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Implementation of Inkjet-printed 3dB Coupler with Equal Power Division and 45^0 Output Phase Difference

S. A. Babale[*1], S.K.A. Rahim[2], M. Himdi[3], S. H. Lawan[1], F. D. Sani[1] and A. D. Usman[4]

[1]Department of Electrical Engineering, Faculty of Engineering,
Bayero University Kano, 3011, Kano, Nigeria.
[2]Wireless Communication Centre (WCC) Faculty of Electrical Engineering,
University of Technology Malaysia, Skudai Campus, 81310, Johor, Malaysia.
[3]Institute of Electronics and Telecommunications of Rennes (IETR),
Université de Rennes I, France.
[4]Department of Electronics and Telecommunications Engineering,
Ahmadu Bello University Zaria, Nigeria.

*corresponding author: sababale.ele@buk.edu.ng

Abstract— Implementation of a 3dB coupler with flexible phase difference was presented in this paper. The coupler has equal power division and output phase difference of 45^0 as against the conventional coupler. It has advantage in many applications that require phase delay like phased antenna array, and beamforming network without necessarily requiring additional phase shifters. It was designed and implemented using the instant inkjet printing technique on a transparent Polyethylene terephthalate (PET) substrate specially coated with resin. The coupler's response shows very good return loss and isolation of $-28dB$ and $-48dB$ respectively. A bandwidth of 31.33% was achieved around the center frequency. However, an output phase difference of 45^0 was recorded with a slight phase variation of about $\pm 1^0$ within the specified bandwidth.

***Index Terms*—3dB coupler, phase differences, silver-nano, return loss and isolation.**

1. Introduction

HYBRID couplers and power dividers are networks used to divide a given power within a system. However, conventional couplers differ from power dividers due to the 90^0 phase shift they provided at the output ports. It forms an integral part in most of the present microwave devices and many communication networks [1], [2].

$3dB/90^0$ couplers have been reported widely with different techniques like substrate integrated waveguide[3], coplanar waveguide [4], microstrip [5], and inkjet printing technique[6]. However, some researchers focus on size reduction [7], [8], dual-band operations[9], wideband applications [10], and harmonic suppression [11]. Phase shifter with arbitrary phase-difference is needed in most of the measurement equipment [12], smart antenna systems [13], and many industrial applications. Despite their importance, little has been done on arbitrary output phase-difference characteristics. Yuk et al proposed a hybrid coupler with flexible output phase-difference [14]. But, suffered some drawback, and corrected in [15]. Also, the phase difference below 90^0 and the fixed power division (3dB) restricts its applications.

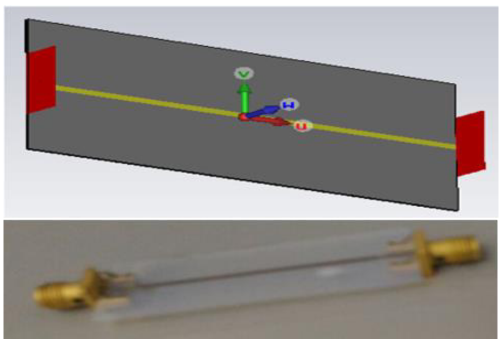
In this research, some set of equations for couplers utilizing non-standard phase-difference and arbitrary power division is proposed and validated by prototyping the coupler using Inkjet-Printed silver-nano technology. Employing 45^0 couplers, the design of 4×4 Butler matrix is possible without phase shifters. This will reduce the dimension of the device and hence the transmission loss by shortening the transmission line path.

2. Inkjet Printing Technique

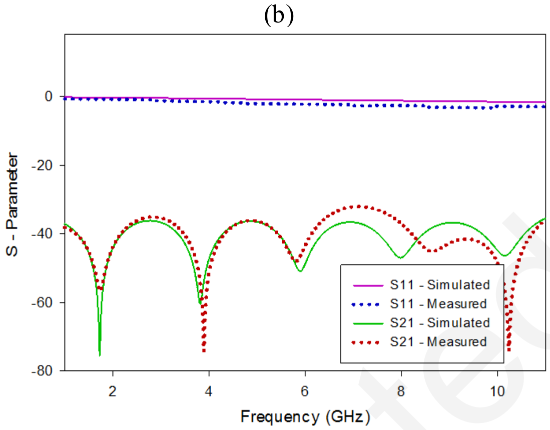
The technique presented in this paper uses a chemical sintering process based on conductive silver nanoparticles ink utilizing an inkjet printer by Brother Industries, Ltd. (model: DCP–J140w). The choice of this type of printer is because of its low cost and availability as compared to another chemical sintering process [16], Another advantage of this type of printer is the effectiveness of its nozzles, that eject a moderate amount of ink volume at a given time which translates to deposition of the conductive ink in a manner the provide an undistorted conductive path [17]. Unlike other printing techniques that require thermal curing, here, the ink dried-up immediately and formed a conductive pattern.

Fig 1 shows the printer setup and a 50cm uniform Transmission Line (TL). The TL was fabricated on the transparent PET substrate to ascertain the system's workability before evaluating complex structures. The measured results illustrate good results throughout the entire frequency band.

(a)



(b)



(c)

Fig. 1. (a) The Brother printer DCP–J140w (b) layout and photograph of a 50Ω microstrip TL simulated and prototyped with the PET substrate. (b): The S- parameter for the microstrip TL.

3. Design Equations

The design equations are formulated and used for the design of the $3dB$ coupler having non-standard 45^0 output phase-difference.The schematic of the coupler shown in Fig. 2has impedances Z_1, Z_2 and Z_3, and electrical lengths areθ_1, θ_2 and θ_3.we assumed $Z_2 = Z_3$ for simplicity. The criteria set to be achieved is to make the power division, $p(f)$ and the output phase difference, ψ of the coupler to be variables. These parameters are defined by equation (1) and (2) [18].

$$\psi(f) = \angle S_{21} - \angle S_{31} \quad (1)$$

$$P(f)^2 = \left|\frac{S_{21}}{S_{31}}\right|^2 \quad (2)$$

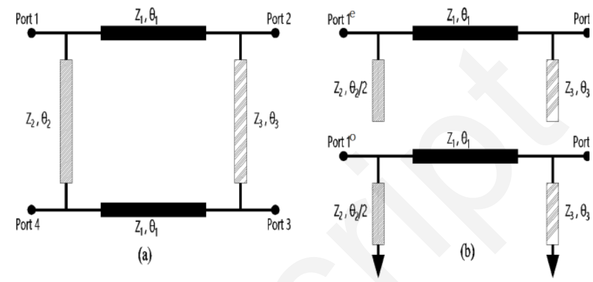


Fig. 2: (a) Schematic diagram of the proposed coupler; (b) The even/odd mode equivalent.

Referring to Fig 2b, the transmission and reflection characteristics of the even and odd mode are obtained by using the ABCD matrix of the network from the individual contributions of the coupler's arms as shown in equation (2).

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = [T_a][T_b][T_a] \quad (3)$$

Considering only the even mode, the ABCD parameter for the open arm of the transmission line, $[T_a]$ is given by

$$[T_a] = [ABCD] = \begin{bmatrix} 1 & 0 \\ jY_1^e & 1 \end{bmatrix} \quad (4)$$

Also, the ABCD parameter for the horizontal arm of the transmission line, $[T_b]$is given by

$$[T_b] = [ABCD] = \begin{bmatrix} \cos\theta_2 & jZ_2{}^e \sin\theta_2 \\ \dfrac{j\sin\theta_2}{Z_2{}^e} & \cos\theta_2 \end{bmatrix} \quad (5)$$

Substituting the values of $[T_a]$ and $[T_b]$from equations(4) and (5) give the overall ABCD parameter as follows:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_e = \begin{bmatrix} 1 & 0 \\ jY_1^e & 1 \end{bmatrix} \begin{bmatrix} \cos\theta_2 & jZ_2{}^e \sin\theta_2 \\ \dfrac{j\sin\theta_2}{Z_2{}^e} & \cos\theta_2 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ jY_1^e & 1 \end{bmatrix} \quad 6)$$

Where the admittance,$Y_1^e = \tan\left(\frac{\theta_1}{2}\right)/Z_1{}^e$and the superscript 'e' represents the even mode excitation.

Similarly, the odd mode ABCD parameters are can be obtained. However, by simple substitution of $\tan\left(\frac{\theta_1}{2}\right)$ with $-j\cot\left(\frac{\theta_1}{2}\right)$ in equation (6), the ABCD parameter for the odd mode excitation could be obtained.

From the definition of s-parameter, and applying matching condition, equations (1) to (6) are manipulated to obtain the design equations as follows:

$$Z_2 = Z_0 P|\sin\psi| \tag{7}$$

$$Z_1 = Z_3 = \frac{Z_0 P \sin\psi}{\sqrt{1 + P^2 \sin^2\psi}} \tag{8}$$

$$\theta_1 = \pi - \tan^{-1}\left(\frac{(Z_0 \tan\psi)}{Z_1}\right) \tag{9}$$

$$\theta_2 = \frac{\pi}{2} \tag{10}$$

$$\theta_3 = \tan^{-1}\left(\frac{(Z_0 \tan\psi)}{Z_1}\right) \tag{11}$$

4. Design of the Modified Coupler

The impedances, electrical lengths, and other parameters of the coupler were obtained from (7) - (11). ψ was innitially set to 45^0 and the lineimpedance, Z_0 was set to 50Ω. Assuming $p = 1$, the parameters of the coupler are obtained and presented in Table 1.

Table 1. Parameters of the Proposed Coupler

Parameter	Z1 (Ω)	Z2 (Ω)	Z3 (Ω)	θ_1 (deg)	θ_2 (deg)	θ_3 (deg)
Value	35.36	28.87	28.87	90^0	120^0	60^0
Parameter (mm)	AL1	AW1	BL1	BW1	PL1	PL2
Value	5.634	1.084	9.413	0.925	2.662	3.886
Parameter (mm)	PL3	PW1	L1	L2	L3	W
Value	5.867	0.667	2.492	4.750	2.817	1.084

These Impedances along with other parameter are used to obtain physical width and lengths of the coupler. Fig. 3 shows the layout and photograph of the fabricated coupler. It is worth notice that the design equations established could also be used to design couplers with any power ratio like 6dB or 10dB with any arbitrary output difference from $0 - 360^0$. Fig. 3 shows the layout and photograph of the fabricated coupler.

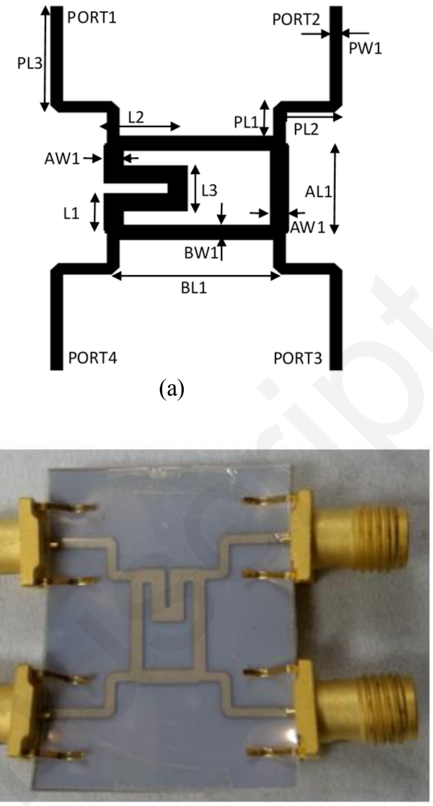
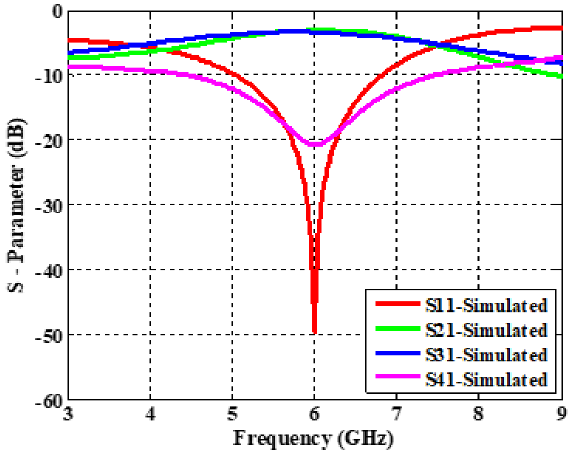


Fig. 3: (a) Schematic layout of the proposed 45^0 coupler, (b) photograph of the front view of the fabricated coupler

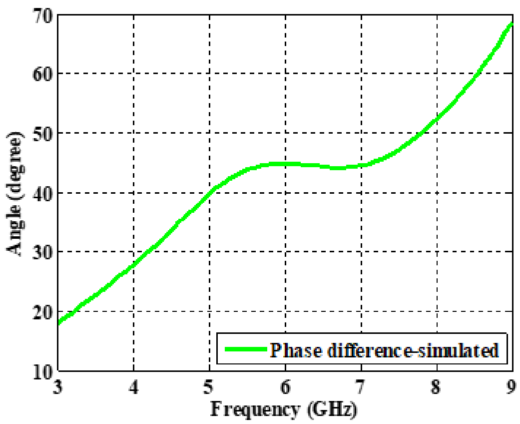
The coupler was simulated and optimized from these parameters using CST studio and was fabricated using the instant inkjet printing technique on the transparent PET substrate having a dielectric constant of 2.71, tangent loss of 0.043, and a thickness of 0.125mm. The printing technique used for the prototype is of low cost and readily available. It provides a means of fast prototyping of electronic circuitries since the process does not require any thermal curing.

5. Results and Discussion

The results obtained from the simulator are shown in Fig. 4. From these results, a very good return loss and isolation of $-28\,dB$ and $-48\,dB$ are obtained respectively, with a fractional bandwidth of about 31.33% and 3dB coupling within the frequency range of 5.09 GHZ to 6.97 GHz. However, the phase difference at the output ports is 45^0 as predicted in theory with a little phase variation, of about $\pm 1^0$ within the operational bandwidth.



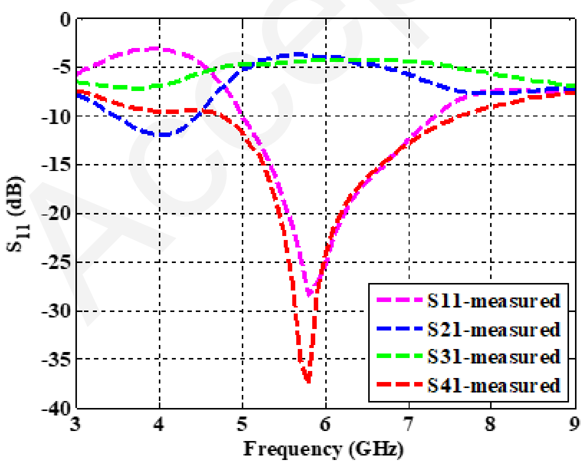
(a)



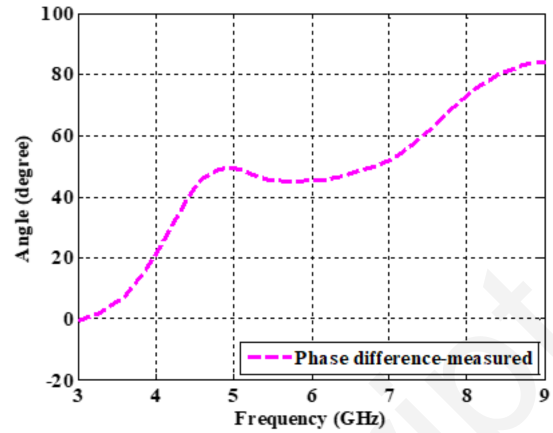
(b)

Fig. 4: S- Parameter result of the coupler (simulated), (a) the magnitude (dB); (b) the Phases difference (degrees).

For verification, the coupler was measured using a Vector Network Analyzer (VNA) to validate the result obtained from simulations and is shown in Fig. 5. The performances of the proposed coupler compared to other couplers is summarized in Table 2.



(a)



(b)

Fig. 5: The S- Parameter for the Proposed Coupler (measured), (a) Magnitude (dB); (b) Phases difference (degrees).

Table 2. Comparison with other published Couplers

Ref.	Freq.	Fabrication/ Technique	Return loss	Area (mm^2)	Output Phase difference
[4]	6 GHz	Etching, CPW technology	$-32dB$	24×39.8	Fixed
[6]	6 GHz	Inkjet Printed, requires curing at 150^0C	$-20dB$	29.7×39	Fixed
[7]	@ 6 GHz	Inkjet Printed, requires curing at 150^0C	$-21dB$	34.4×17.8	Fixed
[11]	7 GHz	Etching, with coupled slot line	$< -10\ dB$	40×50	Fixed
This work	6 GHz	Instant Inkjet Printed, without curing	$-28dB$	13.3×14.2	Flexible

6. Conclusion

A 3-dB hybrid coupler with 45^0 output phase difference was designed and implemented using an instant inkjet printing technique on a transparent Polyethylene terephthalate (PET) substrate specially coated with resin. The printing technique used for the prototype is of low cost, readily available, and will provide a means of fast prototyping of electronic circuitries as the process does not require any thermal curing. Having non-conventional output difference from the coupler's perspective gives it the capability of being useful in several devices like antenna beam steering networks and for feeding phased antenna array without the use of any additional phase shifter. From the results obtained, both the measured and the simulated results agreed with a little discrepancy.

References

[1] S. I. Orakwue, R. Ngah, O. Elija, and S. A. Babale, "Cascaded Butler Matrix with Two-Dimensional Beam Scanning Capability at 28 GHz for 5G Wireless

System," *Adv. Sci. Lett.*, 2018.
[2] D. M. Pozar, *Microw. Engineering, 4th Edition*. 2012.
[3] Y. Zhou *et al.*, "Slow-Wave Half-Mode Substrate Integrated Waveguide 3-dB Wilkinson Power Divider/Combiner Incorporating Nonperiodic Patterning," *IEEE Microw. Wirel. Components Lett.*, 2018.
[4] M. Ben Kilani, M. Nedil, N. Kandil, M. C. E. Yagoub, and T. A. Denidni, "Wideband directional elliptic coupler based on CB-CPW technology," *Electron. Lett.*, 2012.
[5] S. A. Babale, S. K. A. Rahim, K. N. Paracha, and S. I. Orakwue, "3 dB branch-line coupler with improved bandwidth using PDMS and zoflex conductor," *Adv. Sci. Lett.*, vol. 23, no. 11, pp. 11378–11381, 2017.
[6] O. Olukoya, A. Tarczynski, and D. Budimir, "Miniaturised inkjet-printed quadrature hybrid couplers for multiband wireless systems," 2017.
[7] A. A. M. Ali, H. B. El-Shaarawy, and H. Aubert, "Miniaturized hybrid ring coupler using electromagnetic bandgap loaded ridge substrate integrated waveguide," *IEEE Microw. Wirel. Components Lett.*, 2011.
[8] S. A. Babale and S. K. A. Rahim, "Miniaturized quadrature coupler using low-cost instant inkjet printing technology," *Microw. Opt. Technol. Lett.*, vol. 59, no. 8, pp. 1819–1824, 2017.
[9] P. L. Chi and K. L. Ho, "Design of dual-band coupler with arbitrary power division ratios and phase differences," *IEEE Trans. Microw. Theory Tech.*, 2014.
[10] S. Lee and Y. Lee, "Wideband branch-line couplers with single-section quarter-wave transformers for arbitrary coupling levels," *IEEE Microw. Wirel. Components Lett.*, 2012.
[11] M. Hayati and M. Ehteshami, "A miniaturized branch line coupler with harmonic suppression," *Frequenz*, vol. 68, no. 7–8, pp. 321–327, 2014.
[12] J. J. Yao and S. P. Yeo, "Six-port reflectometer based on modified hybrid couplers," *IEEE Trans. Microw. Theory Tech.*, 2008.
[13] F. F. He, K. Wu, W. Hong, L. Han, and X. P. Chen, "Low-cost 60-GHz smart antenna receiver subsystem based on substrate integrated waveguide technology," *IEEE Trans. Microw. Theory Tech.*, 2012.
[14] Y. S. Wong, S. Y. Zheng, and W. S. Chan, "Quasi-arbitrary phase-difference hybrid coupler," *IEEE Trans. Microw. Theory Tech.*, 2012.
[15] M. J. Park, "Comments on Quasi-arbitrary phase-difference hybrid coupler," *IEEE Trans. Microw. Theory Tech.*, vol. 61, no. 3, pp. 1397–1398, 2013.
[16] H. A. Elmobarak, S. K. A. Rahim, M. Himdi, X. Castel, and T. A. Rahman, "Low cost instantly printed silver nano ink flexible dual-band antenna onto paper substrate," 2017.
[17] Y. Kawahara, S. Hodges, B. S. Cook, C. Zhang, and G. D. Abowd, "Instant inkjet circuits: Lab-based inkjet printing to support rapid prototyping of ubicomp devices," 2013.
[18] S. A. Babale, S. K. Abdul Rahim, O. A. Barro, M. Himdi, and M. Khalily, "Single Layered 4 × 4 butler matrix without phase-shifters and crossovers," *IEEE Access*, vol. 6, pp. 77289–77298, 2018.