Wideband Asymmetric Coupler with Optimally Positioned Capacitors for Improved Directivity

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Abstract— **The design and simulation of a wideband coupler for improved directivity is investigated. The coupled line coupler is considered for weak (or lose) coupling purposes. An improved bandwidth performance is achieved by increasing the number of stages of the coupled line coupler, thus resulting in a Multi stage coupler. The research focuses on the 3 stage coupler with optimally positioned capacitances, however the result can be easily extrapolated and generalized to any number of stages. An odd number of stages is considered for structural symmetry and wider bandwidth performance. The performance of the conventional multistage coupler, the compensation with a single capacitance, multiple capacitances and optimally positioned capacitances for both symmetric and asymmetric couplers are investigated in detail with special focus on the asymmetric couplers. This dissertation introduces the novel Pointer-Robust optimization scheme for optimal positioning and the asymmetric compensation for enhanced bandwidth-directivity performance. Several design examples and simulation results are presented and the results are confirmed by measurements. The results confirm the novel optimization scheme and compensation approach.**

Keywords— **Asymmetric Coupler, Capacitive compensation, coupled lines, coupler, directional coupler, directivity, inhomogeneous media, phase velocity compensation, wideband.**

I. Introduction

WIDEBAND couplers have many practical applications at microwave frequencies. These couplers, if realized in an inhomogeneous medium, e.g., using microstip, yield a poor directivity, which results in severe performance degradation. One of the major reasons for poor directivity or isolation in inhomogeneous medium, is due to the mismatch in the odd and even mode phase velocities, along the coupled lines. This mismatch in phase velocities results in poor directivity and port mismatch in directional couplers.

Several methods have been suggested for compensating the phase velocity mismatch, in the literature since the early 1970s. These methods fall into two distinct categories. The first category aims at compensating the mismatch in phase velocities by directly equalizing the different phase velocities along the coupled lines, while the second category is based on the connection of reactive elements along the coupled lines for phase velocity compensation.

Amongst the methods of equalizing the different phase velocities in the first category, the most common approach is to wiggle the adjacent sides of the coupling slots, thus increasing the effective path length of the odd mode current and thereby compensating for its higher phase velocity [1], [2]. Another method is to equalize the effective permittivities of the odd and even mode components achieved by means of dielectric

overlays [3], [4], anisotropic substrates [5], suspended substrates [6] or apertures in the ground plane [7]. Port isolation can also be achieved by internal reflections, using Stepped impedance approaches [8], [9].

Phase velocity compensation is achieved by the connection of reactive components along the coupled line in the second category. The use of inductive elements in series was initially proposed by Schaller and was further theorized and developed by Phromloungsri et.al [10] and Müller et.al [11]. Shunt inductances were later investigated by Lee et.al [12]. However, the compensation that can be achieved by inductive methods, both shunt and series is limited to a narrow bandwidth.

An alternative and a yet more common approach is the placement of capacitances across the coupled lines at each end of the coupler which was initially proposed by Schaller [13]. In theory this approach only reduces the phase velocity of the odd mode component by only considering the effect of the odd mode component. A similar approach, but accounting for the effect of parasitic even mode capacitance was proposed by Kajfez [14]. An accurate design equation for both the odd mode capacitance and the odd mode impedance was derived by Dydyk [15], but the parasitic even mode capacitances were not taken into account. In all the above methods the capacitances were connected to the end of the coupler. Dydyk also proposed the compensation scheme with a single capacitance at the center of the coupler [16], in which case the compensation is narrow band.

Müller et.al derived design equations for lumped capacitances placed at optimal positions, but still symmetrically along the coupler [17]. This method also accounted for the parasitic even mode capacitance. However the proposed method was for a single stage coupler (which is relatively narrowband) and was strictly symmetric.

In this study we investigate the coupled line coupler with multiple stages for improved bandwidth performance and with optimally positioned capacitances for improved directivity and phase compensation. The study also takes into account the asymmetric optimal positioning of the capacitances along the coupler for further improvement of the isolation while maintaining the desired coupling factor. The work presented below is mainly result driven. The capacitances were positioned arbitrarily along each stage of the coupler and the positions were optimized using the Pointer-Robust Algorithm to tweak the directivity, coupling and reflection at each port of the coupler.

This paper is organized as follows. Section II describes the model and outlines the approach. Section III, presents the design methodology and the determination of the necessary coupler parameters. Section IV describes the optimization process. In Section V, we analyze in detail the compensation by means of one, two and three capacitances and determine their optimum position while maintaining symmetry. This section extends the rigorous design to the case of asymmetric positioning of the capacitances, for an arbitrary number of capacitances. Finally, measurements results are reported.

II. THEORY

The coupling of a single-section coupled line coupler is limited in bandwidth due to the λ/4 length requirement. As in the case of matching transformers and waveguide couplers, bandwidth can be increased by using multiple sections [18].

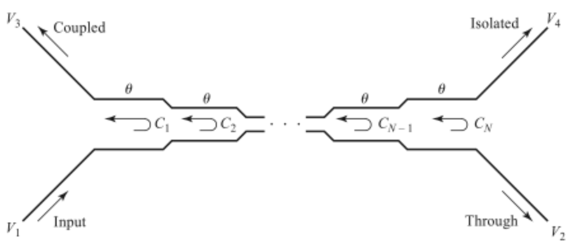


Fig. 1. An N-section coupled line coupler (courtesy of [18])

A. MULTI-SECTION COUPLER DESIGN

Multi-section coupled line couplers are generally made with an odd number of sections, because the phase characteristics are usually better, as shown in Fig. 1. Thus, we will assume that N is odd. We will also assume that the coupling is weak (C ≥ 10 dB), and that each section is λ/4 long (θ = π/2) at the center frequency.

For a single coupled line section, with C << 1, ratio of the voltages at each of the ports 1, 2, 3 and 4 are as given below [18].

$$\frac{V_3}{V_1} = \frac{jCtan\theta}{\sqrt{1-C^2}+jtan\theta} \approx \frac{jCtan\theta}{1+jtan\theta} = jCsin\theta e^{-j\theta} \quad (1)$$

$$\frac{V_2}{V_1} = \frac{\sqrt{1-C^2}}{\sqrt{1-C^2}cos\theta+jsin\theta} \approx e^{-j\theta} \quad (2)$$

Then for θ = π/2 we have that $V_3/V_1 = C$ and $V_2/V_1 = -j$. The above approximation is equivalent to assuming that no power is lost on the through path from one section to the next, and is similar to the approximation used for the multi-section waveguide coupler analysis. It is a good assumption for small C, even though power conservation is violated.

Using these results, we can express the total voltage at the coupled port (port 3) of the cascaded coupler in Figure 01 as;

$$V_3 = \left(jC_1 sin\theta e^{-j\theta}\right)V_1 + \left(jC_2 sin\theta e^{-j\theta}\right)V_1 e^{-2j\theta} + \cdots + \left(jC_N sin\theta e^{-j\theta}\right)V_1 e^{-2j(N-1)\theta} \quad (3)$$

Where C_N is the voltage coupling coefficient of the N[th] section. If we assume that the coupler is symmetric, so that $C_1 = C_N$, $C_2 = C_{N-1}$, etc., we can simplify (3) to

$$V_3 = jV_1 sin\theta e^{-j\theta}\left[C_1\left(1+e^{-2j(N-1)\theta}\right) + C_2\left(e^{-2j\theta}+e^{-2j(N-2)\theta}\right) + \cdots + C_M\left(e^{-j(N-1)\theta}\right)\right]$$
$$= 2jV_1 sin\theta e^{-jN\theta}\left[C_1\cos(N-1)\theta + C_2\cos(N-3)\theta + \cdots + 12CM \quad (4)\right.$$

Where M = (N + 1)/2. At the center frequency, we define the voltage coupling factor C_0:

$$C_0 = \left|\frac{V_3}{V_1}\right|_{\theta=\pi/2} \quad (5)$$

Equation (4) is in the form of a Fourier series for the coupling as a function of frequency. Thus, we can synthesize a desired coupling response by choosing the coupling coefficients, C_N.

Finally, if the characteristic impedance, Z_0, and the voltage coupling coefficient, C, are specified, then the following design equations for the required even- and odd-mode characteristic impedances can be easily derived as indicated in (6), (7).

$$Z_{0e} = Z_0\sqrt{\frac{1+C}{1-C}} \quad (6)$$

$$Z_{0o} = Z_0\sqrt{\frac{1-C}{1+C}} \quad (7)$$

This derivation is taken from [18]. Multi-section couplers of this form can achieve decade bandwidths, but coupling levels must be low. Because of the longer electrical length, it is more critical to have equal even- and odd-mode phase velocities than it is for the single-section coupler. This usually means that strip-line is the preferred medium for such couplers. Mismatched phase velocities will degrade the coupler directivity, as will junction discontinuities, load mismatches, and fabrication tolerances.

III. DESIGN PROCESS

A. THREE STAGE COUPLER

The design of a three-section 20 dB coupled line coupler with a binomial (maximally flat) response is indicated below at a system impedance of 50 Ω, and a center frequency of 3 GHz.

For a maximally flat response for a three-section (N = 3) coupler, it is require that,

$$\left(\frac{d^n}{d\theta^n}C(\theta)\right)_{\theta=\pi/2} = 0 \quad for\; n = 1,2$$

From (4),

$$C = \left|\frac{V_3}{V_1}\right| = 2sin\theta(C_1cos2\theta + C_2)$$
$$= C_1(sin3\theta - sin\theta) + C_2sin\theta$$
$$= C_1sin3\theta + (C_2 - C_1)sin\theta$$

So,

$$\frac{dC}{d\theta} = \{[3C_1cos3\theta + (C_2 - C_1)cos\theta]\}_{\pi/2} = 0$$

$$\frac{d^2C}{d\theta^2} = \{[-9C_1sin3\theta - (C_2 - C_1)sin\theta]\}_{\frac{\pi}{2}} = 10C_1 - C_2 = 0$$

At mid-band, $\theta = \pi/2$ and $C_0 = 20$ dB. Thus, $C = 10^{-20/20} = 0.1 = C_2 - 2C_1$. Solving these two equations for C_1 and C_2 gives,

$$C_1 = C_3 = 0.0125,$$
$$C_2 = 0.125$$

From (6) & (7) the even- and odd-mode characteristic impedances for each section are,

$$Z^1{}_{0e} = Z^3{}_{0e} = 50\sqrt{\frac{1.0125}{0.9875}} = 50.63\ \Omega$$

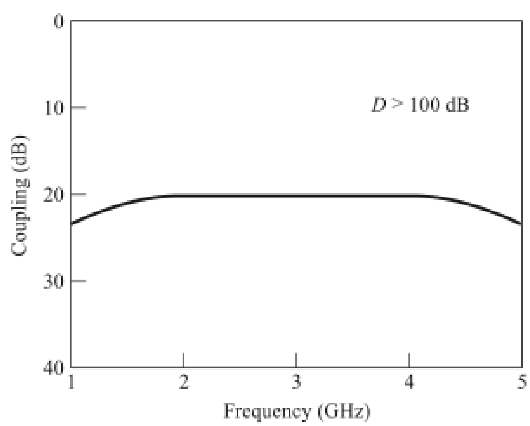


Fig. 2. Coupling versus frequency for the three-section binomial coupler

$$Z^1{}_{0o} = Z^3{}_{0o} = 50\sqrt{\frac{0.9875}{1.0125}} = 49.38\ \Omega$$

$$Z^2{}_{0e} = 50\sqrt{\frac{1.125}{0.875}} = 56.69\ \Omega$$

$$Z^2{}_{0o} = 50\sqrt{\frac{0.875}{1.125}} = 44.10\ \Omega$$

The theoretical plot of the coupling and directivity of this coupler from 1 to 5 GHz is indicated in Fig. 2.

IV. Optimization Process: The Pointer – Robust Optimization

The coupler parameters were optimized using the Pointer-Robust Algorithm available in AWR Microwave Office. The Pointer optimizer combines the power and robustness of four widely used and accepted search methods - linear simplex, downhill simplex, sequential quadratic programming, and genetic algorithm - with the ease of its unique automated training feature. This self-training ability allows the Pointer optimizer to determine the best search procedure for a given problem and also the process of training almost always finds the true global optimum. The target objectives and an allowable number of iterations for the optimization were specified, and the best combination of optimizers and step sizes to find the best solution in that time was obtained from the optimization process.

The quality of the performance of the coupler was measured by the cost function. The cost function is a measure of the error of the measured value to the optimization goals. By minimizing the cost function the quality of the coupler can be improved. This work focuses on improving the directivity of the coupler by minimizing the cost function while maintaining the wideband coupling factor of -20 dB.

The following optimization goals were used throughout the design and fabrication process.

S_{31} = -20 dB, weight = 1,
S_{41} < -50 dB, weight = 2
S_{11} < -30 dB, weight = 1
Exponent L = 2

The cost function was evaluated as depicted in the equation (8). And the cost function was minimized via the Pointer-Robust optimization process.

$$Cost\ Function = Weight\ \times |Measurement - Goal|^L \quad (8)$$

V. Design, Measurements & Analysis

Several 20 dB (coupling factor) couplers were deigned and analyzed on the RT-Duroid substrate (Relative permittivity (□r) = 3.2, Thickness h = 0.762 mm) for a center frequency of 3 GHz, and a desired bandwidth ranging from 2.5 GHz to 3.5 GHz. The capacitances were realized as gap capacitors as depicted in Fig. 3. The design and simulations were carried out considering the transmission effects and the structural features of each element in the coupler. The couplers were layed out on a 2"x2" board, for measurement and analysis using a 2 port Network Analyzer and a 2"x2" test fixture.

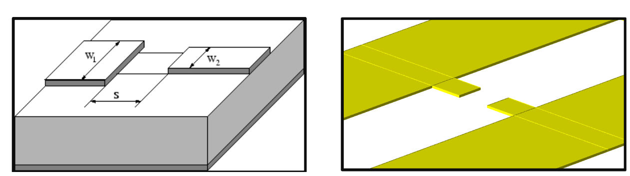


Fig. 3. Symmetrical microstrip gap layout

A. *Conventional Coupler*

Initially the 3 stage coupler with no compensation capacitors was investigated. The coupler was designed with the parameters evaluated in Section III and the coupler dimensions were optimized according to the pointer robust algorithm to achieve the desired coupling factor (S_{31}), a reasonable reflection (S_{11}) and the maximum possible directivity, while considering the transition effects between each segment of the coupler.

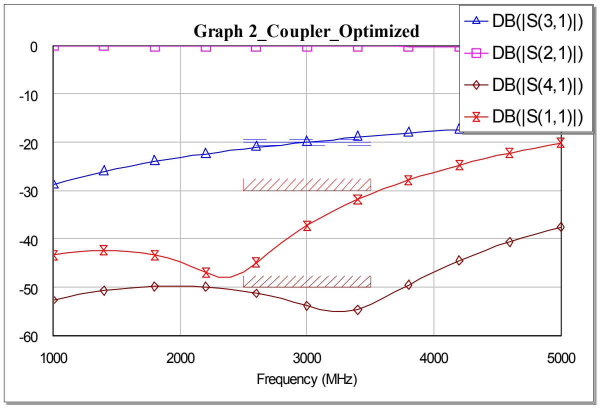


Fig. 4. S parameter response of the Coupler with compensation

The maximum achievable isolation throughout the bandwidth was -50 dB and hence a directivity of 30 dB as depicted in Fig. 4. The minimum value of the cost function after optimization was 1.40008.

B. *Coupler with a single Centre Capacitor*

In an attempt to improve the directivity of the coupler a single capacitance was placed symmetrically across the coupled arms at the center of each stage of the coupler to compensate for the phase velocities as depicted in Fig. 5. The capacitance was implemented as a gap capacitor to facilitate very small frequencies.

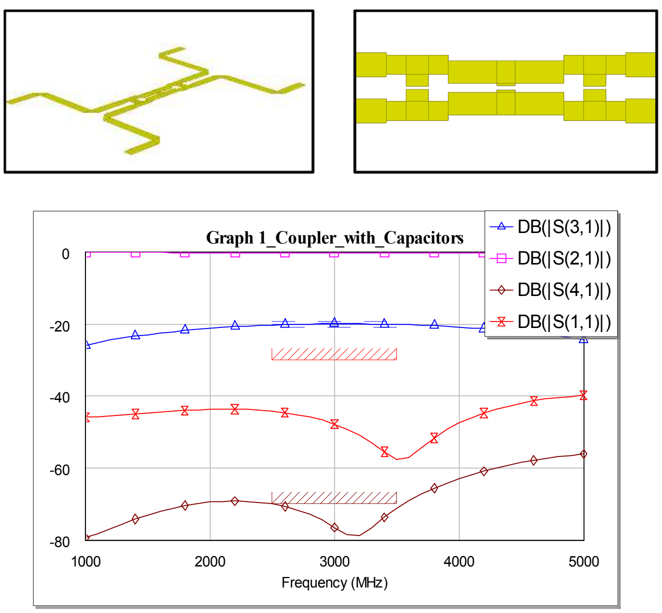


Fig. 5. Layout and performance of the coupler with a single centre capacitance

The maximum achievable isolation throughout the bandwidth was -70 dB and hence a directivity of 50 dB. This exhibited a 20 dB improvement of the directivity over the coupler with no compensation. The minimum value of the cost function after optimization process for a directivity of 50 dB was 0.0107 and exhibited a binomially flat coupling response.

C. *Coupler with a single optimally positioned Capacitor*

The position of the single capacitance was optimized as depicted in Fig. 6 for the purpose of minimizing the cost function further and improving the directivity.

The maximum isolation achieved was -80 dB and a directivity of 60 dB, resulting in a 10 dB improvement over the center positioned capacitance discussed earlier. The minimum value of the cost function after optimization for a directivity of 60 dB was 0.2747. It was also noted that optimizing the position of the single capacitor caused the coupler to lose its two-fold symmetry, however the asymmetric coupler as such was capable of achieving a low cost function with an improved directivity. In this case after optimization the capacitors of each stage was pushed to its extremities. It was observed that the coupler with the asymmetrically positioned single capacitor exhibits a significant improvement in directivity over the case of the symmetrically (center) positioned capacitor.

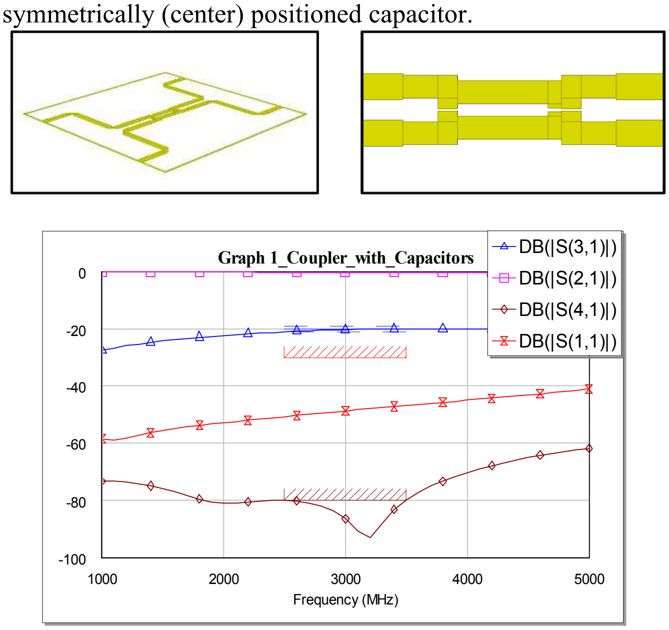


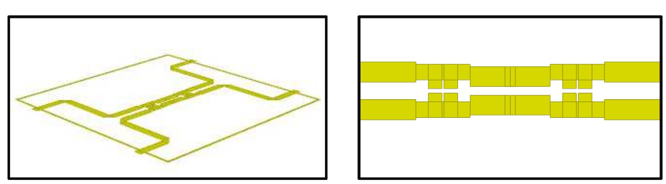
Fig. 6. Layout and performance of the Coupler with a single optimally positioned Capacitor

D. *Multiple optimally positioned capacitor*

Two optimally positioned Capacitors

1) Symmetric Coupler with optimally positioned Capacitors

In order to further enhance the directivity the possibility of placing a multiple number of capacitors was investigated. The placement of 2 capacitors along each coupled line sections was studied first. Two capacitors of identical capacitances were placed arbitrarily but symmetrically along the coupler and their positions were optimized.



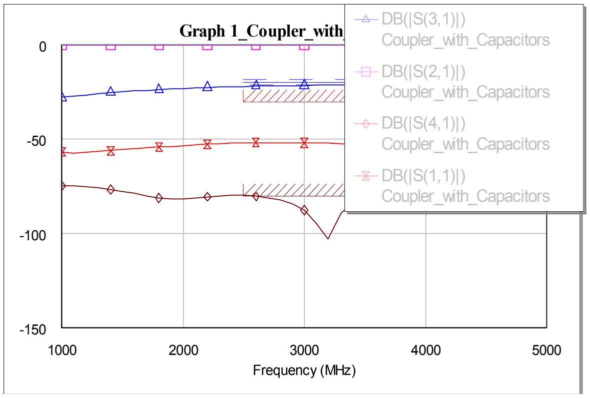


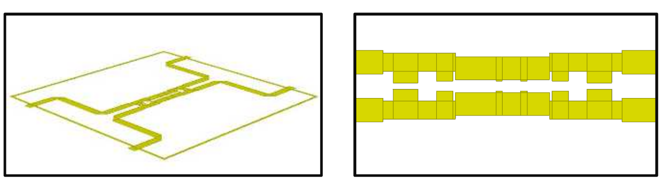
Fig. 7. Layout and performance of the Symmetric Coupler with 2 optimally positioned Capacitors

The maximum Isolation achieved was -80 dB with a directivity of 60 dB and a cost function of 2.80437, which was comparable with the case of the results of the optimally positioned single capacitance. In other words, the symmetric optimized 2 capacitor compensation exhibited no visible improvement over the case of the asymmetrically optimized single capacitor coupler even though it used one additional capacitive compensation.

2) Asymmetric Coupler with optimally positioned Capacitors

Here the 2 capacitors were optimally positioned without the restrictions of symmetry (Capacitors of different optimal capacitances were optimally positioned asymmetrically along the coupler). It was observed that by asymmetrically positioning unequal capacitances and optimizing them (with respect to the value of the capacitances and the position of the capacitances) yielded an improvement in the directivity by 10 dB, resulting in an isolation of -90 dB and an effective directivity of 70 dB. The asymmetry of the coupler is due to the asymmetries of the central section of the coupler.

It was observed that the asymmetric coupler once again displayed a significant improvement over the symmetric coupler for the case with two capacitors.



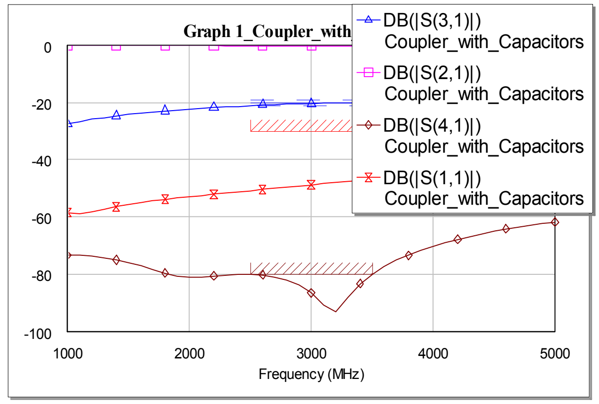


Fig. 8. Layout and performance of the Asymmetric Coupler with 2 optimally positioned Capacitors

3) Three optimally positioned Capacitors

The amount of capacitors was increased to three to verify the validity of the improved directivity performance in asymmetric couplers. The resulting coupler exhibited an increase in directivity by 10 dB, resulting in an isolation of -100 dB and an effective directivity of 80 dB. Once again it was concluded that the asymmetric coupler with 3 capacitances was capable of exhibiting a very good bandwidth directivity performance while maintaining the coupling factor and reasonable reflection.

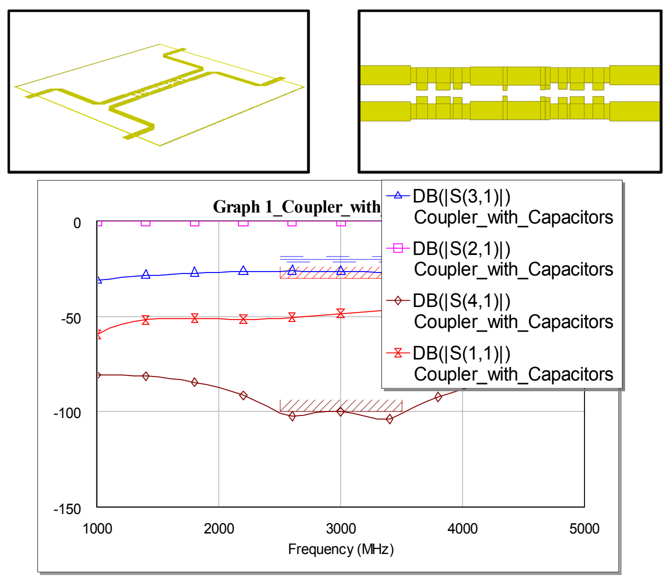


Fig. 9. Layout and performance of the Asymmetric Coupler with 3 optimally positioned Capacitors

It was also noted that the introduction of a third capacitor while improving the directivity did not contribute significantly to the improvement of the coupling bandwidth and that further increment in the amount of parallel capacitors while improving the isolation would slightly degrade the coupling effect of the coupler.

VI. RESULTS

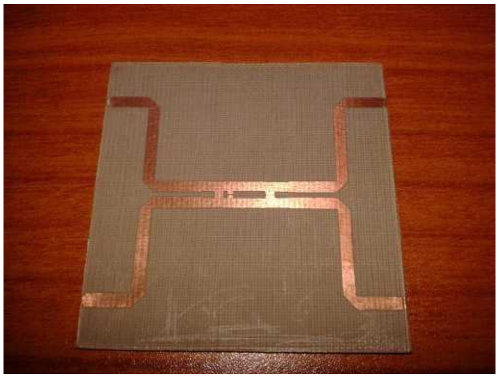


Fig. 10. Layout of the wideband coupler with a single capacitance asymmetrically optimized

VII. CONCLUSION

An accurate design for the directivity improvement via phase velocity compensation of coupled lines by means of parallel capacitances was investigated for wideband directional coupler applications. Although the main objective of this dissertation was to improve the directivity of the wideband coupler, the work focused on enhancing the directivity performance while simultaneously improving the bandwidth of directivity and coupling and maintaining a reasonably good reflection at the input port.

The enhanced bandwidth performance was achieved by the implementation of a multi stage coupler as opposed to the conventional single stage coupler. The directivity was improved by the use of a multiple number of optimally positioned capacitors along the coupler. In contrast to the previous approaches, the asymmetric positioning of the capacitors was considered to create an asymmetric coupler. The position of the capacitors were optimized with respect to the bandwidth-directivity performance and considerations of the coupling factor and the input port reflection. The optimization process relied on minimizing the cost function by employing the Pointer-Robust optimization approach which yielded a significant improvement over the previous approaches for both the symmetric and asymmetric couplers discussed.

It was also concluded that the asymmetric optimal positioning of capacitors (of optimal capacitance values) exhibited a significant improvement in the bandwidth-directivity performance for the cases with a single capacitor or a multitude of capacitors.

Compensated three stage couplers with 1, 2 and 3 capacitors implemented using gap capacitances were designed and simulated. Some of the asymmetric couplers were fabricated and measured. The finalized accurately simulated results yielding a directivity of above 80 dB over the entire bandwidth, is to the authors knowledge unmatched in literature. Thus the results confirm the novel optimization scheme and compensation approach. Ongoing investigations include the inclusion of the number of capacitors in the optimization process for the required bandwidth-directivity performance and the development of design equation for the asymmetric optimal positioning of capacitors.

TABLE I
ISOLATION & DIRECTIVITY FOR THE DESIGNS

Design	Isolation (dB)	Directivity (dB)
1. Conventional Coupler	-50	30
2. Coupler with Center positioned capacitor	-70	50
3. Coupler with optimally positioned capacitor	-80	60
4. Coupler with 2 optimally positioned capacitors	-80	60
5. Coupler with 2 optimally positioned capacitors	-90	70
6. Coupler with 3 optimally positioned capacitors	-100	80

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