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ENHANCEMENT THE PERFORMANCE OF COUPLED LINE COUPLERS BASED ON BOTH CRLH- AND HIGH-TC SUPERCONDUCTING MICROSTRIP LINES

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ABSTRACT

A new structure of composite right/left-handed (CRLH) coupled line coupler compact with high coupling value is presented and compared with the conventional coupled line microstrip coupler. Instead of the normal conductor (Copper) used in strip line, a YBCO thin film high temperature superconductor (HTS) is replaced to achieve superior performance. A high directivity of the coupled line was achieved by using superconductor. The coupled line coupler was designed based on the unit cell fabricated and it has good measured results.

KEYWORDS

Directional Couplers, Coupled Line, Microstrip, Metamaterial & Superconductor

1.INTRODUCTION

Directional couplers are one of most important passive microwave devices with a wide range of application. The coupled line coupler is easy to design and it has the wide frequency band. The high coupling factor is difficult to achieve using the classical coupled line design. Also the directivity of the coupled line coupler is poor, because the micro strip transmission line has an inhomogeneous medium, for this reason, odd mode and even mode phase velocities are unequal [1].

There are several methods of improving the directivity and coupling factor of the coupled line coupler, such as Epsilon Negative Transmission Line [2], lumped-element compensation [3], an inductor loaded micro strip directional coupler [4]. Coupler multilayer micro strip configuration [5]. Although these approaches lead to enhancing the directivity, the composite right-/left-handed (CRLH) [6-9], electromagnetic band gap (EBG) [10], these approaches lead to the desired coupling enhancement.

In this paper, we suggest a new design for coupler consisting of a coupled microstrip section, periodic structure loaded with shunt inductance stubs and defects ground. The structure represents composite right/ left handed (CRLH). This design is used to achieve good coupling. By changing the normal conductor of the strip line to a YBCO thin film high temperature superconductor (HTS) for enhancement the directivity of the coupler.

First, we discuss the effect of the periodic structure based on unit cell composite right/left-handed (CRLH) meta material using micro strip technology [11]. Next, we study the effect of the high temperature superconductor (HTS) on the design. Finally the results are compared with conventional coupled line.

This paper is organized as follows. Section (2), includes CL-CRLH unit cell, section (3), includes the parallel coupled line coupler, section (4), includes the superconductor coupler, followed by the conclusions and the most relevant references.

2. CL-CRLH UNIT CELL

Meta materials are artificially fabricated materials having electromagnetic properties not present among natural ones. Composite right/left-handed (CRLH) unit cells allow the realization of transmission lines with controllable characteristic impedance and dispersion relation [12].

The unit cell is shown in Fig. 1. It consists of two short stubs, two open stubs coupled lines, and slot line, where p is the length of the unit cell. The dispersion relation, when the coupled lines lengths, widths, and separation are 3.5mm, 0.5mm and 0.2mm, respectively, the short stubs lengths and widths are 3 mm, 0.5mm, respectively, finally the slot line lengths, widths and length of the unit cell are 4.925 mm, 0.25mm and 5.6mm, respectively. Radius of via holes 0.5 mm, the substrate height is 0.635mm and dielectric constant ε_r =6.15. Defected ground slot lines have been introduced to overcome the effect of the shunt capacitance. The dispersion relation of a microstrip line is shown in fig. 2. As seen from this figure, the unit cell is a balanced condition because the transition from LH to RH shows the balanced condition without the presence of stop band. Tuning of the slot line was needed to achieve the balance condition.

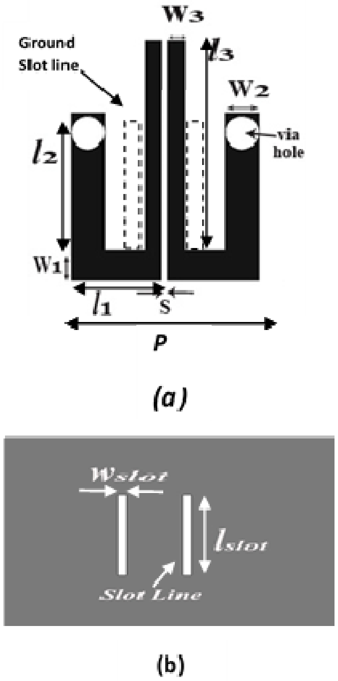


Fig. 1. Proposed microstrip CRLH unit cell: (a) Top layer unit cell (b) Bottom layer ground defects

That the phase constant β for the symmetric CRLH unit cell is

$$\beta = \frac{1}{p} cos^{-1}\left(1+\frac{ZY}{2}\right) = \frac{1}{p} cos^{-1}(A) \qquad (1)$$

The scattering matrix is the voltage wave incident on the ports to voltage wave reflected from the ports. By using the relationship between scattering matrix and [ABCD] matrix [13].

$$A = \frac{(1+S_{11})(1-S_{22})+S_{12}S_{21}}{2S_{21}} \qquad (2.a)$$

$$B = \frac{(1+S_{11})(1+S_{22})-S_{12}S_{21}}{2S_{21}} \qquad (2.b)$$

$$C = \frac{1}{Z_0}\frac{(1-S_{11})(1-S_{22})-S_{12}S_{21}}{2S_{21}} \qquad (2.c)$$

$$D = \frac{(1-S_{11})(1+S_{22})+S_{12}S_{21}}{2S_{21}} \qquad (2.d)$$

The phase constant β is given by

$$\beta = cos^{-1}\left(\frac{(1+S_{11})(1-S_{22})+S_{12}S_{21}}{2S_{21}}\right) \qquad (3)$$

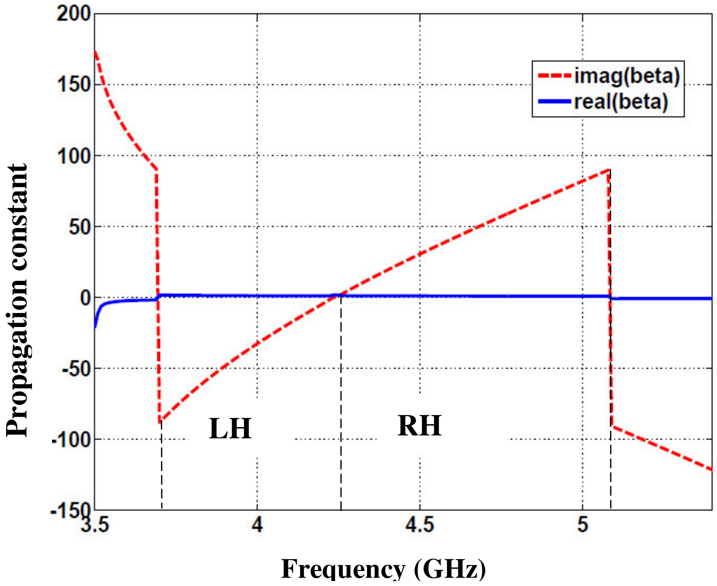


Fig. 2. Dispersion relation for the balanced CRLH unit cell.

3. Parallel Coupled Line Coupler

The parallel conventional coupled line coupler is a four-port device the structure of which is shown in Fig. 3. The proposed coupled line coupler, shown in Fig. 4, consist of three unit cells as two mirrored cells separated by a distance (s). The arbitrary coupling directional coupler can achieve by using interdigital capacitance with nine unit cells [6]. The proposed design has a good coupling by using the three unit cells compact size.

3.1 Coupler Theory

The scattering parameters of the coupled line coupler, as shown in fig. 3, are given by [14].

$$S_{11} = 0, \tag{4a}$$

$$S_{12} = -je^{\frac{-j(\beta_e+\beta_o)l}{2}} \cos\left[\frac{(\beta_e-\beta_o)l}{2}\right] \tag{4b}$$

$$S_{13} = 0, \tag{4c}$$

$$S_{14} = -je^{\frac{-j(\beta_e+\beta_o)l}{2}} \sin\left[\frac{(\beta_e-\beta_o)l}{2}\right] \tag{4d}$$

Where β_e and β_o are even and odd mode propagation constants of coupled lines, respectively. Also, l is the length of the coupled line. The parallel coupled line coupler is analyzed by using the even- and odd-mode. Assume that the phase velocities of the even and odd modes are the same and the electrical lengths for both modes are equal. Directivity of a directional coupler is defined as [2]

$$D = 20 \log \frac{S_{31}}{S_{41}} \tag{5}$$

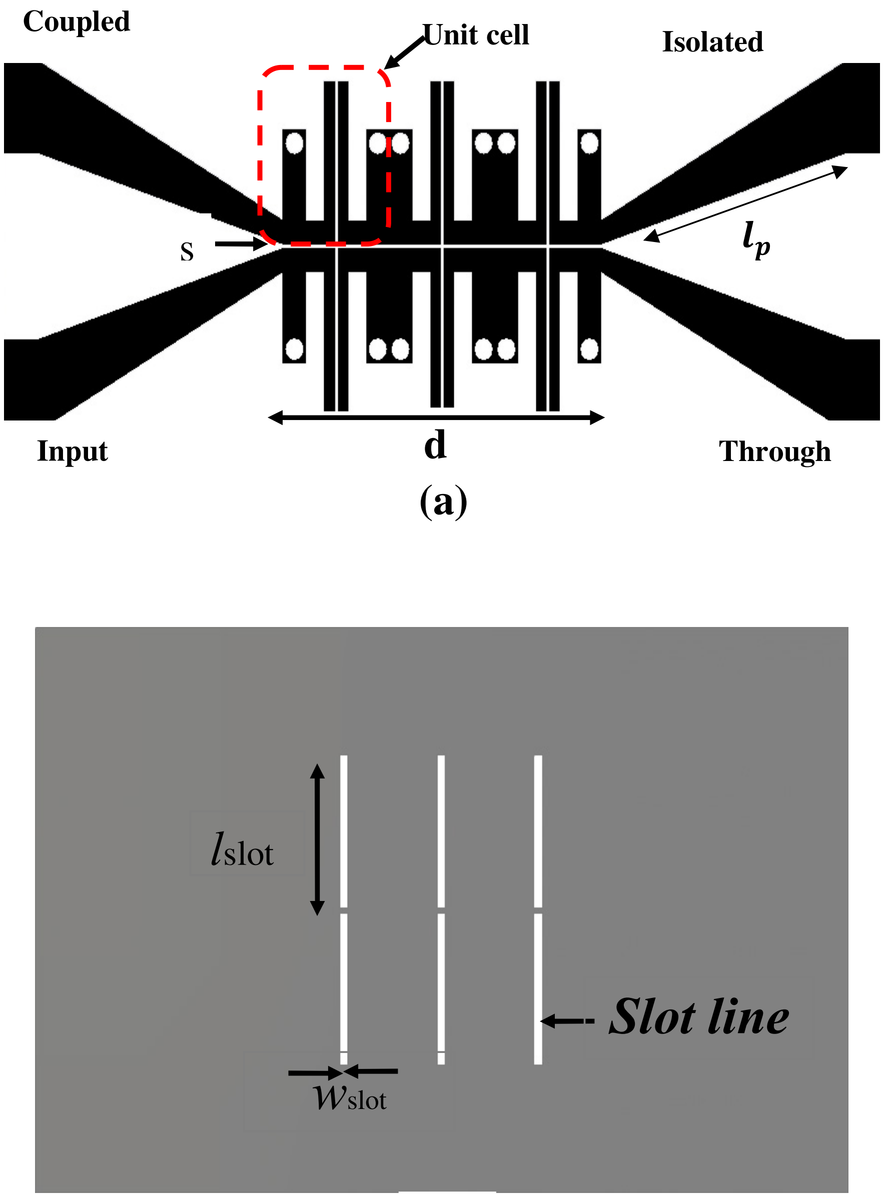
The S_{31}, S_{41} can be calculated as follows

$$S_{31} = \frac{Z_0 + jZ_{0e}\tan(\theta_e)}{2Z_0 + j(Z_{0e}+Z_{0o})\tan(\theta_e)} \tag{6}$$

$$S_{41} = \frac{Z_0 \sec(\theta_e)}{2Z_0 + j(Z_{0e}+Z_{0o})\tan(\theta_e)} \tag{7}$$

Where Z_{0e} and Z_{0o} are the even- and odd-mode characteristic impedances, respectively, and $Z_0 = \sqrt{Z_{0e}Z_{0o}}$ is the port impedance.

Fig. 3. Four-port backward parallel coupled line coupler.



(a)

(b)

Fig. 4. Proposed Coupled line microstrip: (a) Top layer Coupled line (b) Bottom layer ground defects.

3.2 Simulation and Results

Table 1. Shows the design specification of the coupled line using unit cell. These parameters are obtained for a system impedance of 50 Ω. The circuit is simulated on a Rogers RO3006 substrate with a dielectric constant of 6.15 and a thickness of 0.635 mm. The simulation was carried out using a CST microwave studio that implements finite integration technique FIT in time domain [15]. The coupled line was designed on the LH region of the dispersion diagram (3.7 GHz to 4.24) at the centre frequency 3.8 GHz. The results of circuit simulation are shown in Fig. 5. The

coupling in the EM simulation is very good about -1.9 dB, but the directivity is poor about 16 dB, for that we used the superconductor.

Table 1. Design specifications of the coupled line using unit cell.

Dimensions (mm)	**Value**
W_1	1
W_2	1
W_3	0.5
l_1	2.7
l_2	4.1
l_3	6.25
S	0.2
l_{slot}	7
w_{slot}	0.4
l_p	13.6
p	5.6
d	16.8

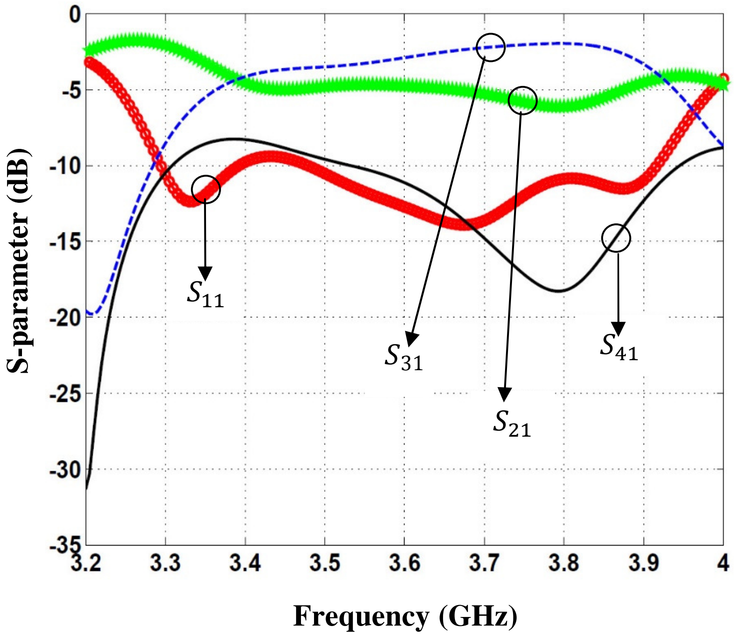


Fig. 5. S-parameters for the CRLH coupler obtained by full-wave simulation

4. Using High Temperature Superconductor

The High temperature superconductor (HTS) microstrip planar structure is attractive for microwave applications due to superior properties to normal metal [16]. The HTS has a lower conductor losses compared to normal conducting circuits at low temperatures[17]. Instead of the normal conductor used in Fig.4, we replaced it by a YBCO thin film.

The YBCO film is modeled by equivalent surface impedance and the effect of the finite thickness of the film is taken into account as given below [18].

$$Z_s = R_s\left[\frac{\coth\left(\frac{t}{\lambda}\right)}{sinh^2\left(\frac{t}{\lambda}\right)}\right] + jX_s cot\,h\left(\frac{t}{\lambda}\right) \qquad (8)$$

Where

$R_s = \frac{\omega^2\mu^2\sigma_1}{2}$, $X_s = \omega\mu\lambda$, λ is its London penetration depth at a temperature T, and $\sigma_1$is the real part of the complex conductivity of the superconductor. $\sigma_1$andλ are calculated using an empirical two-fluid model [18]

$$\sigma_1 = \sigma_{\mathrm{n}}(T)(T/T_c)^{\gamma} \qquad (9)$$

$$\sigma_{\mathrm{n}} = \sigma_{\mathrm{n}}(T_c)[\left(\frac{T}{T_c}\right)^{\gamma-1} + \alpha\left[1 - \left(\frac{T}{T_c}\right)^{\gamma}\right]] \qquad (10)$$

$$\lambda(T) = \lambda(0)/\sqrt{1 - \left(\frac{T}{T_c}\right)^{\gamma}} \qquad (11)$$

In these relations t is the thickness of the HTS film, λ, or $\lambda\ (T)$, is the London penetration depth at a temperature T, T_c is the transtion temperature, $\sigma_{\mathrm{n}}(T_c)$ is the conductivity of the normal charge carriers at T_c, α is an empirical parameter which is the residual resistance rate of the superconductor at $T \rightarrow 0\ K$, γ is a model parameter, and $\lambda(0)$ is London peneteration depth at $T = 0\ K$. The values of these parameters for YBCO fims are given by:

$$T_c = 92\ K, T = 86\ K, \lambda = 0.14 \times 10^{-6}\ at\ T = 0, t = 0.045 \times 10^{-6}\ .$$

The HTS for microwave applications, must be the substrates have a low dielectric loss tangent (tan δ) [19]. Firstly, we used a Rogers RO3006 substrate with a dielectric constant of 6.15 for comparison the results with CRLH structure of the coupler as normal conductor at the same frequency (3.8 GHz), next we used the Sapphire substrate with a dielectric constant of 9.4 and loss tangent1.5×10^{-8}, as the superconductor substrate, that's possible to fabrication superconductor. As shown in the Fig. 6, the comparison between the normal conductor and the superconductor film, the directivity of the superconductor coupler is enhanced nearly 38 dB compared with the normal conductor about 16 dB.

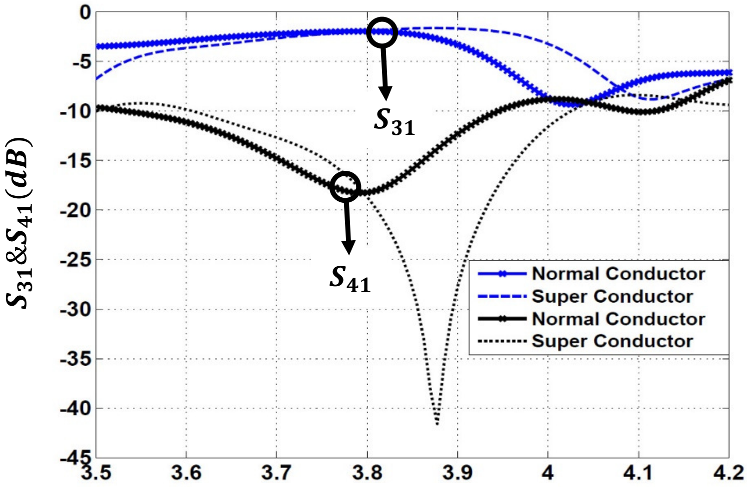


Fig. 6. $S_{31}\&S_{41}$-parameters for the CRLH coupler normal case comparison with superconductor.

As shown in the Fig. 7, the comparison between the normal conductor and the superconductor film, the return loss of the superconductor coupler is enhanced nearly -44 dB compared with the normal conductor about -14 dB and the insertion loss of the normal conductor coupler is changed from -6 dB to -5 dB for the superconductor.

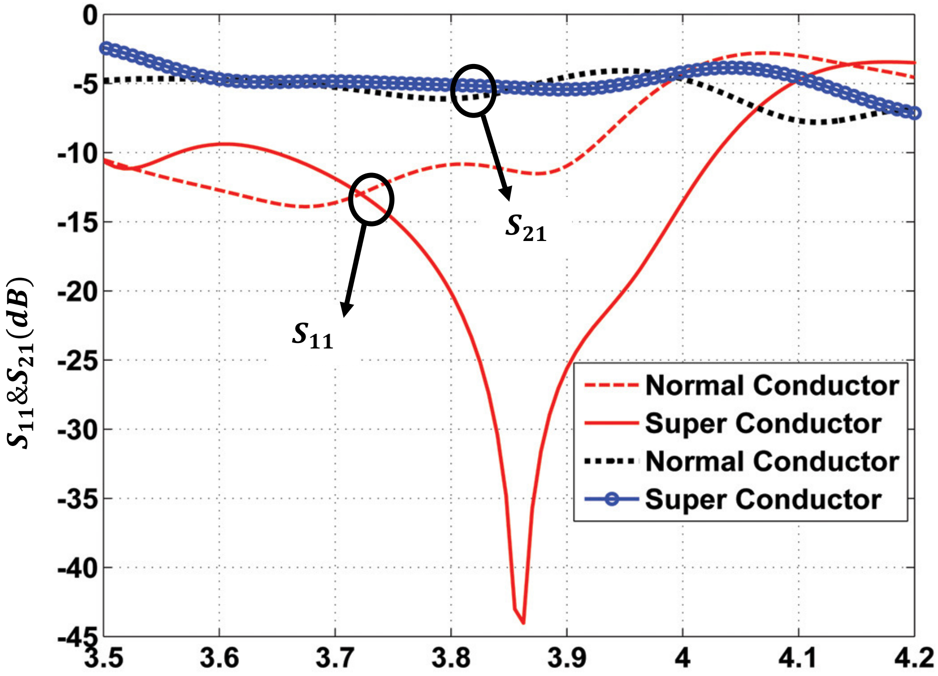


Fig. 7. $S_{11}\&S_{21}$-parameters for the CRLH coupler normal case comparison with superconductor.

Figures 8, 9 show the results of the proposed design with the superconductor and the Sapphire substrate (dielectric constant of 9.4) compared with a conventional coupled line in Fig. 3, the centre frequency is shifted from 3.8 GHz to 3.2 GHz, because the dielectric is changed from 6.15 for the normal conductor to 9.4 dielectric substrate for the superconductor. Fig. 8, shows the coupling in S_{31} is greatly improved from -10 dB conventional design to -1.5 dB proposed superconducting design and the directivity is greatly enhanced from 11 dB for the conventional design to 31 dB for proposed superconducting design.

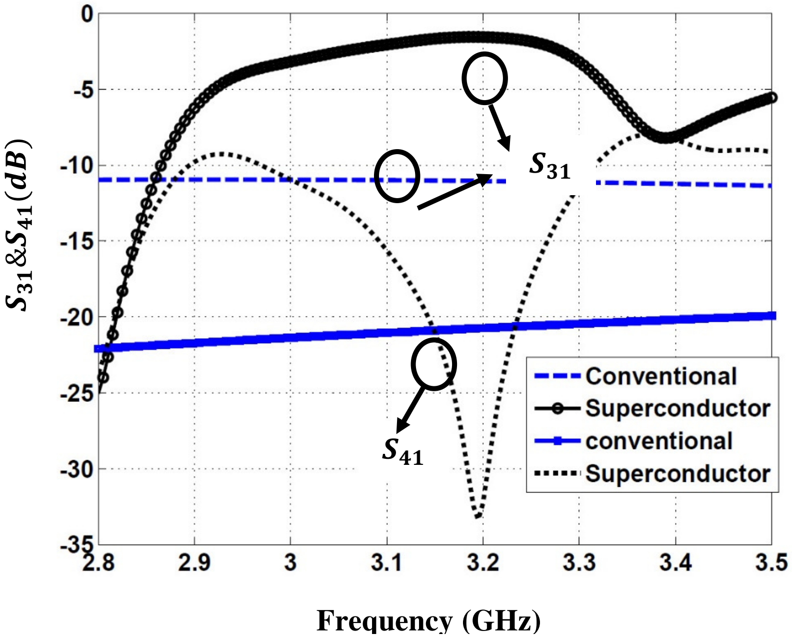


Fig. 8. S_{31} & S_{41} -parameters for the CRLH coupler superconductor case comparison with conventional coupled line normal case.

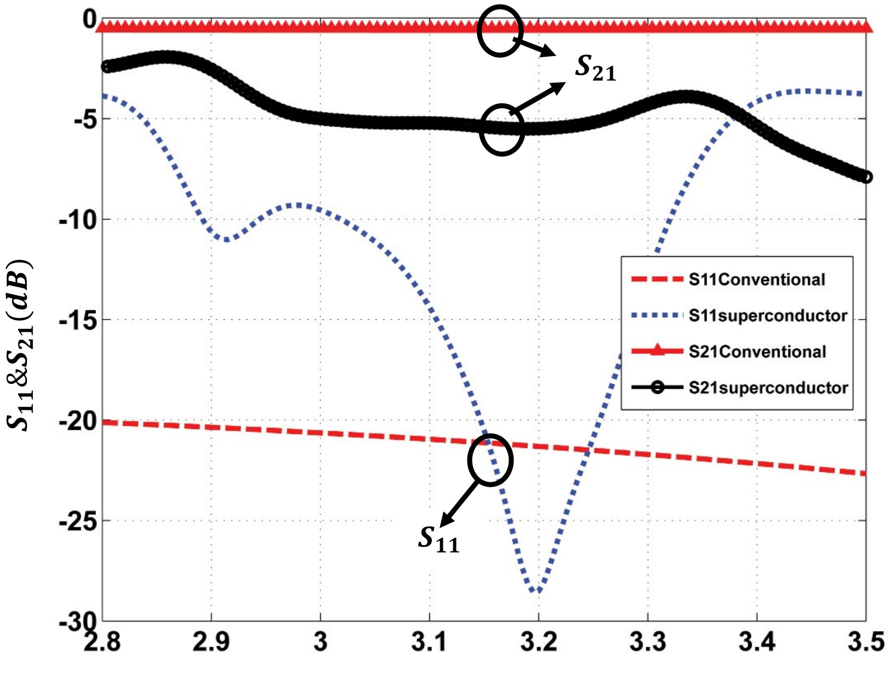


Fig. 9. S_{11}&S_{21}-parameters for the CRLH coupler superconductor case comparison with conventional coupled line normal case.

Table 2, demonstrates the comparison between the three proposed structures:

a) The CRLH with a normal conductor (Copper).
b) Adding HTS in replace of Copper to the CRLH.
c) Conventional coupled line coupler with a normal conductor.

Table 2. A comparative Study of the different coupled line coupler structures.

Property	CRLH [Proposed]	HTS 86k [Proposed]	Conventional coupler
S_{11}**(dB)**	-10.8	-28.55	-21.3
S_{21}**(dB)**	-6.1	-5.5	-0.51
S_{31}**(dB)**	-1.9	-1.5	-11
S_{41}**(dB)**	-18.2	-33.3	-20

5. Conclusion

In this paper, a new type of directivity and coupling factor-enhanced parallel coupled line coupler based on CRLH has been proposed. The use of high temperature superconductor (HTS) material instead of normal conductors has reduced conductor losses and consequently improved the performance of the coupled line. The maximum directivity of the coupler is nearly -31 dB at 3.1 GHz. The coupling is greatly improved from -10 dB for conventional design to -1.5 dB for the proposed superconducting design.

REFERENCES

[1] Y. Wu, W. Sun, S.-W. Leung, Y. Diao, K.-H. Chan, and Y.-M. Siu, “Single-layer microstrip high-directivity coupled-line coupler with tight coupling,” IEEE Trans. Microw. Theory Tech., vol. 61, no. 2, pp. 746–753, 2013.

[2] A. Pourzadi, A. R. Attari, and M. S. Majedi, “A directivity-enhanced directional coupler using epsilon negative transmission Line,” Microw. Theory Tech. IEEE Trans., vol. 60, no. 11, pp. 3395–3402, 2012.

[3] M. Dydyk, “Microstrip directional couplers with ideal performance via single-element compensation,” Microw. Theory Tech. IEEE Trans., vol. 47, no. 6, pp. 956–964, 1999.

[4] S. Lee and Y. Lee, “An inductor-loaded microstrip directional coupler for directivity enhancement,” Microw. Wirel. Components Lett. IEEE, vol. 19, no. 6, pp. 362–364, 2009.

[5] D. Jaisson, “Multilayer microstrip directional coupler with discrete coupling,” 2000.

[6] C. Caloz, A. Sanada, and T. Itoh, “A novel composite right-/left-handed coupled-line directional coupler with arbitrary coupling level and broad bandwidth,” Microw. Theory Tech. IEEE Trans., vol. 52, no. 3, pp. 980–992, 2004.

[7] Chi, P.-L., & Liu, “Novel Dual-Band Quasi-0-dB Coupled-Line Coupler Using the Composite Right/Left-Handed Transmission Lines,” IEEE Trans. Compon. Manufacturing Tech., Vol. 4, no. 2, pp. 259 - 267, 2014.

[8] Ma, Y., Zhang, H.-W., & Li, Y, “Novel Symmetrical Coupled-Line Directional Coupler Based on Resonant-Type Composite Right-/Left-Handed Transmission Lines,” Progress In Electromagnetics Research, vlo. 140, pp. 213–226, 2013.

[9] Keshavarz, R., & Movahhedi, “A Compact and Wideband Coupled-Line Coupler with High Coupling Level Using Shunt Periodic Stubs,”. Radioengineering, vol. 22, no 1, 2013.

[10] M. Chudzik, I. Arnedo, A. Lujambio, I. Arregui, F. Teberio, M. A. G. Laso, and T. Lopetegi, "Microstrip coupled-line directional coupler with enhanced coupling based on EBG concept," E lectron. Lett., vol. 47, no. 23, pp. 1284–1286, 2011.

[11]Khalid. M. Ibrahim, EL-Sayed M. El-Rabaie, Abdel-Aziz T. Shalaby, Ahmed S. Elkorany, "Design of compact composite right-left-handed transmission line unit cells," Int. J. Electron. Commun. Comput. Technol., vol. 7, 2014.

[12]A. E. Fouda, A. M. E. Safwat, and H. El-Hennawy, "On the applications of the coupled-line composite right/left-handed unit cell," Microw. Theory Tech. IEEE Trans., vol. 58, no. 6, pp. 1584–1591, 2010.

[13]W. M. Fai, "A novel compact microstrip type composite right/left handed transmission Line (CRLH TL) and its Applications," University of Hon Kong.

[14]R. Keshavarz and M. Movahhedi, "A compact and wideband coupled-line coupler with high coupling level using shunt periodic stubs," Radioengineering, vol. 22, no. 1, p. 323, 2013.

[15]CST "Computer Simulation Technology," Varsion 2012.

[16]H.-F. Huang and J.-F. Mao, "The inductance model of coupled high-Tc superconducting microstrip lines," Appl. Supercond. IEEE Trans., vol. 14, no. 1, pp. 7–12, 2004.

[17]M. M. Mansour, M. A. Elmala, A.-A. T. Shalaby, and E.-S. M. El-Rabaie, "Thin film ferroelectric tunable zeroth- order resonator based on CRLH metamaterial ," J. Circuits, Syst. Comput., vol. 23, no. 01, 2014.

[18]O. G. Vendik, I. B. Vendik, and D. I. Kaparkov, "Empirical model of the microwave properties of high-temperature superconductors," Microw. Theory Tech. IEEE Trans., vol. 46, no. 5, pp. 469–478, 1998.

[19] J.-S. HONG and M. J. Lancaster, Microstrip filters for RF/Microwave applications, 2001.