# Wideband Quadrature Hybrid Coupler Using Microstrip-to-Slot Transition with Multilayer Technology

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***Abstract*- This paper presents the planar design of three-section quadrature hybrid coupler for frequency operation of 2 to 6 GHz. This coupler offers a tight coupling of 3 dB and measured return loss better than 13 dB which occupies the size of 50 mm × 20 mm excluding the 50 Ω SMA ports. The proposed quadrature hybrid design is implementing the microstrip-to-slotline transition with multilayer structure. The configuration of this design consists of two substrates layers and one layer ofa ground plane in the middle of the two substrates. Where, the proposed design is formed by rectangular-shaped microstrip line at the top and bottom with rectangular slot at the common ground plane. CST Microwave Studio software is used for coupler design and optimization. Then, the simulated results are compared to the measured results for verification. The characteristics of electric field for odd and even-mode are presented via cross section analysis of the coupler design.**

***Keywords- Cross-section Analysis; Coupler; Wideband; Microstrip-slot; Quadrature Hybrid***

## I. INTRODUCTION

Communication systems in modern technology are usually connected with the microwave components with passive configurations. This passive form of the device is to ensure the compact and optimum performance of the system. One of the microwave components that are usually used is directional coupler, which has a function to combine or split the input signal [1-2]. Directional coupler has shown a great demand in many microwave applications such as six-port networks, beam forming networks, modulators and demodulators. For the case of a directional coupler with wideband capability, it is able to maintain the wide operating bandwidth even when integrated with other systems. Furthermore, the passive planar form of directional coupler, which is realized in stripline or microstrip offers an advantage for easy installation. One of the considerations in designing a coupler is to achieve a tight coupling coefficient for the designated frequency band. Tight coupling can be achieved using tandem configuration as presented in [3-5]. One of the tandem designs has implemented the technique of symmetry wiggly coupled-line, which is presented by Uysal and Aghvami in [3]. However, the requirement of this technique is to have wire for crossovers. This may lead to low tolerance in the fabrication and installation stage. In addition to that, the crossover also limits the operation bandwidth of the proposed coupler. In other words, the symmetry wiggly coupled-line offers trade-off between tight coupling and wide bandwidth. Since tight coupling and wide bandwidth are required in this design, another method to solve this problem is required.

Owing to the problems, the technique of microstrip-to-slot transition [6-13] is introduced to improve the limitations of coupling and wide frequency range. This technique not only offers tight coupling and wider bandwidth but also promises compact and small size of a directional coupler. The significant difference between those designs is the patch size at top and bottom layer together with slotline at middle ground layer controls the offered flat coupling coefficient over very broad frequency band. In this research, the directional coupler with 90º phase difference is presented. It is also known as the three-section quadrature hybrid directional coupler that can operate for wideband frequency range of 2 to 6 GHz. The technique of microstrip-to-slot transition technology is implemented into the design of coupler with a multilayer configuration. Even and odd mode of excitation is analyzed to figure out the electric field characteristics. Furthermore, the initial dimensions of the quadrature hybrid coupler are determined by referring to the even and odd mode equations in [14]. Implementing the initial calculated dimensions, the design of coupler is simulated and optimized using CST Microwave Studio software. The characteristics of S-parameter and phase difference are studied and the effect of patch size is analyzed. This coupler offers a wideband of 2 to 6 GHz with measured return loss better than 13 dB, tight coupling of 3 dB and 50 mm x 20 mm of overall size.

## II. SUBSTRATES PROPERTIES

Prior to the design of any microwave components, it is essential to study the properties of the used planar dielectric material. This is required in choosing the most suitable substrate to obtain the optimum performance. In this research, a substrate of Rogers RO4003C is loaded to CST Microwave Studio simulator and used for fabrication via wet etching technique. Summary of the properties of Rogers RO4003C is presented in Table 1.

TABLE I PROPERTIES OF ROGERS RO4003C

| **Composition** | **Thermoset polimer ceramic filler woven glass** |
|---|---|
| Relative dielectric constant, $\varepsilon_r$ | 3.38 |
| Tolerance on dielectric constant +/- | 0.05 |
| Dissipation factor tan, δ | 0.0027 |
| Temperature coefficient of $\varepsilon_r$(ppm/C) | 40 |
| Mass density (gr/cc) | 1.79 |
| Specific heat (J/g/ºC) | - |
| Thermal conductivity (W/mºC) | 0.64 |
| Coefficient of thermal expansion PPM/ºCx/y/z | 11/14/46 |

This substrate can be used for applications that required soldering or wire bonding. Referring to Table 1, Rogers RO4003C is composed of woven glass/ceramic filled with thermoset materials, which are suitable for high frequency and very high glass transmission temperature (Tg> 280ºC). It also has stable electrical properties over frequency. These important points drive the choice of RO4003C in the design. On top of that, it is very suitable for the wideband applications with multilayer configurations and the involvement of soldering work.

Rogers RO4003C has appropriate Z-axis expansion, which is the key point in using multilayer designs. Besides that, it has low thermal coefficient of dielectric constant. These suitable properties make Rogers RO4003Cbechosen for the proposed quadrature hybrid coupler. Rogers RO4003Cwith thickness of 0.508 mm and conductive coating of 0.017 mm are used.

## III. WIDEBAND QUADRATURE HYBRID COUPLER DESIGN

The structure of the multilayer microstrip-slot quadrature hybrid coupler is shown in Fig. 1 with the common ground plane in between substrates layer. The three layers of the conductor are interleaved between the layers of Rogers RO4003C substrate. The signal is coupled through the substrate via the slotline placed at the middle layer, which is representing the ground layer.

Fig. 2 shows the quadrature hybrid from the top view (z-axis) with the separated layers to show the overall view of the top, slotted ground plane at the middle layer and the microstrip patches at bottom layer. The three-section of rectangular-shaped microstrip patch is identical at the top and bottom layer except the use of 50 ohm microstrip line connected with the ports. The function of slotline at the ground plane in middle layer is to provide broadside coupling as the input signal is coupled from top microstrip patch to bottom microstrip patch and vice versa.

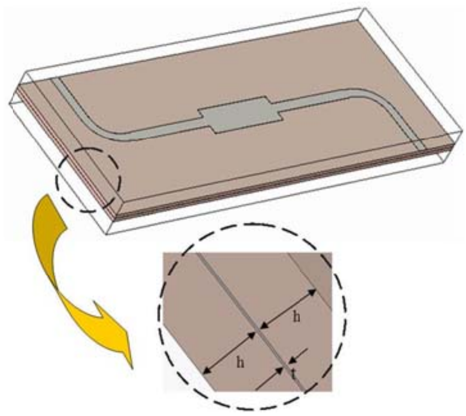



Fig. 1 The structure of the quadrature hybrid shows the two substrate layers that are sandwiched by the three conductor layers and one layer of conductive coating in the middle representing the ground plane

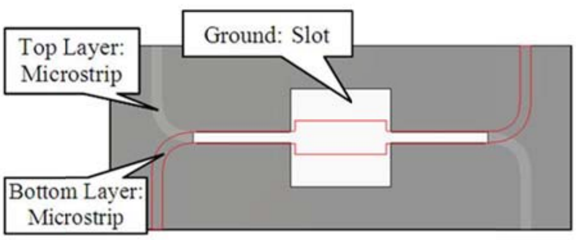



Fig. 2 Top view of the proposed quadrature hybrid coupler with the transparent overview of each layer

In this research, the design of quadrature hybrid coupler is based upon the properties of Rogers RO4003C substrate that comes with the important compositions of dielectric constant of 3.38, loss tangent of 0.0027, substrates thickness, $h$ of 0.508 mm and thickness of conductor coating, $t$ of 17µm. The final quadrature hybrid coupler size excluding the ports occupies an area of 50 mm × 20 mm. The width of the slotline at ground plane and width of the microstrip line at the top and bottom layer is the parameter to control the coupling coefficient. Meanwhile, the designated frequency range is controlled by the number of sections and the length of the designed coupler.

Therefore, the width of slotline and microstrip line is initially calculated based on the characteristic of the odd and even-mode analysis, common microstrip line equation and conformal transformations [12, 14]. The different widths of the microstrip and slotline create the different characteristic impedances and coupling coefficients. The characteristic impedance of odd mode ($Z_{0o}$) and even mode ($Z_{0e}$) are obtained by referring to each excitation mode. The equations of characteristic impedance of both modes are expressed in equation (1) to (4) [14]:

$$Coupling\ factor, C(dB) = -20log_{10}\left(\frac{Z_{0e}-Z_{0o}}{Z_{0e}+Z_{0o}}\right) \tag{1}$$

$$Z_o = \sqrt{Z_{0e}Z_{0o}} \tag{2}$$

$$Z_{0e} = Z_0\left(\frac{1+10^{-\frac{C}{20}}}{1-10^{-\frac{C}{20}}}\right)^{0.5} \tag{3}$$

$$Z_{0o} = Z_0\left(\frac{1-10^{-\frac{C}{20}}}{1+10^{-\frac{C}{20}}}\right)^{0.5} \tag{4}$$

where, $Z_0$ is the 50 ohm characteristic impedance of microstrip line. By having the characteristic impedance (odd mode and even mode), the width size of the microstrip and slotline can be determined, which will be explained next.

First, the initial dimensions of the quadrature hybrid coupler are determined. The length of microstrip patch is determined in a straightforward manner as a quarter of the effective wavelength, $\lambda_e$ at the centre frequency. By using these initial dimensions, the simulation and optimization of the design are carried out in CST Microwave Studio. The crucial dimension is the width of the microstrip line, $w_m$ (labeled as $w_{t1}$ and $w_{b1}$ in Fig. 3) that is responsible for the characteristic impedance of the $Z_{0o}$ [14]. The common microstrip equation (5) and (6) can be used by assuming that the slotline is closed by conducting ground plane. Equation (5) and (6) are presented as follows:

$$\frac{w_m}{h} = \frac{2}{\pi}\left[B-1-\ln(2B-1)+\frac{\varepsilon_r-1}{2\varepsilon_r}\left\{\ln(B-1)+0.39-\frac{0.61}{\varepsilon_r}\right\}\right] \tag{5}$$

$$B = \frac{377\pi}{2Z_{0o}\sqrt{\varepsilon_r}} \tag{6}$$

where, $h$ and $\varepsilon_r$ are the substrate thickness and the relative permittivity of the substrate, respectively. After obtaining the dimension for the microstrip line, the width of the slotline, $w_s$ (labeled as $w_{g1}$ in Fig. 3) can be determined using conformal transformations from even-mode characteristics impedance, $Z_{0e}$ as in Equation (7) and (8).

$$Z_{0e} = \frac{60\pi}{\sqrt{\varepsilon_r}}\frac{K(k)}{K'(k)} \tag{7}$$

$$\frac{K(k)}{K'(k)} = \begin{cases} \frac{2}{\pi}\ln\left\{2\sqrt{\frac{1+k}{1-k}}\right\}, & for\ 0.707 \le k \le 1 \\ \frac{\pi}{2ln\left\{\frac{1+\sqrt{1+k^2}}{1-\sqrt{1-k^2}}\right\}}, & for\ 0 \le k \le 0.707 \end{cases} \tag{8}$$

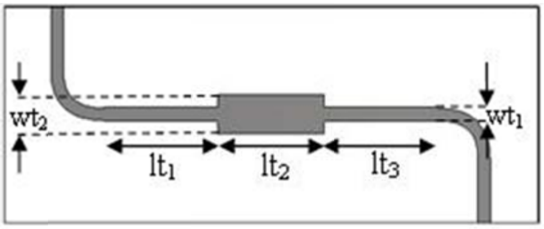
From equation (7) and (8), the $K(k)$ is the first kind elliptical integral, where $K(k)$=$K(\sqrt{1-k^2}$. To solve equation (8), the unknown parameter, $k$ is required by referring to equation (9) as follows:

$$k = \sqrt{\frac{\sinh^2\left(\frac{\pi w_s}{4h}\right)}{\sinh^2\left(\frac{\pi w_s}{4h}\right)+\cosh^2\left(\frac{\pi w_m}{4h}\right)}} \tag{9}$$

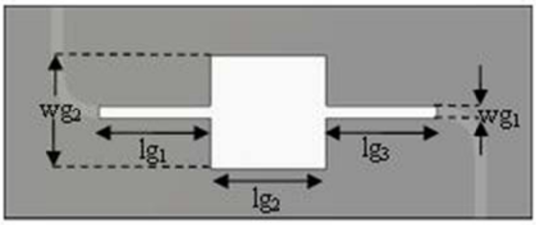
From the observation in Fig. 2, the length of slotline is chosen slightly longer than the microstrip line section length. The different lengths of the microstrip and slotline will introduce gradual transition of impedances from one section to another. The gradual change of impedance can reduce losses compared to the abrupt change of impedance. This method can also reduce the effect of the different phase velocities for odd and even mode.

Then, the final and optimized configuration of the three-section quadrature hybrid coupler is illustrated in the Fig.3.The dimensions of the microstrip patch at top and bottom layer are identical, where $wt_1 = wb_1 = 1.35$ mm, $wt_2 = wb_2 = 3.67$ mm, $lt_1 =$

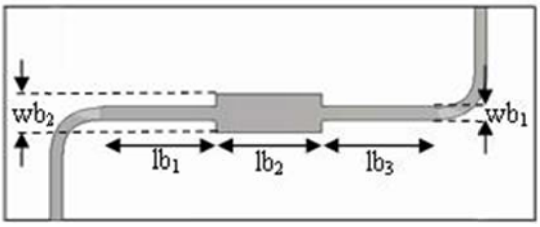
$lt_3 = lb_1 = lb_3$ = 10.73 mm and $lt_2 = lb_2$= 9.97 mm. Meanwhile, the slotline dimension at the ground plane is as follows: $wg_1$ = 1.18 mm, $wg_2$ = 10.74 mm, $lg_1 = lg_3$ = 10.54 mm and $lg_2$ = 10.93 mm.




(a)




(b)




(c)

Fig. 3 The dimensions of quadrature hybrid coupler: (a) top layer, (b) ground plane(middle layer) and (c) bottom layer

## IV. CROSS-SECTION ANALYSIS OF QUADRATURE HYBRID COUPLER DESIGN

Since the dimension of microstrip and slotline is referred to as the even and odd mode characteristic, it is important to determine the electric field characteristic. The best way to study the electric field behavior is using the cross section analysis for both excitation modes. The odd-mode excitation for the designed coupler is performed by replacing the ground slot with the electric wall. The simulated electric field for odd mode excitation is shown in Fig. 4 at the cross-section of rectangular-shaped quadrature hybrid coupler at the centre frequency of 4 GHz. The 4 GHz is used to show the odd and even-mode because the initial dimensions are calculated based on this frequency. From the observation, the electric field is almost perpendicular to the strip and the ground position.

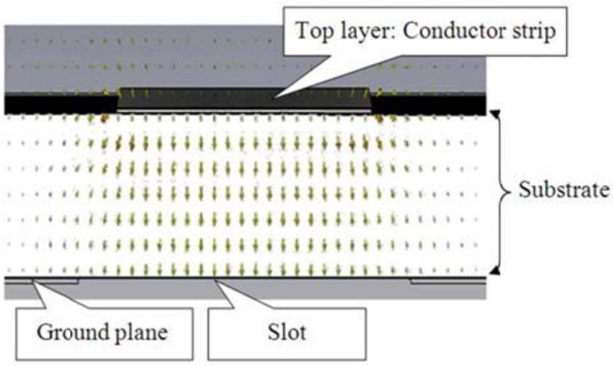



Fig. 4 Simulated electric field during odd-mode excitation at the cross-section of the rectangular-shaped coupler at the centre frequency of 4 GHz

In this case of odd-mode excitation, the microstrip patches at top and bottom layer of the coupler as shown in Figs. 2, 3(a) and 3(c) become a microstrip line with characteristic impedance of $Z_{0o}$. The dimension of microstrip width, $w_m$ can be determined from $Z_{0o}$ by using common microstrip line equation [14] as expressed in equation (5)-(9). In the parallel plate region between the microstrip patch at the top and bottom layer, the small value of impedance of odd mode, $Z_{0o}$ is less affected by the fridge effect. The condition of this mode is the size of patch width (microstrip), $w_m$ is larger compared with the thickness of substrate, *h* [14].

The difference between even-mode excitation and the odd-mode excitation is the magnetic wall which is applied to the slot at the ground plane. From the observation in that region in Fig. 5, the launched electric field from the top conductor strip is pushed outside of the slot region to the conductor area at the ground plane. This happens because the magnetic wall forming the lower plate does not allow the electric field to be perpendicular to its surface as shown in Fig. 5.

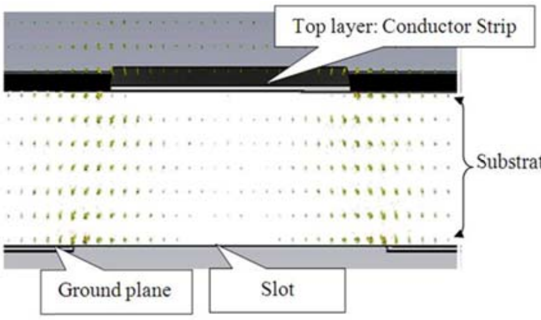



Fig. 5 Simulated electric field of even-mode at the cross-section of the quadrature hybrid coupler at the center frequency of 4 GHz

## V. ANALYSIS OF COUPLER DESIGN

The next concerned investigation of the designed quadrature hybrid coupler isto analyze the effect of the varied length of the middle section microstrip patch, where the length of $lt_2$is equal to $lb_2$ ($lt_2$= $lb_2$). In this design, the length is expected to control the operating frequency range. Furthermore, with optimum length of middle section microstrip patch, the effect of different phase velocities for both propagation modes of odd and even mode can be reduced.

Owing to the aim to examine the effect of length in the signal propagation and performance, the length of middle section microstrip patch at top and bottom layer ($lt_2 = lb_2$) varies from 8 mm to 20 mm with step of 4 mm and the performances of $S_{11}$, $S_{21}$and $S_{31}$ characteristics are observed as presented in the following Figs. 6 to 8.

From the observation, the optimum $S_{11}$ can be achieved as the length is increased to 20 mm. At 8 mm length of $lt_2$, the worst performance of return loss, which is just slightly better than 10 dB can be noted. The bandwidth is getting wider when the length of microstrip patch of $lt_2$ and $lb_2$ up to 20 mm is increased. This confirms that the main microstrip patch controls the operating frequency range of the coupler, which corresponds to the bandwidth performance. The changes in length create step-impedance, thus the effect on the bandwidth is expected. Meanwhile, the length analysis for $S_{21}$ and $S_{31}$characteristic of the coupler does not show a significant change to the performance as the length is increased. The magnitude of $S_{21}$ and $S_{31}$varies between 3±1dB. Thus, length of $lt_2$ does not influence the performance of $S_{21}$ and $S_{31}$ in coupler design.

In addition to length, it is important to look into the effect of airgap between the two substrates to the return loss performance of the designed coupler. The prototype of designed coupler is using plastic screws to attach the two substrates together. Therefore, there is a tendency of air gap to be existed between the substrates. In this analysis, the airgap between the two substrates varies from 0 to 1 mm with step of 0.25 mm by assuming that the airgap is less than 1 mm. From the observation, it is noticed that the appearance of airgap will decrease the return loss. However, the simulation shows that the return loss is better than 10 dB if the airgap is less than 1 mm.

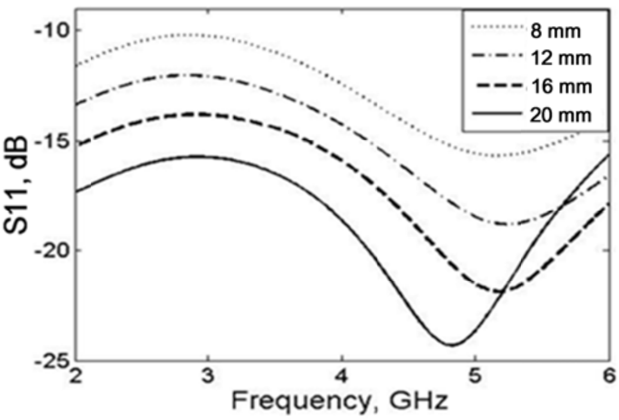



Fig. 6 The simulated length analysis for $lt_2$and $lb_2$, in term of $S_{11}$ performance, where $lt_2$= $lb_2$

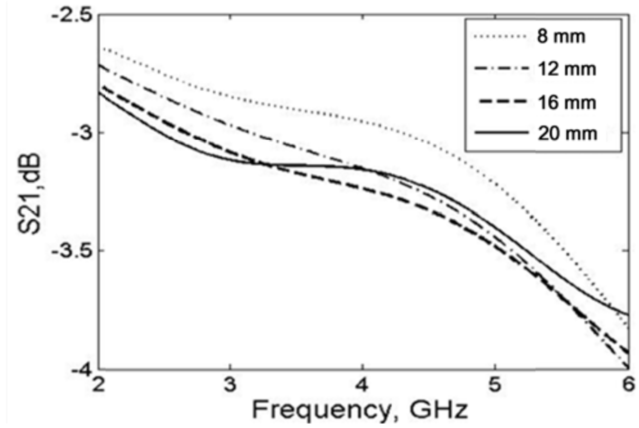



Fig. 7 The simulated length analysis for $lt_2$ and $lb_2$, in term of $S_{21}$ performance, where $lt_2 = lb_2$

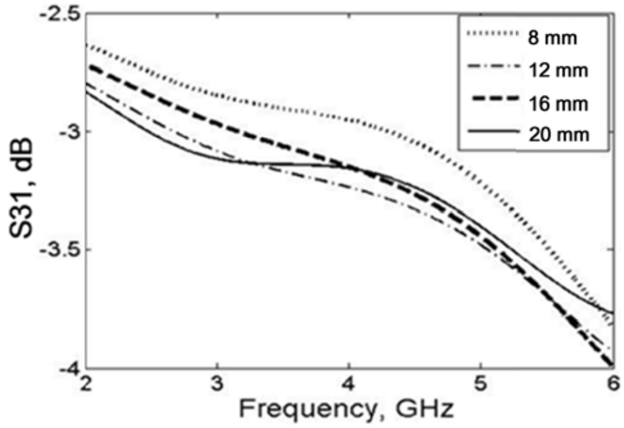



Fig. 8 The simulated length analysis for $lt_2$ and $lb_2$, in term of $S_{31}$ performance, where $lt_2 = lb_2$

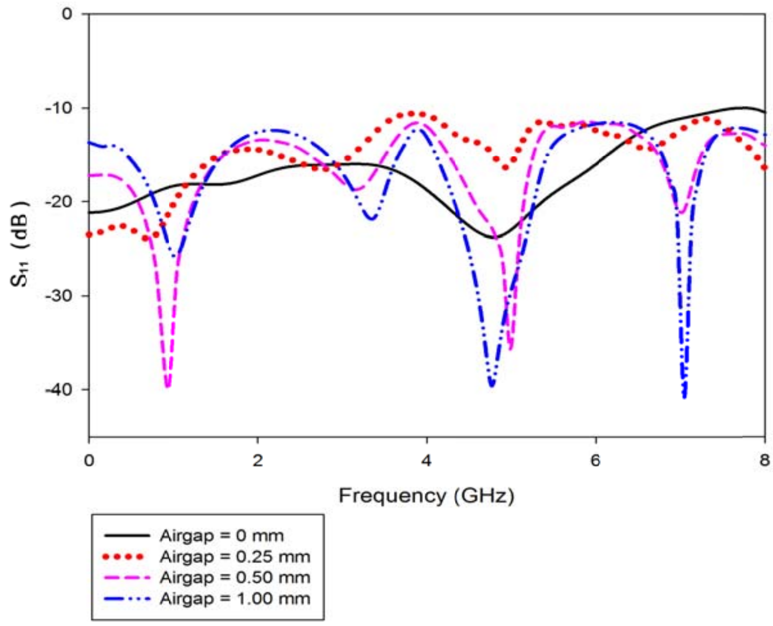



Fig. 9 The simulated $S_{11}$ when airgap between the two substrates varies

## VI. RESULTS OF WIDEBAND QUADRATURE HYBRID COUPLER

The prototype of the quadrature hybrid is fabricated using Rogers RO4003C substrate and connected with the 50Ω SMA ports as shown in Fig. 10. The two layer substrates are attached with the plastic screw to make sure the layers are tightened and less air gap between the substrates.

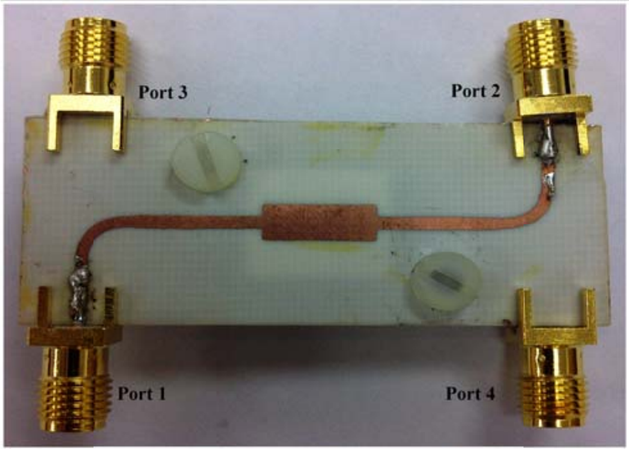



Fig. 10 Prototype of the quadrature hybrid

The simulated and measured wideband performance of the designed three-section quadrature hybrid coupler for the frequency range of 2 to 6 GHz is shown in Figs.11 and 12. As observed from S-parameter in Fig. 11, the lowest value for simulated return loss and isolation is approximately at 5.5 GHz, while the lowest value for measured return loss and isolation for the fabricated design shows frequency shift from 5.5 GHz to 4.3 GHz. The frequency shift can occur because of inaccurate value of permittivity used in simulation and some misalignment of the microstrip line. However, the performances are comparable, since both return loss and isolation are better than 13 dB for the designated frequency range.

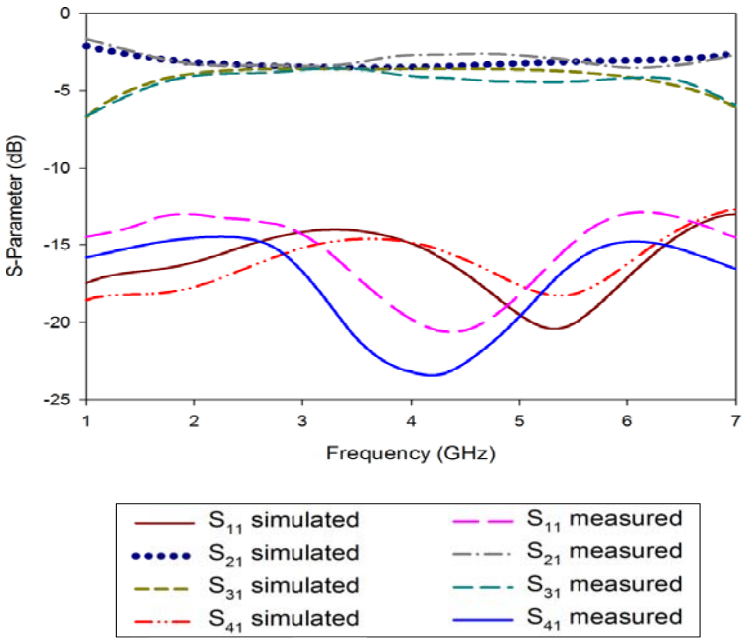



Fig. 11 S-Parameter performance of the designed quadrature hybrid coupler from 2 to 6 GHz frequency range

The through and coupling performances of the prototype coupler are shown in Fig. 11 with simulation results of $S_{21s} = 3\pm1$ dB and $S_{31s} = 3\pm1$ dB, respectively. Whereas, the measured through and coupling performances are $S_{21m} = 3\pm1.5$dB and $S_{31m} = 3\pm2$ dB, accordingly. Meanwhile, the good phase difference in simulation can be observed. The designed coupler offers phase different characteristics between the through and coupled ports of 90° ± 1.5°, but the measured shows slightly higher deviation with ±4°. The deviation can be noted as it is proportional to frequency. The graph of the simulated and measured phase difference is presented in Fig. 12.

## VII. CONCLUSION

The design of three-section quadrature hybrid coupler using multilayer microstrip-slot technology has been presented. The final design is optimized and achieves the required design goal using CST Microwave Studio simulator. The behaviors of odd and even excitation mode at the center frequency 4 GHz are presented at cross section of the designed coupler. The centre frequency, 4 GHz is used to analyze the behaviors of odd and even since the initial dimensions are determined at this frequency. The performance of S-parameters and phase difference between output ports are evaluated and verified via real measurement for the frequency range of 2 to 6 GHz.

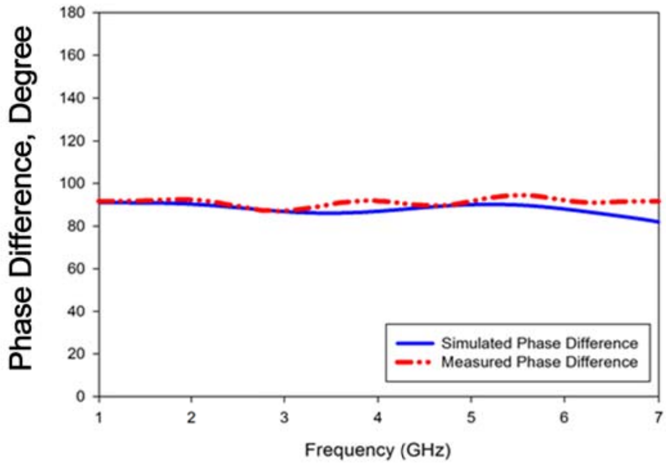



Fig. 12 Phase difference characteristic of the designed quadrature hybrid coupler between port 2 and port 3 from 2 to 6 GHz frequency range

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