature coupler, which can operate at microwave frequencies with good isolation and wide bandwidth. A bit newly approach is described in [15], where the even-mode phase velocity effectively by meandering the parallel microstrip coupled lines. All of the techniques given above are focused on reduction of the effective odd-mode phase velocity. Another way to increase the coupling between the two edge-coupled microstrip lines is to use several parallel narrow microstrip lines interconnected with each other by the bondwires (Lange directional coupler) [16]. Recently, the parasitic reactances associated with the regions of connected coupled and signal lines in coupled-stripline or microstripline 3 dB directional couplers [17] were investigated and it seems to be the reason for the poor return losses and isolations of these couplers; also, they are greatly improved by introducing capacitive compensation.

This paper will address how to take advantage of this method and apply it to the easy realization of a single microstrip directional coupler. This paper solves this issue by introducing capacitive compensation method by gap coupling of open stub formed in sub-coupled line [18].

2. Material and Methods

Figure 1 shows the capacitive compensated mictrostrip directional coupler consisted of two symmetrical lumped capacitors between coupled lines for high directivity characteristics. The capacitance in Figure 1 is implemented by gap coupling between main line and open stub formed in sub-coupled line to compensate the phase difference of each mode.

If we apply an even and odd mode to the length of coupled lines we can derive the design equations for directional coupler. Such an equivalent circuit is shown in Figure 2.

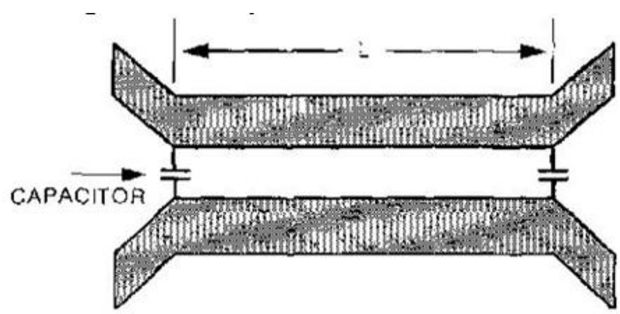

Figure 1. Microstrip directional coupler with symmetric compensating capacitors [18]

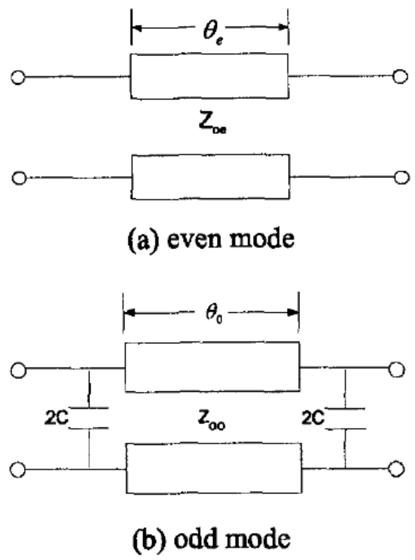

Figure 2. The equivalent circuit of even (a) and odd mode (b) [18]

Since the compensating capacitors in Figure 2 do not affect the even mode circuit, the equivalent circuit of the even mode is equal to the typical one. Due to that, we only consider the equivalent circuit of the odd mode and the ideal and actual odd mode is shown in Figure 3.

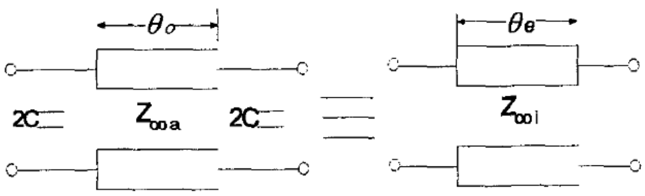

Figure 3. The equivalent relationship of actual and ideal odd mode circuit [18]

Equations (1) and (2) represent the transmission (ABCD) matrix of Figure 3.

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_o = \begin{bmatrix} cos\theta_o - Z_{oo}2\omega C sin\theta_o & jZ_{oo}sin\theta_o \\ j(4\omega C cos\theta_o + (Y_{oo} - Z_{oo}(2\omega C)^2)sin\theta_o) & cos\theta_o - 2\omega C Z_{oo} sin\theta_o \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_{oi} = \begin{bmatrix} cos\theta_e & jZ_{ooi}sin\theta_e \\ jY_{ooi}sin\theta_e & cos\theta_e \end{bmatrix} \tag{2}$$

The electrical length of the actual odd mode has to make an equal to the one of the ideal odd mode to obtain the high directivity characteristics. Therefore, we can derive from the equal relationship of the ABCD-parameter for both circuits.

Equating the A and B element in Equations (1) and (2) yields

$$cos\theta_e = cos\theta_o - 2\omega C Z_{oo} sin\theta_0 \tag{3}$$

$$Z_{oo}sin\theta_o = Z_{ooi}\ sin\theta_{0e} \tag{4}$$

Combining Equations (3) and (4) we get

$$cos\theta_e = cos\theta_o - 2\omega C Z_{ooi} sin\theta_e \tag{5}$$

and recognizing that at the center frequency

$$\theta_e = \pi/2 \tag{6}$$

then

$$C = \frac{\cos\theta_o}{2\omega C Z_{ooi}} \tag{7}$$

Since

$$\theta_o = \frac{2\pi}{\lambda g_o} l = \frac{\pi}{2}\sqrt{\frac{\epsilon_{effo}}{\epsilon_{iffe}}} \tag{8}$$

The compensating capacitance dependency becomes

$$C = cos\left(\frac{\pi}{2}\sqrt{\frac{\epsilon_{effo}}{\epsilon_{iffe}}}\right) \tag{9}$$

The actual odd mode characteristic impedance is deduced to be

$$Z_{ooa} = \frac{Z_{ooi}}{\sqrt{1-\left(cos\left(\frac{\pi}{2}\sqrt{\frac{\epsilon_{effo}}{\epsilon_{iffe}}}\right)\right)^2}} \tag{10}$$

Z_{ooa}: actual odd mode characteristic impedance
Z_{ooi}: ideal odd mode characteristic impedance
ϵ_{effo}: effective permittivity of odd mode
ϵ_{effe}: effective permittivity of even mode

Equation (5) demands Z_{ooa} to be higher than Z_{ooi}. To achieve this, the inner-conductor must become narrower and the separation must increase to keep the even mode characteristics impedance constant which actually is possible.
With this equalization, at the center frequency at which the directional coupler is designed to operate, we find that Equations (1) and (2) reduce to:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_o = \begin{bmatrix} O & jZ_{ooi} \\ jY_{ooi} & O \end{bmatrix} \tag{11}$$

and

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_{oi} = \begin{bmatrix} O & jZ_{ooi} \\ jY_{ooi} & O \end{bmatrix} \tag{12}$$

This is identical to an ideal directional coupler with the following S-parameters.

$$S = \begin{pmatrix} O & k & -j\sqrt{1-k^2} & O \\ k & O & O & -j\sqrt{1-k^2} \\ -j\sqrt{1-k^2} & O & O & k \\ O & -j\sqrt{1-k^2} & k & O \end{pmatrix} \tag{13}$$

$$k = \frac{Z_{oe} - Z_{oo}}{Z_{oe} - Z_{oo}} \quad (14)$$

$$Z_o = \sqrt{Z_{oe} Z_{oo}} \quad (15)$$

The fact that the isolation (S14) is zero leads to infinite directivity. Of course, it is understood that this ideal directivity will degrade when losses are introduced and frequency departs from design center.

By employing the above method, we expanded two-section asymmetric microstrip coupler with Chebyshev polynomial. Figure 4 shows the equivalent circuit for the two-section asymmetric coupler. The required characteristic impedance of even and odd mode can be extracted from the design equation of the [19]. Therefore, this method can apply to asymmetric and symmetric multi-section microstrip couplers.

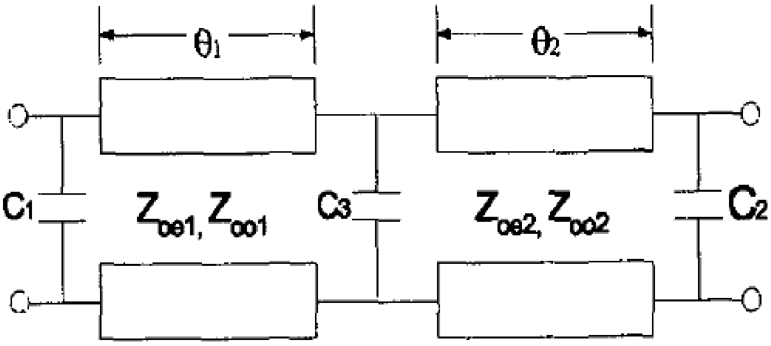

Figure 4. The equivalent of the two-section directional coupler (C3 = C1+C2) [18]

3. Simulation results and parametric study

To compensate the phase difference in the microstrip coupler, the necessary capacitive compensation is implemented by the gap coupling of open stub formed in sub-coupled line.

Figure 3 shows the top view of single section microstrip coupler with the gap coupling for realizing the compensated capacitance. The substrate properties for simulation and fabrication were a dielectric constant of 2.5 with 0.78mm thickness. Dimensions of gap (separation) were obtained by simulation in Sonnet Software. Other dimensions are also visible in Figure 3. Figure 4 shows the results obtained by simulation of a coupler in Sonnet software with coupling of -30 dB (S13). As we can see from this figure, insertion loss

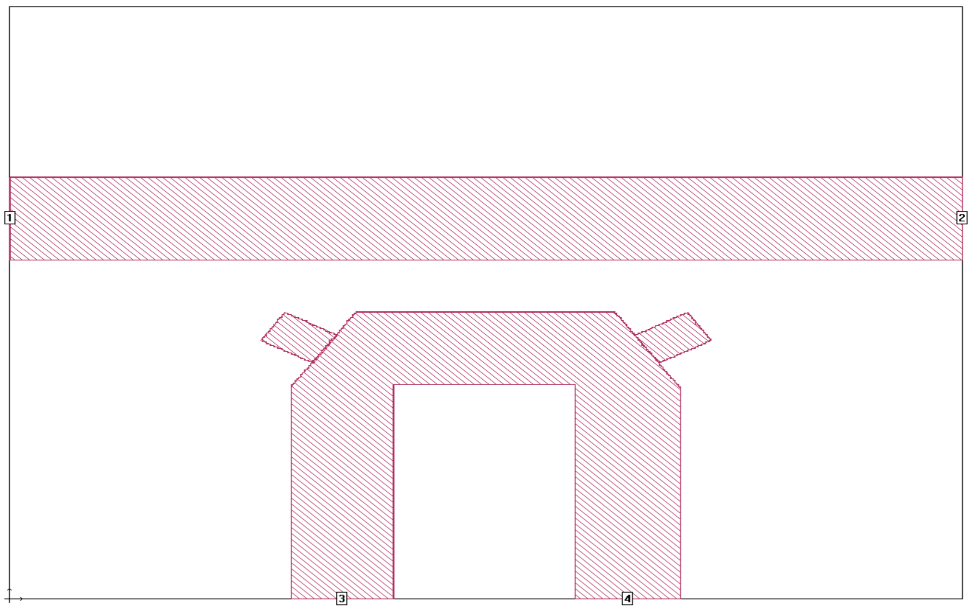

Figure 5. Schematic of the microstrip coupler with compensating capacitance

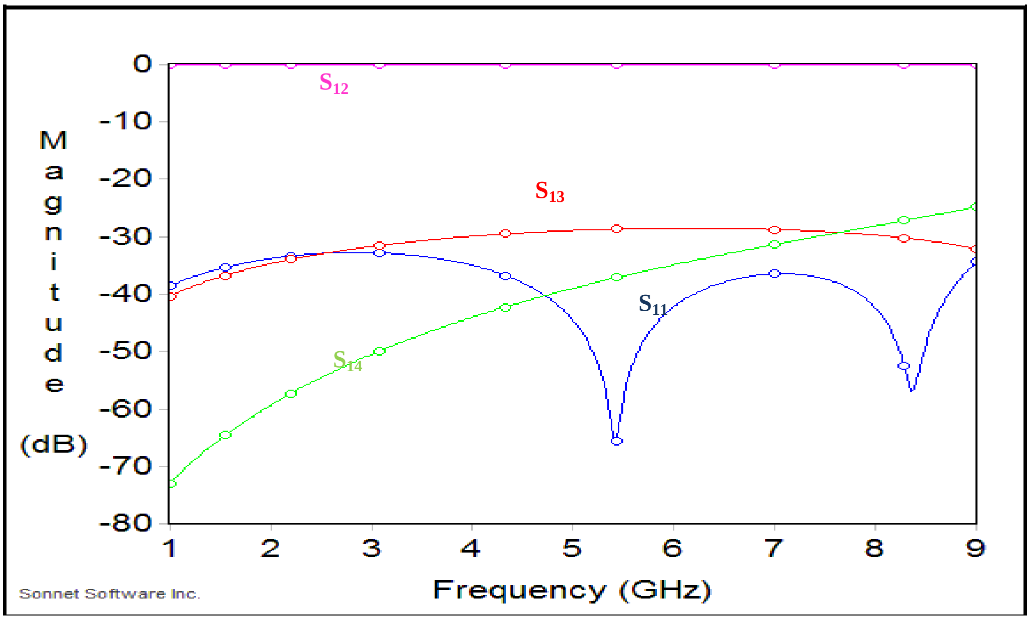

Figure 6. Microstrip coupler compensated by gap capacitance with 30 dB coupling (S_{11} - input match, S_{12} - insertion loss, S_{13} -coupling, S_{14} - isolation)

Table 1, Table 2, and Table 3 are presenting coupling bandwidth and coupling amplitude balance in dependence of width of separation gap, thickness of dielectric and width of an oblique stub, respectively.

Table 1. *Coupler performances vs. width of a gap (S)*

S (mm)	Coupling BW (GHz)	Coupling Amplitude Balance (dB)
1.22	5.35	2.38
1.26	5.25	2.29
1.28	5.1	2.26
1.30	4.85	2.05

Table 2. *Coupler performances vs. dielectric thickness (DT)*

DT (mm)	Coupling BW (GHz)	Coupling Amplitude Balance (dB)
0.36	2.575	2.13
0.6	3.375	1.50
0.78	4.7	1.86
1	5.175	1.91
1.6	3.1	1.90

Table 3. *Coupler performance vs. an oblique stub (W)*

W (mm)	Coupling BW (GHz)	Coupling Amplitude Balance (dB)
0.6007	4.55	1.77
0.6381	4.8	1.94
0.6674	4.75	1.90
0.7059	4.825	1.98
0.7337	4.825	1.95

4. Conclusion

Inhomogeneous dielectric involved in microstrip directional couplers causes poor directivity and low coupling level. Further, this situation is causing phase velocities to be unequal, meaning that the odd-mode phase velocity commonly is faster than the even-mode.

Microstrip directional couplers are implemented for realizing the high directivity characteristic. This paper compensates for this inequality by introducing the distributed capacitive compensation which is performed by gap coupling between main coupled line and the open stub formed in sub-coupled line. The main goal was to obtain coupling around -30 dB, which was shown after simulation done and the design has a wide band from around 3.5GHz to nearly 9 GHz. In addition, isolation and input match reached -70 dB.

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