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Modeling and Characteristics of a 3 dB Hybrid Coupler for 5G Applications

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The 3 dB, 90° coupler is a passive device with four ports that allows each output to collect half the input power but in phase quadrature. The 3 dB coupler is often made in microstrip technology where different quarter-wave sections are present to ensure impedance matching. In order to be able to design a duplexer operating on several frequency bands, a tunable hybrid coupler was designed in this work. The coupler must be adjustable to operate on the bands 3.3-3.6 GHz and 4.8-5 GHz. The proposed coupler will cover the bandwidth requirements of 5 bands (3.3-3.6 GHz) and (4.8-5 GHz) to be deployed in China. The hybrid coupler will be designed by two methods. At the first stage, the coupler will be designed by lumped elements, and then it will be designed using transmission lines. Via the ADS tool, the 3 dB 90° coupler is dimensioned and simulated to work well at the center frequency of 3.45 and 4.9 GHz. These two frequencies are belonging to the 5G bands. The main purpose of this work is to simulate and analyze the proposed coupler for 5G frequency bands. The simulation of the reflection coefficient, i.e., S11 parameters in amplitude and phase are presented and discussed. From simulation results we observed that the proposed coupler works under the requirement of 5G application.

Keywords: 5G, 3 dB hybrid coupler, RF, Lumped elements, Equivalent circuit.

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1. INTRODUCTION

Many consumer applications have emerged since the 2000s for telecommunications. As early as 1995, the enthusiasm for RF and millimeter had been tipped in [1]. More recently we have heard a lot about the Internet of Things (IoT) which has taken a big rise since 2012 (first start-ups) and finally since 2015 we notice a craze for the autonomous car which will soon become the main market of electronics [2]. These applications require in RF band (from a few hundred MHz to a few GHz) low consumption, such as for IoT. In millimeter bands (between 30 GHz and 300 GHz), we will target either broadband (in particular for 5G around 28 GHz [3] and 38 GHz [4], and future generations beyond 100 GHz [5] for which the rate can reach 10 Gbps), or resolution (for medical imaging between 100 and 200 GHz), [6, 7]. Today, RF applications are used in different scientific fields. From a commercial point of view, modern applications that integrate RF include smartphones, 3G, 4G and Wi-Fi wireless networks, millimeter-wave collision sensors for vehicles, satellite communications, global Positioning Systems, RFID radio frequency identification marking [8], etc. the global electronics market is still guided to this day by cellular telephony (future 5G) but in a couple of years it is really connected objects (IoT) [2].

As a result, active and passive components will play a vital role in the operation of any electronic device. The millimeter passive functions are for example impedance matching networks, couplers and baluns, power dividers or filters. Although the footprint of the components passes decreases with frequency, the area used to make these circuits is much larger than that required for the active elements. The development of passive microwave circuits relies on the optimization of effective transmission lines and waveguides. The design of high-performance and compact transmission lines is an important challenge to realize miniaturized circuits in RF and millimeter bands. In this sense, the objective of this work is to design a coupler to be used for the duplexer architecture. In fact, couplers are extremely useful and versatile microwave components including the first function is to pair or split the incident signal or power in such a way disproportionately or equally. In the latter case, we speak of power divider or 3 dB directional coupler. They are used in many applications including wireless telecommunications systems, radar systems, and in systems biomedical [9]. The coupler can be used in many applications [19-13].

The purpose of this work is to propose a coupler for designing a duplexer for 5G applications. In this direction, a tunable hybrid coupler was designed in this work. The hybrid coupler was designed by two methods. A coupler with by lumped elements is designed and simulated. For the same object, the same coupler was designed by using transmission lines. Via the ADS tool, the 3 dB 90° coupler is dimensioned and simulated to work well at the center frequency of 3.45 and 4.9 GHz. The S_{11} parameter simulation is carried out in order to analyze the performance of the proposed coupler. It has been demonstrated that the 3 dB coupler presented in this work can be used in 5G circuits.

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2. 3 DB HYBRID COUPLER

The primary function of couplers is to couple or divide the incident signal or power disproportionately or equally. They are used in many applications including wireless telecommunications systems, radar systems, measurement and instrumentation systems such as test systems, vector analyzers, power meters, loop automatic gain controllers, reflectometers and in biomedical systems. Therefore, in order to carry out different treatments at the antennas or circuits it is often essential to have a coupler. The coupler, which we will discuss in this paper, is the 3 dB coupler. Fig. 1 shows a micro ribbon line directional coupler. The fluency graph of this quadriport is shown in Fig. 2.

A 3 dB hybrid coupler is a 4-port device that allows the signal injected on a port to be separated into two identical signals equivalent to half the initial power, or – 3 dB, but with a phase difference that can be either 90° or 180° as shown in Fig. 3. If the outputs are mismatched, part of the signal ends up on the isolated port. The hybrid coupler is a microwave device that is widely used as a protection circuit against reflected waves and as an adder, as for example in a balanced PA [14]. Since the hybrid coupler is composed of passive elements, it is reciprocal.

It is possible to consider using the hybrid coupler directly as a duplexer. In this case, the T_x signal will be applied to port 1 and it will be transmitted to the antenna (port 3). In reception, the signal from the antenna will be transmitted to R_x connected to port 2. However, this topology is not optimized at all for optimal transmission of T_x and R_x signals. Indeed, part of the T_x signal will load on port 4 while part of the signal received by the antenna will be found on port 1, i.e., T_x.

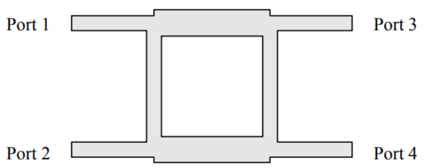

Fig. 1 – Microstrip line directional coupler

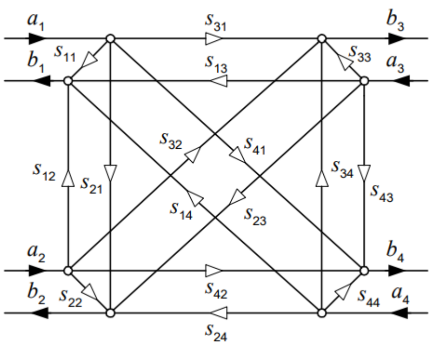

Fig. 2 – fluency graph of a quadriport

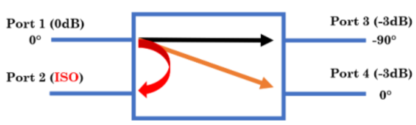

Fig. 3 – A 3 dB hybrid coupler

3. MODELING AND CHARACTERISTICS OF A 3 DB HYBRID COUPLER

In order to be able to characterize the hybrid coupler in amplitude and phase, we use the parameters *S*. regarding this 4-port device, assuming that all ports are suitable, the parameters S are described as follows:

$$[s] = \begin{pmatrix} 0 & S_{12} & S_{13} & S_{14} \\ S_{21} & 0 & S_{23} & S_{24} \\ S_{31} & S_{32} & 0 & S_{34} \\ S_{41} & S_{42} & S_{43} & 0 \end{pmatrix}.$$

Knowing that the hybrid coupler chosen in this study has a phase of – 90° on the direct channel, that it has a port on which the signal is totally isolated and that the injected signal is divided in half as shown in Fig. 1, the ideal s parameters will then be:

$$[s] = \begin{pmatrix} 0 & 0 & \frac{-j}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 0 & 0 & \frac{1}{\sqrt{2}} & \frac{-j}{\sqrt{2}} \\ \frac{-j}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 & 0 \\ \frac{1}{\sqrt{2}} & \frac{-j}{\sqrt{2}} & 0 & 0 \end{pmatrix}.$$

In general, a hybrid coupler can be designed either in discrete elements or using transmission lines.

4. SIMULATION RESULTS

4.1 Hybrid Coupler Design Using Lumped Elements

The design of the hybrid coupler will be done using lumped elements. The generally used topology of a hybrid coupler using discrete elements is shown in Fig. 4. In order to characterize the structure, the admittances parameters are used to extract the *S* parameters.

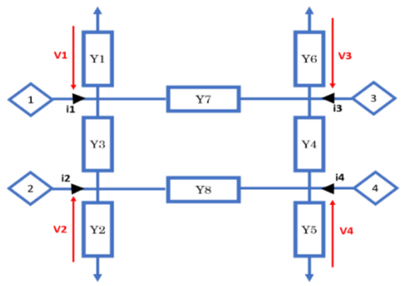

Fig. 4 – 3 dB hybrid coupler using lumped elements

The matrix of a 4-port device in admittance is of the following form:

$$\begin{pmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{pmatrix} = \begin{pmatrix} Y_{11} & Y_{12} & Y_{13} & Y_{14} \\ Y_{21} & Y_{22} & Y_{23} & Y_{24} \\ Y_{31} & Y_{32} & Y_{33} & Y_{34} \\ Y_{41} & S_{42} & Y_{43} & Y_{44} \end{pmatrix} \begin{pmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \end{pmatrix}.$$

Each Y_{ij} parameter is calculated by canceling the corresponding voltages. Thus, we can build our matrix in admittance for the hybrid coupler:

$$\begin{pmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{pmatrix} = \begin{pmatrix} Y_1 + Y_7 + Y_3 & -Y_3 & -Y_7 & 0 \\ -Y_3 & Y_2 + Y_3 + Y_8 & 0 & Y_8 \\ -Y_7 & 0 & Y_6 + Y_4 + Y_7 & Y_4 \\ 0 & Y_8 & Y_4 & Y_5 + Y_4 + Y_8 \end{pmatrix} \begin{pmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \end{pmatrix}$$

where Y_1, Y_2, Y_3, Y_4, Y_5, Y_6, Y_7, Y_8, Y_9 are the admittance represented in Fig. 2. From the matrix [Y] it is possible to extract the matrix [S]. For this, we assume that the impedance matching is checked, so we have:

$$a_i = \frac{1}{2\sqrt{Z_0}}(V_i + Z_0 I_i),$$

$$b_i = \frac{1}{2\sqrt{Z_0}}(V_i - Z_0 I_i),$$

So, $b_i = [s]a_i$,

which mean

$$(V_i - Z_0 I_i) = [s](V_i + Z_0 I_i),$$

$$(V_i - Z_0[Y]V_i) = [s](V_i + Z_0[Y]V_{i_i}),$$

$$(Id - Z_0[Y]) = [s](Id + Z_0[Y]),$$

while Id represents the unit matrix. Thus, the matrix [S] is described as

$$[S] = (Id - Z_0[Y])(Id + Z_0[Y])^{-1}.$$

We are therefore able to model and apply pass-through relationships between component values and admittance or S parameters for a coupler.

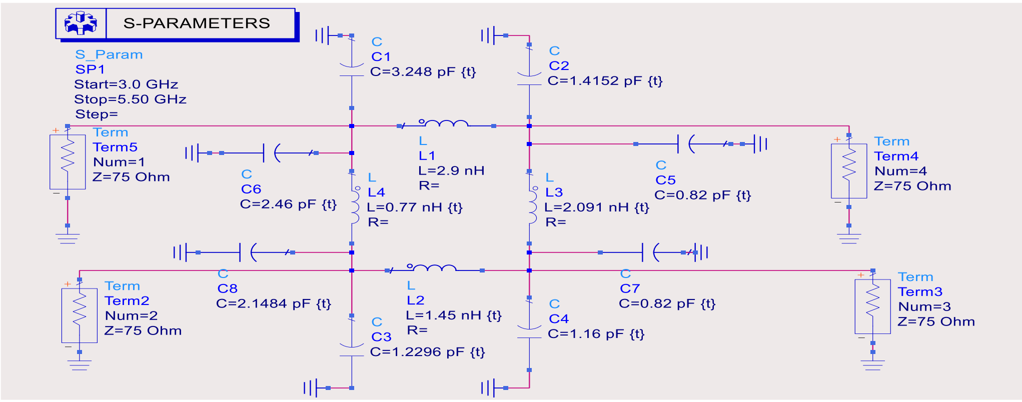

Fig. 5 – Schematic of the hybrid coupler using lumped elements

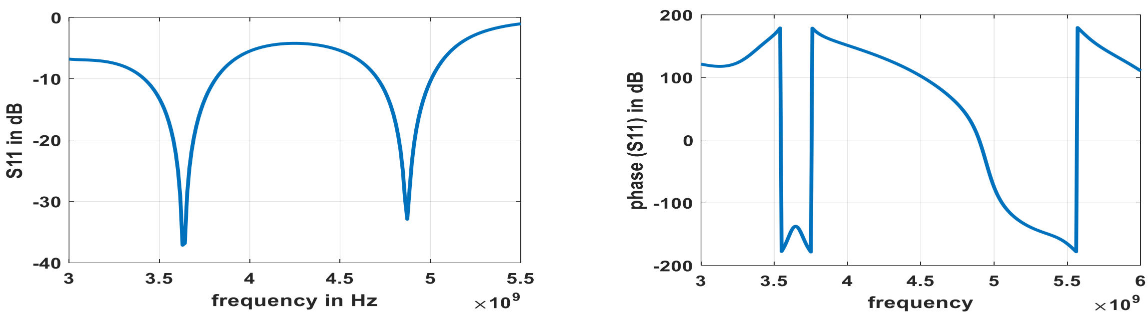

Fig. 6 – S_{11} (a) and the phase (b) of the proposed coupler

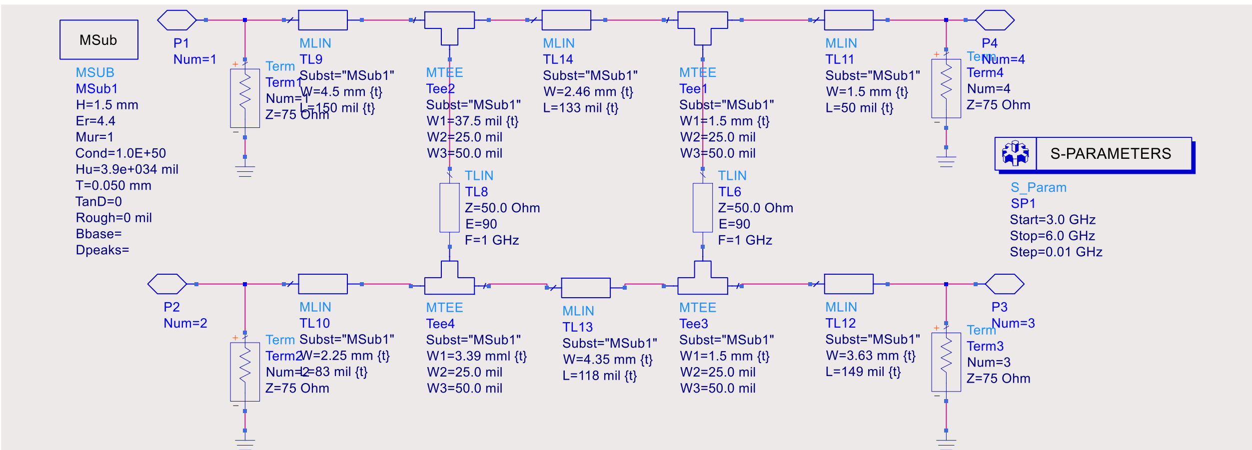

Fig. 7 – Schematic of the hybrid coupler using transmission line

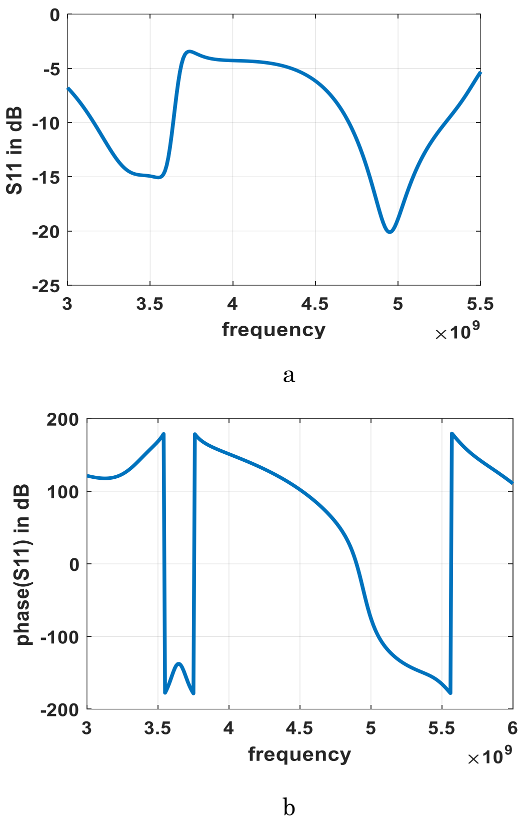

Fig. 8 – S_{11} (a) and the phase (b) of the proposed coupler

In order to be able to design a duplexer operating on several frequency bands, a tunable hybrid coupler was designed. It must be adjustable to work on bands cited above. The tuning is achieved by varying the impedances of each branch of the coupler according to the desired frequency band (Fig. 5). The choice of the band is made by selecting different capacitance values through RF switches. It will be easier to achieve switchable capabilities than inductive chokes. Thus, for branches consisting of an inductance, a serial capacitance is added to vary the impedance.

The simulation results of S_{11} and phase are depicted in Fig. 6. From this figure, we can conclude that the proposed coupler works in the two mentioned bands.

4.2 Hybrid Coupler Design Using Transmission Line Method

Via ADS, a 3 dB, 90° coupler is dimensioned and simulated to work well in the two 5G bands cited above (Fig. 7). The simulation of S_{11} parameters is shown in Fig. 8a. From this figure, we see that there is a very good adaptation. S_{11} remains less than – 10 dB on the two bands. The phases of the decoupling pathways are shown in Fig. 8b. We can conclude from the simulation results that the results obtained of this coupler are quite acceptable.

5. CONCLUSIONS

In this work we designed a coupler which works on the operating bands 3.3-3.6 GHz and 4.8-5 GHz. The proposed coupler can be used for 5G application. It has been designed by two methods. The simulation of the S_{11} parameters in amplitude and phase are presented. From simulation results we observed that the proposed coupler works under the requirement of 5G application.

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Моделювання та характеристики гібридного антенного з'єднувача (з коефіцієнтом підсилення 3 дБ) для додатків 5G

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Антенний з'єднувач з коефіцієнтом підсилення 3 дБ та зсувом фази на 90° між вихідними портами – це пасивний пристрій з чотирма портами, який дозволяє кожному виходу збирати половину вхідної потужності, але у фазовій квадратурі. Такий з'єднувач часто виготовляється мікросмуговою технікою, в якій присутні різні чвертьхвильові ділянки для забезпечення узгодження імпедансу. Для того, щоб мати можливість сконструювати дуплексер, який працює на декількох частотних діапазонах, у роботі був розроблений регульований гібридний з'єднувач. З'єднувач повинен регулюватися для роботи на діапазонах 3,3-3,6 ГГц та 4,8-5 ГГц. Запропонований з'єднувач задовольнить вимоги до пропускної здатності 5 діапазонів, що будуть розгорнуті в Китаї. Гібридний з'єднувач буде спроектовано двома методами. На першому етапі з'єднувач буде сконструйований елементами з зосередженими параметрами, а потім проектуватиметься за допомогою ліній електропередачі. З використанням інструменту ADS з'єднувач з коефіцієнтом підсилення 3 дБ та зсувом фази на 90° між вихідними портами розрахований та змодельований для роботи на центральній частоті 3,45 і 4,9 ГГц. Ці дві частоти належать до діапазонів 5G. Основною метою роботи є моделювання та аналіз запропонованого з'єднувача для частотних діапазонів 5G. Представлено та обговорено моделювання коефіцієнта відбиття, тобто параметра S_{11} за амплітудою та фазою. З результатів моделювання ми помітили, що запропонований з'єднувач працює за вимогами додатків 5G.

Ключові слова: 5G, Гібридний антенний з'єднувач (з коефіцієнтом підсилення 3 дБ), Радіочастота, Елементи з зосередженими параметрами, Еквівалентна схема.