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# Compact Wideband Metamaterial Quadrature Coupler for 5G Beamforming Applications

*Abstract. A design of a compact wideband quadrature coupler based on metamaterial is presented at 3.5 GHz. The quadrature coupler is a significant component in beamforming networks with problems of narrow bandwidth and bulky size. The proposed quadrature coupler is designed with the implementation of composite right/left-handed (CRLH) arms metamaterial transmission line (TL). The metamaterial fingers are implemented in each branch section to reduce the size and improve the bandwidth. The proposed coupler is simulated using CST software and then fabricated on the FR4 substrate with (εr=4.4 and h=1.6 mm). The coupler performance achieved a fractional bandwidth of 55.42% operated at 2.25 GHz to 4.19 GHz. The coupling factor at 3.5 GHz is -3 ±0.5 dB with a phase difference of 88.01°. Compared to conventional BLC, the proposed coupler achieved a size reduction of 40.43%. The proposed coupler is suitable to be used in future 5G beamforming applications.*

***Streszczenie**. Przedstawiono projekt kompaktowego szerokopasmowego sprzęgacza kwadraturowego opartego na metamateriałach dla częstotliwości 3,5 GHz. Sprzęgacz kwadraturowy jest istotnym elementem w sieciach kształtujących wiązkę z problemami związanymi z wąskim pasmem i nieporęcznymi rozmiarami. Proponowany sprzęgacz kwadraturowy został zaprojektowany z wykorzystaniem kompozytowej linii transmisyjnej metamateriałów (TL) ramion prawo/lewoskrętnych (CRLH). Palce metamateriałów są zaimplementowane w każdej sekcji odgałęzienia, aby zmniejszyć rozmiar i poprawić przepustowość. Proponowany łącznik jest symulowany za pomocą oprogramowania CST, a następnie wytwarzany na podłożu FR4 przy (εr=4,4 i h=1,6 mm). Wydajność sprzęgacza osiągnęła ułamkową przepustowość 55,42% przy pracy w zakresie od 2,25 GHz do 4,19 GHz. Współczynnik sprzężenia przy 3,5 GHz wynosi -3 ±0,5 dB przy różnicy faz 88,01°. W porównaniu z konwencjonalnym BLC, proponowany łącznik pozwolił zmniejszyć rozmiar o 40,43%. Proponowany sprzęgacz nadaje się do wykorzystania w przyszłych zastosowaniach kształtowania wiązki 5G. (**Kompaktowy szerokopasmowy łącznik kwadraturowy z metamateriałami do zastosowań związanych z formowaniem wiązki 5G**)*

**Keywords:** CRLH metamaterial, quadrature coupler, Beamforming, 5G, Wideband.
**Słowa kluczowe**: antena szerokopasmowa 5G, metamateriał

## Introduction

Recently, antenna array and beamforming networks (BFNs) have trended for more traffic capacity, higher receiving sensitivity, huge data rates, and high efficiency in the fifth-generation (5G) wireless communication systems [1-4]. In such systems, smart antenna systems are crucial to providing high directivity and enhanced coverage [5-7]. In smart antenna systems, beamforming networks such as the Butler matrix and Nolen matrix play a significant role in delivering a directive beam toward desired targets and eliminating unwanted interferences [8, 9]. Generally, the development of BFNs consists of three main components; quadrature coupler, crossovers, and phase shifters [10]. A quadrature coupler, also known as a branch line coupler (BLC), is a device that splits input signals into equally or unequally magnitudes with a 90° phase difference between output ports [11]. The traditional quadrature coupler has two inputs and two outputs using four sectionals λ/4 transmission lines that include an impedance of Z_0=50Ω, and Z_0=35.35Ω [12]. However, two main problems in conventional quadrature couplers are highlighted, with a narrow bandwidth of 10-20% and large size due to λ/4 transmission lines [13]. Several techniques have been proposed to resolve these problems, such as using two cross-section lines and metamaterials [14-19]. A conventional BLC is replaced with a T-shape transmission line in order to reduce the size by 32% and enhance the bandwidth by 24% [14]. In [15], the use of a composite left-handed metamaterial unit cell (D-CRLH) is presented with a size reduction of 52% and bandwidth improved by 18%. In [16], the authors presented a compact BLC design using a CRLH-TL arms structure at 3.5 GHz that reduces the total size by 54% and improves the bandwidth by 40%.

Hence, in this paper, a compact wideband coupler based on metamaterial using CRLH-TL fingers sectional at 3.5 GHz is presented. The two sectional transmission lines of the coupler are replaced with T-shape and fingers unit cell arms which finds to be the best method for reducing the size and improving the bandwidth. The proposed coupler is designed using an FR-4 substrate with εr= 4.4 and a height of 1.6 mm. The simulation and measurement results agreed well throughout the 2.25 to 4.19 GHz frequency band and can be used in future 5G beamforming networks.

## Design of wideband metamaterial coupler

By employing T-shape for all branch lines of two sectional BLC, the modified coupler terminated by arbitrary coupling for arbitrary real impedances, as shown in Fig. 1. T-shape structure composes of two identically transmission line sections $(Z_A, \theta_A)$ with a reactive shunt element of $(jY_T)$. Hence, the T-shape matrix (ABCD) can be found as [20-23]:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} \cos\theta_A & jZ_A \sin\theta_A \\ \frac{j\sin\theta_A}{Z_A} & \cos\theta_A \end{bmatrix} \begin{bmatrix} 1 & 0 \\ JY_T & 1 \end{bmatrix} \begin{bmatrix} \cos\theta_A & jZ_A \sin\theta_A \\ \frac{j\sin\theta_A}{Z_A} & \cos\theta_A \end{bmatrix} \quad (1)$$

The unit cell based on interdigital capacitor metamaterial and its equivalent circuit is illustrated in Fig. 2. The widths of the overall interdigital capacitor fingers are Wf and $W_c$. The gap between each finger is S and $l_f$ is the finger length. Generally, interdigital capacitor metamaterial consists of capacitance in series ($C_{id}$), inductance ($L_f$), resistance ($R_f$), and connected ground stray capacitance $C_f$), as shown in

Fig.2. However, to match the proposed T-shape with the interdigital capacitor metamaterial, an additional series inductance ($L_s$) with a parallel capacitor ($C_s$) are determined. The inductance ($L_l$) is calculated by assuming that $\frac{W_f}{h} < 1$ with $\frac{lf}{2}$ [24,25]:

$$(2)\quad L_f = \frac{1}{2}\frac{Z_0\sqrt{\varepsilon_{eff}}}{C_0} l_f \text{ (H)}$$

Where $Z_0$= 50Ω and $\varepsilon_{eff}$ is the effective permittivity of the microstrip line with width $W_f$. $C_o$ is the speed of light in the air. Similarly, the capacitance $C_f$ can be found using the same length and width transmission line $(\frac{lf}{2}, W_f)$ as in [26-28]:

$$(3)\quad C_f = \frac{1}{2}\frac{\sqrt{\varepsilon_{eff}}}{Z_0 C_0} l_f \text{ (F)}$$

To determine the resistance $R_f$ due to conductor loss, the following formula is given [29]:

$$(4)\quad R_f = \frac{4}{3}\frac{l_f}{W_f N} R_s \ \Omega$$

Where, N is the number of fingers and $R_s$ is the conductor resistivity.

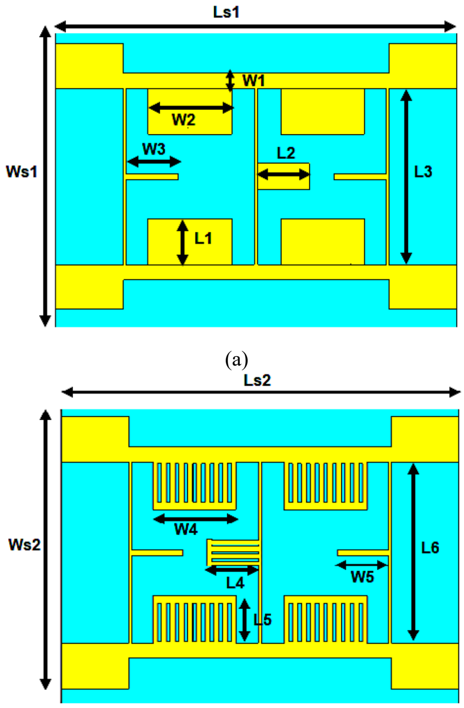


Fig. 1. Two sectional quadrature coupler. (a) Modified T-shape coupler, (b) Proposed metamaterial coupler.

Finally, the series inductance ($L_s$) with parallel capacitor ($C_s$) and capacitance in series ($C_{id}$) are calculated by [30-35]:

$$(5)\quad L_s = 0.000987 \times h\left(1 - Z_0\sqrt{\varepsilon_{eff}}\right) \times 10^6 \text{ H}$$

$$C_s = 0.00137 \times h \times \frac{\sqrt{\varepsilon_{eff}}}{Z_0}\left(1 - \frac{W_c}{W_f}\right)\left(\frac{\varepsilon_{eff}+0.3}{\varepsilon_{eff}-0.258}\right) \times$$

$$(6)\quad \left(\frac{\frac{W_c}{h}+0.264}{\frac{W_c}{h}+0.8}\right) \text{(pF)}$$

$$(7)\quad C_{id} = (\varepsilon_r + 1) l_f [(N-3)A_1 + A_2] \text{ (F)}$$

Where, h is the thickness of the substrate and $\varepsilon_r$ is the permittivity of chosen substrate FR4.

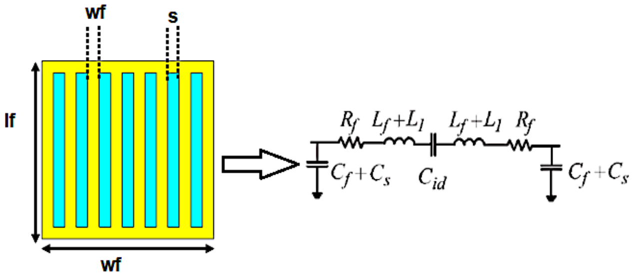


Fig. 2. Interdigital capacitor unit cell finger and its equivalent circuit.

Hence the coupler dimensions (All in mm) are obtained as follows; ($L_{s1} = 40.5, L_{s2} = 30.25, L_1 = 10.7, L_2 = 6.71, L_3 = 20.5, L_4 = 3.61, L_5 = 2.8, L_6 = 10.53, W_{s1} = 45.2, W_{s2} = 25.9, W_1 = 3.55, W_2 = 12.5, W_3 = 9.6, W_4 = 6.5, W_5 = 3.9$). A simulation of modified and proposed coupler is performed using CST software to analyze their performance in terms of S-parameters and phase difference as shown in Fig. 3.

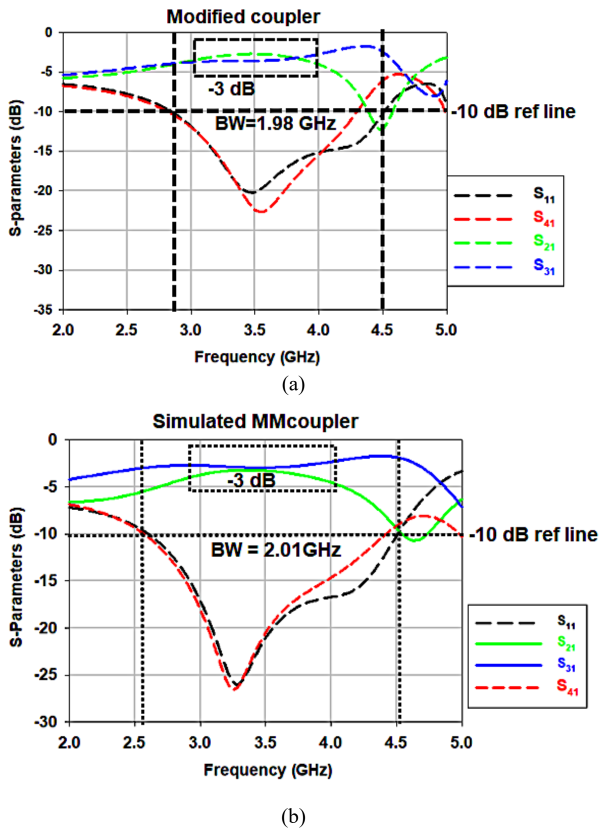


Fig. 3. S-parameters analysis of two sectional coupler. (a) modified T-shape coupler, (b) Proposed metamaterial coupler.

It can be clearly noticed that the scattering parameters of the modified coupler achieved a good return loss, isolation and desired coupling level. However, the coupling level differed from -3 dB with ± 1.5 dB error. For the proposed coupler, a perfect return loss with wideband characteristics up to 2 GHz is achieved. As the coupling level is perfectly divided, the power is into -3 ±0.2 dB coupling factor. Hence, the proposed coupler is then fabricated for further comparative analysis.

### Results and discussion

Fig. 4 shows the printed metamaterial coupler with dimensions of 30.25 mm × 25.9 mm that highlighted the compact size of the BLC. The performance of the proposed coupler in terms of S-parameters is compared with simulated results in Fig. 5.

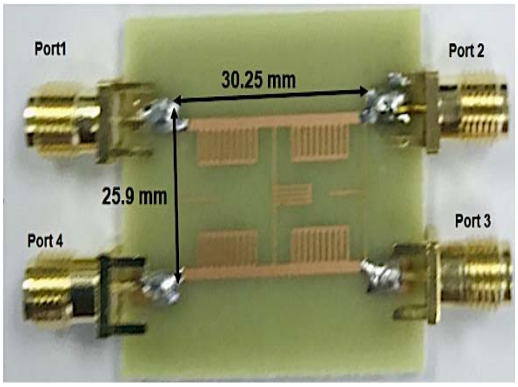


Fig. 4. Fabricated prototype of metamaterial coupler

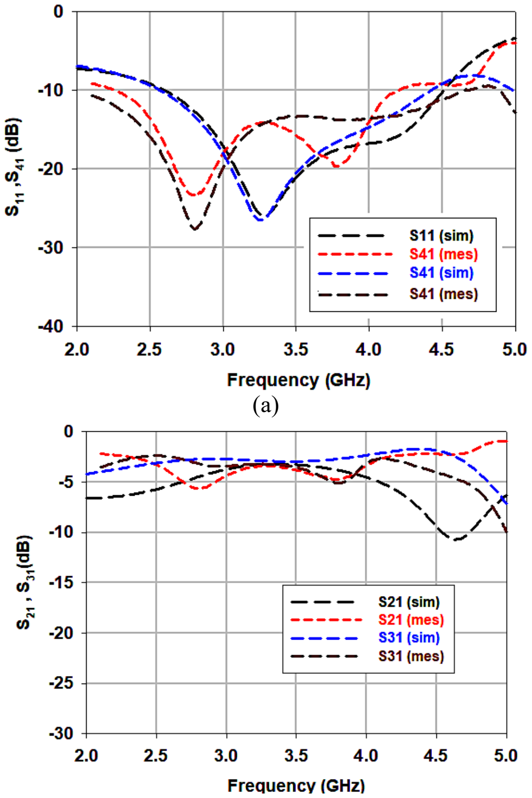


Fig. 5. Comparison of simulated and measured S-parameters of the proposed coupler. (a) Return loss and Isolation, (b) Insertion and coupling loss.

The measured return loss (S11) and isolation (S41) results in Fig. 5 (a) showed that the proposed coupler achieved a wideband of 1.98 GHz in the range between 2.25 GHz to 4.19 GHz. Meanwhile, at the desired frequency of 3.5 GHz, the measured insertion loss (S21) and coupling loss (S31) achieved equally split power across port 2 and port 3 with -3.5 dB and -3.9 dB respectively, as shown in Fig. 5(b). The comparison of measured and simulated phase difference when port 1 is excited is shown in Fig. 6. The measured phase difference between port 2 and port 3 is 88.01° compared to the simulated 90°. Hence, the phase error is 1.99° within the desired 90° phase difference.

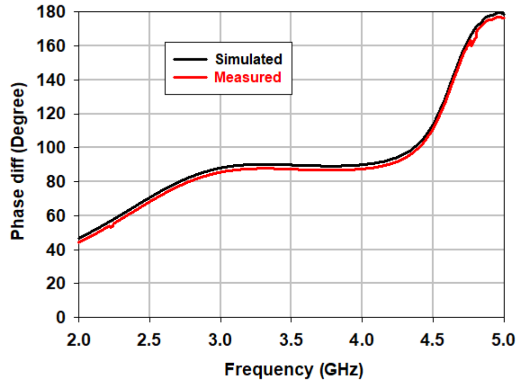


Fig. 6. Phase difference comparison of the proposed coupler at port 2 and port 3.

A total size of 738.5 mm² is achieved for metamaterial coupler compared to the modified coupler of 1830.6 mm² with an overall reduction of 40.34%. A comparison between the proposed coupler and previously published works is summarized in Table 1. The proposed coupler shows a size reduction and bandwidth improvement together, in which benefits the main requirements for 5G systems and applications.

Table 1 Comparison of Proposed Coupler With Related Existing Blc Works

| Ref/year | BW (GHz) | Size reduction | Phase error | Loss error |
|---|---|---|---|---|
| [20]/2018 | 1.35 | 40% | 2.5° | 0.5 dB |
| [15]/2020 | 1.41 | 54% | 2° | 0.8 dB |
| [30]/2021 | 0.75 | 30% | 2° | 2 dB |
| [31]/2021 | 1.5 | 37% | 1.5° | 3 dB |
| This work | 1.98 | 40.43% | 1.99° | 0.5 dB |

### Conclusion

A developed quadrature coupler based on metamaterial is presented in this letter at 3.5 GHz. the coupler is designed based on T-shape interdigital capacitor finger unit cell TL metamaterial properties. The performance of the proposed coupler agreed well with the simulated results. Excellent S-parameters and phase difference performance at 3.5 GHz is achieved for the designed coupler. The metamaterial coupler operates in the frequency band of 2.25 GHz to 4.19 GHz with a high fractional bandwidth of 55% and balanced power coupling of -3 ±0.5 dB. The coupler achieved a good profile of compact size by 40.43%. The proposed coupler is suitable to be used later in beamforming networks for the 5G based antenna array system.

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