JOURNAL OF NANO- AND ELECTRONIC PHYSICS *ЖУРНАЛ НАНО- ТА ЕЛЕКТРОННОЇ ФІЗИКИ*
Vol. **15** No 3, 03003(6pp) (2023) Том **15** № 3, 03003(6cc) (2023)

A Broadband Microstrip 1 × 8 Magic-T Power Divider for ISM Band Array Antenna Applications

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(Received 20 May 2023; revised manuscript received 14 June 2023; published online 30 June 2023)

This article deals with the design and analysis of a microstrip 1 × 8 magic-T power divider (MTPD) for ISM band (industrial and medical band) array antenna application. First, a basic 1 × 2 magic-T power divider is designed and optimized. It can divide the power supply in two equal parts (3 dB) in-phase agreement. Then a 1 × 4 power divider has been designed using two identical 1 × 2 magic-T basic power dividers; it divides the power supply into four equal parts (6 dB) in-phase agreement. Finally, the proposed broadband 1 × 8 magic-T power divider is constituted by the assembly of two identical 1 × 4 magic-T power dividers; it can divide the power supply into 8 equal parts (9 dB) in phase agreement. As results obtained, the proposed 1 × 8 power divider has a − 10 dB wide bandwidth equals about 506 MHz (2.022 GHz to 2.528 GHz) with a minimum reflection coefficient S_{11} equals about – 19.12 dB at the operating frequency 2.4 GHz. Moreover, the module of the transmission coefficients (S_{12}, S_{13}, S_{14}, S_{16}, S_{16}, S_{17}, S_{18} and S_{19}) equal about – 9 dB with a negligible phase shift equals to 2.8° between the output signals. The design and simulation results of the proposed 1 × 8 power divider is carried out by HFSS EM simulator using the substrate Rogers RT/duroid 5880 with the total size 424 × 49 × 1.56 mm^3. The proposed power divider is a potential candidate to feed an array antenna, amplifiers and modulators of eight elements in the ISM band around 2.4 GHz (2.022 GHz-2.528 GHz).

Keywords: Broadband antenna, ISM band, Power divider, Array antenna, Magic-T, Broadband power divider, Wilkinson power divider.

DOI: 10.21272/jnep.15(3).03003 PACS number: 83.40.Ba

1. INTRODUCTION

In the last few decades, the power dividers are widely used in microwave and wireless communication systems, especially for designing an array antenna [1-2], amplifiers and modulators [3]. They are used for power division or power combining. For an effective data reception and transmission; an equal power splitter is necessary in wireless communication. Nowadays, in the ISM band (industrial and medical band) especially around the 2.4 GHz there are many modern applications that need an equal power splitter to feed their antenna such as: RFID (radio frequency identification) technology, GPS (Global Positioning Systems), WI-FI (wireless-fidelity), Bluetooth WLAN and Wi-Max [4], etc.

The microwave power dividers available in the literature are the Wilkinson power dividers [4-5] and the magic-T power dividers [6]. However, these devices suffer from some weakness' such as narrow bandwidth and huge size due to the use of the quarter wave length branch line [7]. This is why, recently, the power dividers have been the subject of many studies with the aim to widen their impedance bandwidth especially in the ISM band.

In this work, we have focused on the study and design of a broadband microstrip magic-T power divider because of its simplicity of integration with PCB (Printed Circuit Boards) devices, the good impedance matching at its ports and the good isolation between its output ports. The proposed 1 × 8 magic-T power divider has one input port and 8 output ports. It contains of four identical 1 × 2 magic-T power dividers fed by two identical 1 × 4 T magic power dividers. So, this article presents and analyze the designed power dividers in 1 × 2, 1 × 4 and 1 × 8 array structures.

This article has been organized into five sections: after this brief introduction section 1, Section 2 is dedicated to study and design of the basic 1 × 2 power divider. Section 3 discusses study and design of 1 × 4 power divider. Section 4 deals with the design of the proposed broadband 1 × 8 power divider. Finally, the last section will conclude this paper.

2. STUDY AND DESIGN OF THE BASIC 1 × 2 POWER DIVIDER (3 DB)

A power divider is a linear and passive electronic

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component that obeys the Ohm's law. It can be used for power division or power combination as shown in Fig. 1. Typically, this component provides in-phase output signals with an equal power division ratio (3 dB, 6 dB or 9 dB…). But an unequal power division ratio is possible as well. This component is an inevitable element for designing an array antenna.

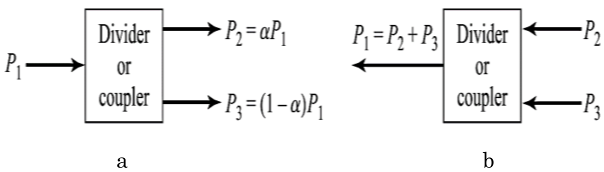


Fig. 1 – (a) Power divider. (b) Powers combiner [8]

The most popular magic-T power divider is the basic 1 × 2 T-shaped power divider. It consists of three T-shaped transmission lines as shown in Figure 2.

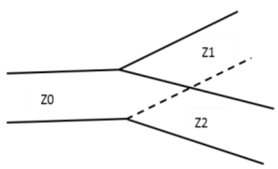


Fig. 2 – 1 × 2 T-shaped power divider port layout

To have a lossless T-junction, the impedances Z_0, Z_1 and Z_2 must verify the following equation [8]:

$$\frac{1}{\boldsymbol{Z}_0} = \frac{1}{\boldsymbol{Z}_1} + \frac{1}{\boldsymbol{Z}_2} \tag{1}$$

Generally, the scattering matrix S of a 1 × 2 power divider consists of 9 independent parameters as shown below:

$$[S] = \begin{bmatrix} S_{11} & S_{12} & S_{13} \\ S_{21} & S_{22} & S_{23} \\ S_{31} & S_{32} & S_{33} \end{bmatrix} \tag{2}$$

A power divider that does not contain any anisotropic materials is reciprocal. Therefore, its S matrix becomes symmetric ($S_{ij} = S_{ji}$) as follow:

$$[S] = \begin{bmatrix} S_{11} & S_{12} & S_{13} \\ S_{12} & S_{22} & S_{23} \\ S_{13} & S_{23} & S_{33} \end{bmatrix} \tag{3}$$

If this structure is lossless with adapted ports ($S_{11} = S_{22} = S_{33} = 0$) the S matrix becomes as follows:

$$[S] = \begin{bmatrix} 0 & S_{12} & S_{13} \\ S_{12} & 0 & S_{23} \\ S_{13} & S_{23} & 0 \end{bmatrix} \tag{4}$$

Unfortunately, there's no lossless structure, but we accept that if S_{11}, S_{22}, S_{33} are less than – 10 dB, the structure is considered as a low-loss structure.

In microstrip technology, to design a power divider, the equations (5) and (6) should be considered [9-11]. These equations allow to switch between the characteristic impedance and the width of each branch line.

The most widely used feed line in microstrip technology is the one whose characteristic impedance is equals to 50Ω.

Equation (5) can be used to calculate the characteristic impedance of Z_{50} knowing its width W_{50}:

$$Z_{50} = \frac{120\pi}{\sqrt{\varepsilon_r}\left(\frac{W_{50}}{h} + 1.393 + 0.0667\ln\left(\frac{W_{50}}{h} + 1.44\right)\right)} =< \frac{126}{\sqrt{\varepsilon_r}}$$

$$\text{with} \quad W_{50} > h \tag{5}$$

Conversely, equation (6) can be used to calculate the width W_{50} knowing the impedance Z_{50}:

$$\frac{W_{50}}{h} = \frac{2}{\pi}\left[B - 1 - \ln(2B-1) + \frac{\varepsilon_{r-1}}{2\varepsilon_r}\left(\ln(B-1) + 0.39 - \frac{0.61}{\varepsilon_r}\right)\right] \tag{6}$$

With: $B = \frac{377\pi}{2\boldsymbol{Z}_{50}\sqrt{\boldsymbol{\varepsilon_r}}}$, $\frac{W_{50}}{h} > 2$, h: the thickness of the substrate, and ε_r its relative primitiveness. Z_{50}, W_{50} represent impedance and width, respectively, when the line has a characteristic impedance of 50 Ohm.

The design of the basic 1 × 2 magic-T power divider is shown in Figure 3.

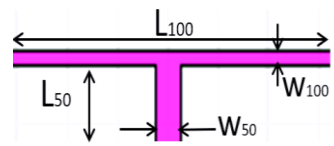


Fig. 3 – Design of the proposed 1 × 2 MTPD

The calculation of the different parameters of this structure were carried out using the following approach:

i) Knowing the input impedance $Z_0 = Z_{50} = 50$ Ω, we found out the output impedances $Z_1 = Z_{100} = 100$ Ω using equation (1),

ii) Equation (6) is used to calculate the width W_{50} and W_{100} of each branch line from their impedances Z_{50} and Z_1 (= Z_2) respectively.

iii) the length of the impedance line 100 Ω is initially chosen $L_{100} \leq \frac{\lambda}{2}$.

iv) A parametric study on lengths L_{50} and L_{100} was carried out to obtain a low loss structure (S_{11} lower – 10 dB) capable to divide the power feed into two equal parts ($S_{12} = S_{13} = -3$ dB) in phase.

The final optimal dimensions obtained of this structure are: W_{100} = 2.78 mm, W_f = 4.48 mm, L_{100} = 60.7 mm, L_{50} = 15 mm.

The simulation results obtained by HFSS, in terms of reflection coefficient S_{11} and transmission coefficients S_{12} and S_{13} are shown in Fig. 4. In Fig. 4(a) the modules of the parameters S_{11}, S_{12} and S_{13} in dB are represented versus frequency. It can be noted that the bandwidth is wide, equals about 1.4 GHz (from 1.3 to 2.7 GHz), that at the operating frequency 2.4 GHz, S_{11} = – 11 dB (< – 10 dB which means there is a low loss structure), S_{12} = – 3.27 dB and S_{13} = – 3.26 dB, which are close to the ideal value – 3 dB. Therefore, the input power was divided into two parts equal in modules.

Fig. 4(b) shows the phases of S_{12} and S_{13} versus frequency. It can be seen that their phases are respectively equals to – 175.86° and – 174.88°, the phase shift between them is 0.98° which means that the two signals are in phase.

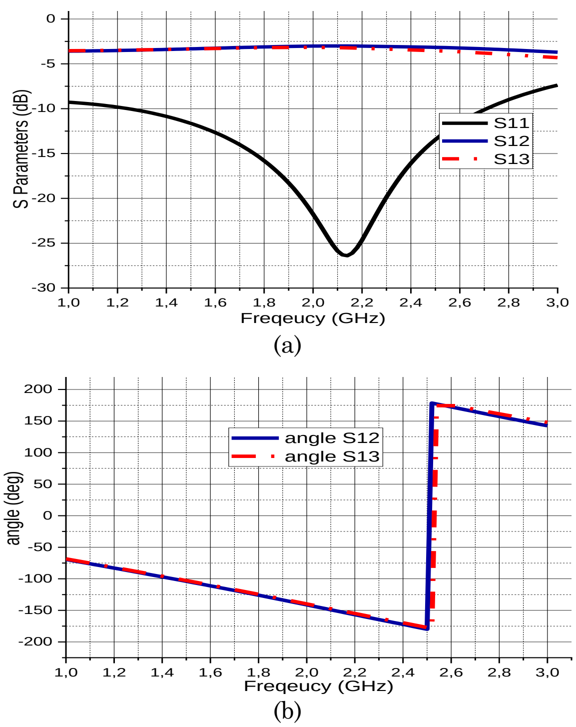


Fig. 4 – (a): S_{11}, S_{12} and S_{13} (dB) vs. frequency, (b): phases of S_{12} and S_{13} vs. frequency of the proposed 1 × 2 MTPD

3. STUDY AND DESIGN OF A 1 × 4 MAGIC-T POWER DIVIDER (6 dB)

The proposed 1 × 4 divider is a T junction having one input port and 4 output ports. It divides the input power into 4 equal quantities (6 dB) in phase. This type of divider will be able to feed an array antenna of 4 elements.

For a reciprocal, lossless, symmetric and isotropic T junction 1 × 4, the *S* matrix is given by:

$$[S] = \begin{bmatrix} 0 & S_{12} & S_{13} & S_{14} \\ S_{12} & 0 & S_{23} & S_{24} \\ S_{13} & S_{23} & 0 & S_{34} \\ S_{14} & S_{24} & S_{34} & 0 \end{bmatrix}$$

Based on the 1 × 2 MTPD, proposed in the previous paragraph, the design process has been extended to magic-T 1 × 4 power divider as shown in Fig. 5. It has one input port and four output ports. It consists of two identical 1 × 2 MTPD which feeds another 1 × 2 MTPD.

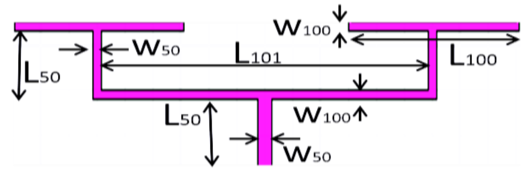


Fig. 5 – Structure of the proposed 1 × 4 MTPD

The parameters of this optimized structure are given as follows: W_{100} = 2.78 mm, W_{50} = 4.48 mm, L_{100} = 60.7 mm, L_{50} = 15 mm, L_{101} = 123 mm.

The simulation results of this structure in terms of *S* parameters are shown in Fig. 6. Fig. 6(a) represents modules of the parameters S_{11}, S_{12}, S_{13}, S_{14} and S_{15} in dB versus frequency. It can be noted that the structure has a wide bandwidth equals to 900 MHz (from 1.75 to 2.65 GHz), that it's a very low loss at the operating frequency 2.4 GHz with S_{11} = – 40 dB; and that the transfer parameters with the values of S_{12} = – 6.42 dB, S_{13} = – 6.36 dB, S_{14} = – 6.51 dB and S_{15} = – 6.47 dB are almost equal and are close to the desired ideal value – 6 dB. Therefore, the input power was divided into 6 equal quantities.

Figure 6. (b) shows the phases of S_{12}, S_{13}, S_{14} and S_{15} versus frequency. According to this figure it is clear that these parameters are in good agreement. Indeed, at the operating frequency the phases of the parameters S_{12}, S_{13}, S_{14} and S_{15} are – 104.86°, – 106.72°, – 102.63°, – 105.46° respectively.

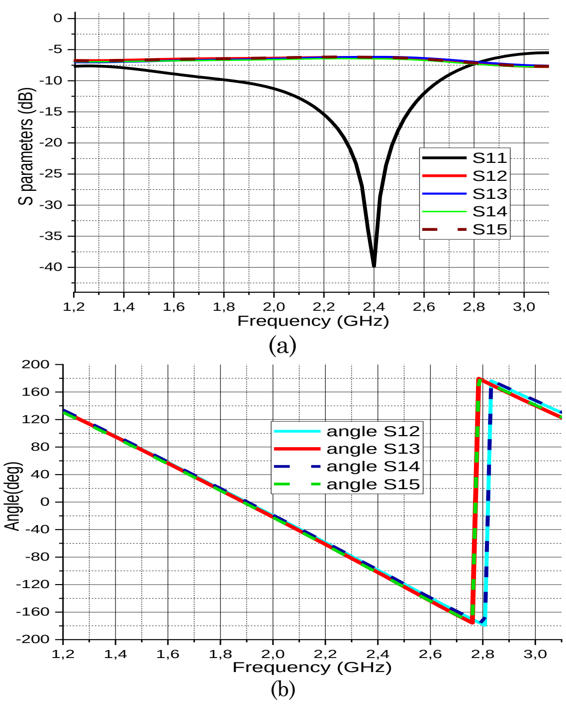


Fig. 6 – (a): *S* parameters vs. frequency, (b): phases of S_{12}, S_{13}, S_{14} and S_{15} vs. frequency of the proposed 1 × 4 MTPD

4. STUDY AND DESIGN OF THE PROPOSED MAGIC-T 1 × 8 POWER DIVIDER (MTPD 9 dB)

The 1 × 8 MTPD is a 9-ports T-type junction; one input port and 8 output ports. It can be used to feed an 8-element array antenna. For a symmetric, reciprocal and lossless structure its matrix [*S*] is as follows:

$$[S]=\begin{bmatrix} 0 & S_{12} & S_{13} & S_{14} & S_{15} & S_{16} & S_{17} & S_{18} & S_{19} \\ S_{12} & 0 & S_{23} & S_{24} & S_{25} & S_{26} & S_{27} & S_{28} & S_{29} \\ S_{13} & S_{23} & 0 & S_{34} & S_{35} & S_{36} & S_{37} & S_{38} & S_{39} \\ S_{14} & S_{24} & S_{34} & 0 & S_{45} & S_{46} & S_{47} & S_{48} & S_{49} \\ S_{15} & S_{25} & S_{35} & S_{45} & 0 & S_{56} & S_{57} & S_{58} & S_{59} \\ S_{16} & S_{26} & S_{36} & S_{46} & S_{56} & 0 & S_{67} & S_{68} & S_{69} \\ S_{17} & S_{27} & S_{37} & S_{47} & S_{57} & S_{67} & 0 & S_{78} & S_{79} \\ S_{18} & S_{28} & S_{38} & S_{48} & S_{58} & S_{68} & S_{78} & 0 & S_{89} \\ S_{19} & S_{29} & S_{39} & S_{49} & S_{59} & S_{69} & S_{79} & S_{89} & 0 \end{bmatrix} \quad (10)$$

Based on the previously designed 1 × 2 and 1 × 4 MTPD, the design can be extended to 1 × 8 MTPD, it consists of four identical 1 × 2 MTPD which are fed by two others identical MTPD as shown in Fig. 7. The proposed 1 × 8 MTPD divide the input signal power into eight equal quantities (a power division ratio equals to 9 dB) in phase agreement.

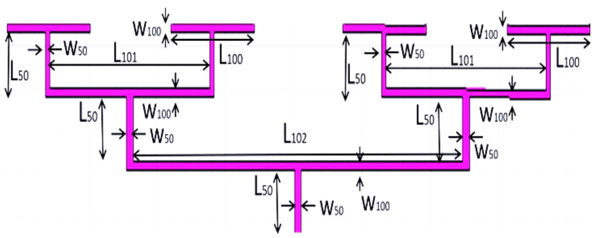


Fig. 7 – Structure of the proposed 1 × 8 MTPD

The final dimensions of this optimized magic-T 1 × 8 power divider are as follows: W_{100} = 2.78 mm, W_{50} = 4.48 mm, L_{100} = 60.7 mm, L_{50} = 15 mm, L_{101} = 123 mm, L_{102} = 240.7 mm. The simulation results of the optimized 1 × 8 MTPD in terms of *S* parameters are shown in Fig. 8 and 9. Fig. 8(a), (b), (c) and (d) show a comparison between the reflection coefficient S_{11} and two transmission coefficients of two neighboring output ports having the same power supply. it's clear that the structure has a wide bandwidth equals 506 MHz (from 2.022 GHz to 2.528 GHz) with a minimum reflection coefficient of – 19.12 dB at the operating frequency 2.4 GHz. Moreover, the values of the transmission coefficients S_{12}, S_{13}, S_{14}, S_{16}, S_{16}, S_{17}, S_{18} and S_{19} are almost equal to – 9 dB throughout this band. The value – 9 dB confirms that the input power has been divided by 8 and distributed equally to the 8 output ports.

Fig. 9(a), (b), (c) and (d) show the phases of the transmission coefficients of two neighboring output ports having the same power supply, versus frequency. They show that almost all curves are in good agreement which means that all output signals are in phase agreement.

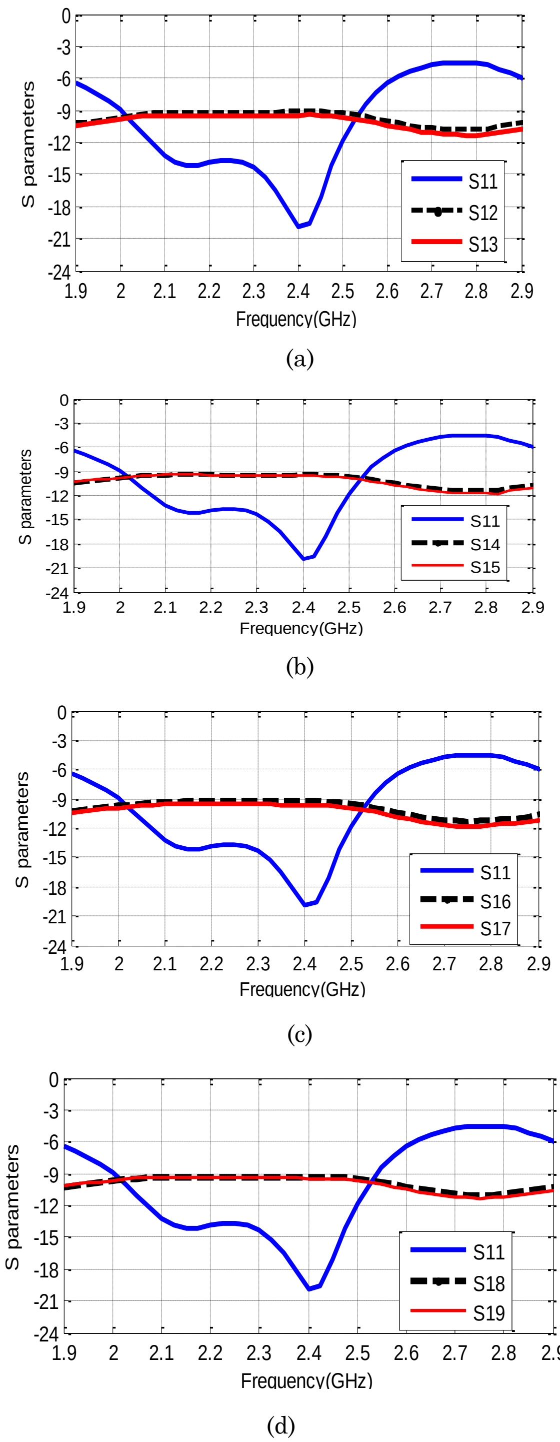


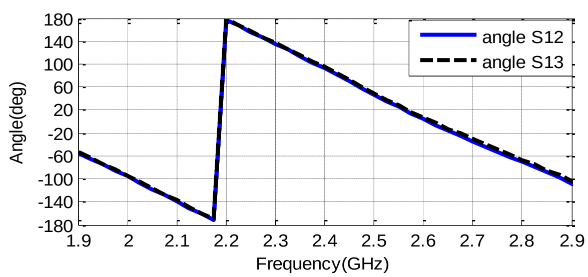
Fig. 8 – (a) S_{11}, S_{12}, S_{13} versus frequency; (b) S_{11}, S_{14} and S_{15} versus frequency; (c) S_{11}, S_{16}, S_{17} versus frequency; (d) S_{11}, S_{18} and S_{19} versus frequency of the proposed 1 × 8 MTPD

Table 1 summarizes the modules and phases of the transmission coefficients (S_{12}, S_{13}, S_{14}, S_{16}, S_{16}, S_{17}, S_{18} and S_{19}), and the phase shift between two neighboring output ports having the same power supply at the operating frequency 2.4 GHz.

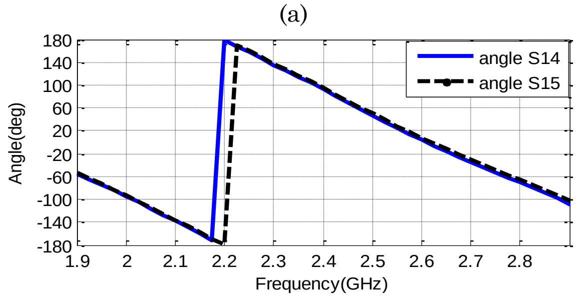
Table 1 – Summary of transmission coefficient values and their angles at operating frequency 2.4 GHz

S parameters	Value (dB)	Angle(deg)	Phase shift
S_{12}	– 9.13	91.91	2.23
S_{13}	– 9.44	94.14	
S_{14}	– 9.43	92.45	2.67
S_{15}	– 9.53	95.12	
S_{16}	– 9.27	92.12	2.84
S_{17}	– 9.62	95.06	
S_{18}	– 9.33	90.99	2.83
S_{19}	– 9.45	90.83	

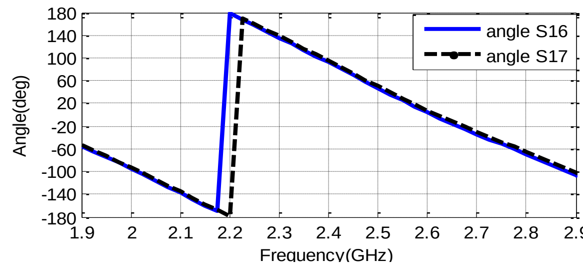
Based on these results, it can be concluded that proposed power divider has a power distribution ratio equal to 9 dB with negligible phase shift of about 2.8° between the output signals. Therefore, this divider is a potential candidate for feeding an 8-element array antenna.



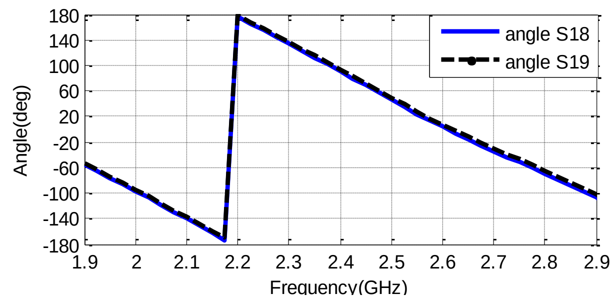
(a)



(b)



(c)



(d)

Fig. 9 – (a) angles of S_{11}, S_{12}, S_{13} parameters versus frequency; (b) angle of S_{11}, S_{14} and S_{15} versus frequency; (c) angles of S_{11}, S_{16}, S_{17} versus frequency; (d) angles of S_{11}, S_{18} and S_{19} versus frequency of the proposed 1 × 8 MTPD

5. CONCLUSION

A design methodology a broadband 1 × 8 magic-T power divider with good matching at all its ports is discussed. The design is conducted on substrate Rogers RT/duroid 5880 with the total size is 424 × 49 × 1.56 mm^3. the proposed broadband 1 × 8 magic-T power divider has an impedance bandwidth of 506 MHz with the ability to divide the power feed into 8 equal quantities (9 dB) in phase agreement. It is a potential candidate to feed an array antenna or power amplifier network that works in the ISM band around 2.4 GHz.

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Широкосмуговий мікросмужковий дільник потужності 1 × 8 Magic-T для використання в ISM антенних решітках

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Стаття присвячена розробці та аналізу мікросмужкового дільника потужності 1 × 8 magic-T (MTPD) для застосування антенної решітки діапазону ISM (промисловий і медичний діапазон). Спочатку розроблено та оптимізовано базовий дільник потужності 1 × 2 magic-T. Він може розділити живлення на дві рівні частини (3 дБ) за синфазним узгодженням. Потім був розроблений дільник потужності 1 × 4 з використанням двох ідентичних базових дільників потужності 1 × 2 magic-T; він ділить джерело живлення на чотири рівні частини (6 дБ) за синфазним узгодженням. Нарешті, запропонований широкосмуговий дільник потужності 1 × 8 magic-T складається з двох ідентичних дільників потужності 1× 4 magic-T; він може розділити джерело живлення на 8 рівних частин (9 дБ) у фазовому узгодженні. Згідно з отриманими результатами, запропонований дільник потужності 1 × 8 має ширину смуги пропускання -10 дБ, що дорівнює приблизно 506 МГц (від 2,022 ГГц до 2,528 ГГц) з мінімальним коефіцієнтом відбиття S11, що дорівнює приблизно – 19,12 дБ на робочій частоті 2,4 ГГц. Крім того, модуль коефіцієнтів передачі (S12, S13, S14, S16, S16, S17, S18 і S19) дорівнює приблизно – 9 дБ з незначним фазовим зсувом, рівним 2,8° між вихідними сигналами. Результати проектування та моделювання запропонованого дільника потужності 1 × 8 виконано на симуляторі EM HFSS з використанням підкладки Rogers RT/duroid 5880 із загальним розміром 424 × 49 × 1,56 мм^3. Запропонований дільник потужності є потенційним кандидатом для живлення антенної решітки, підсилювачів і модуляторів з восьми елементів у діапазоні ISM близько 2,4 ГГц (2,022 ГГц-2,528 ГГц).

Ключові слова: Широкосмугова антена, Діапазон ISM, Дільник потужності, Антенна решітка, Magic-T, Широкосмуговий дільник потужності, Дільник потужності Wilkinson.