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Miniaturized High Frequency Ratio Quadrature Coupler for Dual Band Wireless Systems

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Abstract. Dual band high frequency ratio quadrature couplers are needed in wireless systems to work with similar performances in low and high frequency bands, keeping the dimensions reduced and being easy to manufacture and integrate in planar structures. To address these challenges, in this paper, a miniaturized dual-band branch-line coupler with large frequency ratio and coupling losses around 3.5 dB for both bandwidths is proposed, implemented, and measured. Miniaturized impedance inverter transmission lines were used to replace the classical transmission lines (TLs) of the branch-line coupler. Two arbitrary frequencies, 0.7 GHz and 5.6 GHz, with a ratio of 8.28 were chosen to implement and measure the coupler's performances. The simulation results of the dual band coupler show good agreement with the measurements. The return loss and isolation loss are greater than 30 dB, while the insertion and coupling losses are around 3.5 dB for both bandwidths. The phase difference is 90^{o} and a relative bandwidth of more than 20% for both frequencies is obtained considering a phase imbalance of ±5^{o}. The bandwidth for the coupling attenuation is around 50% for both frequency ranges when imposing a magnitude imbalance of ±1.5 dB. The dimensions of the proposed coupler are around $0.45\lambda_g 0.23\lambda_g$ at the central frequency of 3.25 GHz, showing that excellent performances can be attained with miniaturized dual band transmission line.

Key-words: Dual-band microwave passive component; high band ratio; measurement of S-parameters; miniaturized branch-line coupler; wireless applications.

1. Introduction

Branch line couplers are key components in measurement instruments as they can be used in setups for signal monitoring and calibration, to obtain larger reflected signal levels in the time-domain measurement of well-matched microwave components [1], to measure the voltage standing wave ratio [2], to separate the incident and reflected waves [3], to divide or combine quadrature signals or to be employed in the feed network of phased array antennas for dividing the input power among multiple radiating elements [4], [5].

A classical branch-line coupler consists of two pairs of quarter-wavelength transmission lines, and it is a narrow band device. The bandwidth is around 20% for a 20 dB isolation. To increase the bandwidth, multiple branches can be added, but this will increase the size of the coupler as well [6]. Also, a branch-line coupler works at only one frequency or harmonics of that frequency, but not at multiple arbitrary frequencies, with no dependency between them. To overcome these limitations, different approaches have been reported in the literature.

To increase the bandwidth, in [7], techniques like defected ground structure are reported to improve the 20 dB return-loss bandwidth to up to 70%, but this approach provides reduced in-band isolation. Other techniques refer to designing the four branches using lumped and distributed elements, which ensures a bandwidth increase to 84% for a return loss better than 15 dB, respectively a bandwidth of 68% for an isolation loss larger than 20 dB, as shown in [6]. The main drawback of this technique is that the coupler's size is considerable large.

To transform the single band classical coupler into a dual band one, in literature, several configurations have been used, such as: π shaped dual lines [8], short-ended and open-ended [9], Composite Right Left-Handed transmission lines (CRLH TLs) [10]. Most of the dual band couplers presented in literature are designed to work at two arbitrary frequencies, but with a frequency ratio less than 3.

Last, but not least, the size reduction of the coupler is very important and has been addressed by several references in literature. A 46.62% size reduction compared to the standard one has been achieved in [11], as a T-shaped line replaced the conventional line in which both the lines and stubs were folded. The coupler does not operate at two arbitrary frequencies, but at a central frequency and its harmonic. In [12], the proposed topology is constructed using a coupled line, two series transmission lines, and open-ended stubs. The physical area of the prototype is reduced by 87.7% of the conventional coupler's size and the fractional bandwidth is greater than 52%. The only drawback of this coupler is that it is a single band coupler operating at 0.9 GHz.

Therefore, the main contribution of this paper is the design of a 3 dB branch-line coupler having the largest frequency ratios reported in the literature to the authors' knowledge, of 8.28, an important size reduction due to utilizing miniaturized unit cells and exhibiting similar performances at both frequencies. The coupler is implemented and measured, and the results are very similar to the simulated ones, showing very good performance for all parameters in both frequency ranges.

The paper consists of five sections. The first section is the introduction. The design of the dual band transmission lines with large frequency ratio is presented in Section 2. The design and implementation of the ideal dual band branch-line coupler with large frequency ratios are given in Section 3. The results and comparative analysis are presented in Section 4. Based on the results presented in Section 4, the conclusions are drawn in Section 5.

2. Design of the Dual Band Transmission Lines with Large Frequency Ratio

The branch line coupler is designed using dual band miniaturized quarter wave transmission lines. These types of transmission lines were first introduced by the authors in [13], where the analytical expressions were demonstrated, their dual properties were identified and were then used to design an ideal miniaturized rat-race coupler. The classical hybrid rat-race coupler consists of three identical transmission lines, each having a characteristic impedance of 70.71 Ω and a phase difference of 90^{o} and another transmission line with a characteristic impedance of 70.71 Ω and a phase difference of 270^{o}. On the other hand, the hybrid branch-line coupler is made of four transmission lines, each introducing a phase shift of 90^{o} and having different values for the characteristic impedance: 35.35 Ω, respectively 50 Ω. The two couplers have different design conditions, and this would lead to different properties of the coupler's response in frequency and other constraints in the design. For example, the significance of the ports changes when considering the same input port, the phase difference at the output ports is ±180^{o} for the rat-race coupler instead of ±90^{o} for the branch-line coupler, one being a differential coupler, the other one being a quadrature coupler. Also, when transforming the classical rat-race coupler or branch-line coupler into a dual-band one using the proposed transmission lines, different configurations are required. Because the design of the branch-line coupler and rat-race coupler is different, the approach is different, and the analytical expressions used to design successfully a rat-race coupler may not be suited for overcoming the branch-line designing constraints and even more offer improved results in comparison to existing branch-line couplers reported in literature. This is what will be further investigated in this paper and what is essentially different from the coupler's design reported in [13]. Nevertheless, the differential coupler presented in [13] is an ideal one, without considering any technological constraints or limitations. Moreover, in [13], the coupler is designed to work at two arbitrary frequencies: 930 MHz, respectively 1780 MHz, having a low frequency ratio of only 1.91, instead of the ratio imposed in this research, 8.28, making the design more challenging.

In this paper, the novelty consists in designing miniaturized quarter wave transmission lines to address the branch-line's designing requirements of working at two arbitrary frequencies with a large frequency ratio, 0.7 GHz and 5.8 GHz, exhibiting improved performances, and enhanced bandwidth and reducing the dimensions of the circuit in comparison to other similar couplers reported in literature. Also, in this paper, all technological constraints will considered, which appear both when designing a different type of coupler than in [13], imposing large difference between the two working frequencies and addressing them, so that the performances are better than the ones reported in the literature for similar work.

The main advantages of the lines presented in [13] are the fact that they have a minimum number of components, they have a symmetric design, they act as impedance inverters at two frequencies and analytical relations can be used to compute the exact value of the components. All these advantages are useful when designing the branch-line coupler. The frequency behavior of the miniaturized quarter wave transmission lines at the two frequencies is of a quarter wave transmission line, meaning that at the first frequency their electrical length is 90^{o}, respectively at the second frequency is -90^{o}. They will replace the classical single band quarter wave transmission lines from the design of a Branch-line coupler, thus transforming the coupler into a dual band component.

If the "π" configuration given in Fig. 1 is considered using normalized values, then it can be demonstrated that these unit cells act as impedance inverters at two arbitrary frequencies [13]. There are two configurations given in Fig. 1, each of them corresponding to an arbitrary frequency. The schematic uses only normalized impedances, each impedance being normalized to the characteristic impedance of the transmission line, Z_C. In this case, the normalized input impedance is denoted by $z_{IN}=Z_{IN}/Z_C$, where Z_{IN} [Ω] is the input impedance in the circuit and Z_C [Ω] is the characteristic impedance of the transmission line, and the normalized load resistance is denoted by $r=R/Z_C$. It can be demonstrated that these configurations allow to obtain at the input of the circuit a normalized impedance, $z_{IN}=Z_{IN}/Z_C$ equal to the inverted normalized load resistance, $z_{IN}=1/r$, so acting as impedance inverters [13].

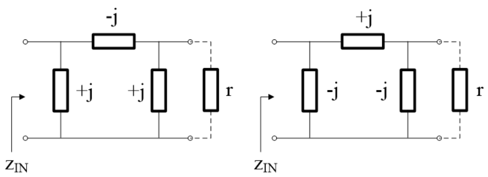

Fig. 1. "π" shape unit cell for quarter wavelengths transmission lines.

The next step is to denormalize the configurations given in Fig. 1. For this, in the longitudinal branch, an inductor of inductance L_s is considered in series with a capacitor of capacitance C_s and in the transversal branch an inductor of inductance L_p in parallel with a capacitor of capacitance C_p. For denormalizing, the ratio of the two arbitrary frequencies $k = \frac{\omega_2}{\omega_1}$ is considered, and the characteristic impedance of the transmission lines, Z_C:

$$\begin{aligned} x_1 - x_2 &= +1 \\ \Rightarrow \omega_1 \cdot L_s - \frac{1}{\omega_1 \cdot C_s} &= Z_c \\ kx_1 - \frac{x_2}{k} &= -1 \\ \Rightarrow \omega_2 \cdot L_s - \frac{1}{\omega_2 \cdot C_s} &= -Z_c \end{aligned} \tag{1}$$

Solving Equation (1) results in:

$$\begin{aligned} L_s &= \frac{1}{k-1} \cdot \frac{Z_c}{\omega_1} \\ C_s &= \frac{k-1}{k} \cdot \frac{1}{\omega_1 \cdot Z_c} \end{aligned} \tag{2}$$

For the parallel group (with admittance $Y_c = 1/Z_c$):

$$
\begin{aligned}
b_1 - b_2 &= -1 \\
\Rightarrow \omega_1 \cdot C_p - \frac{1}{\omega_1 \cdot L_p} &= -Y_c \\
k \cdot b_1 - \frac{b_2}{k} &= 1 \\
\Rightarrow \omega_2 \cdot C_p - \frac{1}{\omega_2 \cdot L_p} &= Y_c
\end{aligned} \tag{3}
$$

Finally, the solutions are:

$$
\begin{aligned}
C_p &= \frac{1}{k-1} \cdot \frac{1}{\omega_1 \cdot Z_c} \\
L_p &= \frac{k-1}{k} \cdot \frac{Z_c}{\omega_1}
\end{aligned} \tag{4}
$$

These relations will be considered to design dual band quarter wave transmission lines with large frequency ratios and then they will be used to transform the classical branch-line coupler into a dual band one operating with a large frequency ratio.

3. Design and Implementation of the Ideal Dual Band Branch-line Coupler with Large Frequency Ratio

In the application considered in this paper, two frequencies in WLAN bands are chosen: f_1=0.7 GHz and f_2=5.8 GHz, with the frequency ratio k=8.28. The first frequency is used for both commercial wireless and public safety communications as it offers the advantages of efficient coverage and penetration capabilities [14], while the second one meets the needs of high-bandwidth applications to support a large number of users, eight non-overlapping channels, which make the deployment more scalable and flexible [15]. Nevertheless, the frequencies can be chosen from any standards, with any frequency ratio that is needed as the designing algorithm remains the same.

The next step is to compute the values for lumped elements given by Equations (2) and (4). For this, it is needed to impose not only the frequencies, but also the value of characteristic impedance. For the design, a four arms branch-line coupler is considered, as shown in Fig. 2.

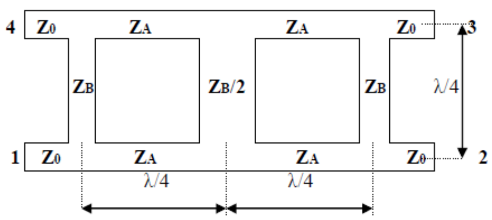

Fig. 2. Classical single band branch-line coupler with four arms and four ports.

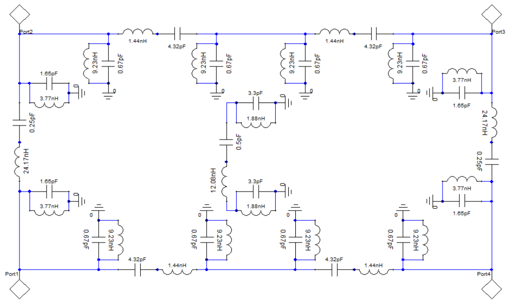

Fig. 3. The schematic of the proposed branch-line coupler with ideal lumped components.

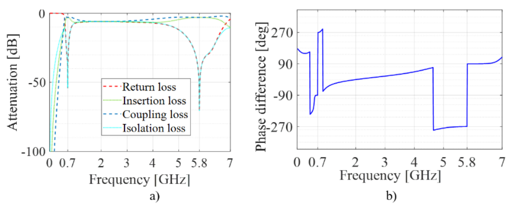

Fig. 4. Return loss, insertion loss, coupling loss, isolation loss and phase difference of the signals at the output ports for the dual band coupler with the frequency ratio 8.28.

The characteristic impedances Z_A, Z_B are computed by imposing the coupling attenuation of the coupler to 3 dB. Considering the impedance of the measurement cables, Z_0=50 Ω, then the characteristic impedance for each transmission line is determined: Z_A=46.2 Ω, respectively Z_B = 120.91 Ω [6]. The values of the lumped components are computed with relations (2) and (4), considering the values of the characteristic impedance for each transmission line and the pair of frequencies: f_1=0.7 GHz, respectively f_2=5.8 GHz. The values of the computations for the lumped elements when the characteristic impedance is Z_A=46.2 Ω are: L_p=9.23 nH, C_p=0.67 pF, L_s=1.44 nH, C_s=4.32 pF, when the characteristic impedance is Z_B = 120.91 Ω are: L_p=24.17 nH, C_p=0.25 pF, L_s= 3.77 nH, C_s=1.65 pF and when the characteristic impedance is $Z_B/2$=60.455 Ω are: L_p=12.08 nH, C_p=0.5 pF, L_s= 1.88 nH, C_s=3.3 pF.

The ideal branch-line coupler using only ideal lumped components is given in Fig. 3.

The results of the simulations for the ideal model of the branch-line coupler using the impedance inverter unit cells are given in Fig. 4 a) and b). The return loss, insertion loss, coupling loss and isolation loss are given in Fig. 4 a), while Fig. 4 b) presents the simulation results for the phase difference between signals at the output ports.

In the ideal case, there should be no reflections at the input port and no power transfer from the input port to the isolated port, so both the return loss and isolation loss should be an ∞. Analyzing the results in Fig. 4, it can be observed that the return loss and isolation loss take values up to 54 dB for the first frequency, respectively up to 72 dB for the second frequency, which are finite, very high values. The insertion loss and coupling loss take values equal to 3 dB, as imposed by design, showing that the proposed method to design the coupler is an accurate one, providing excellent results. Considering port 1 as the input port, ports 2 and 3 are the output ones and port 4 is the isolated one. A phase difference of ±90° at both frequencies proves that the coupler is indeed a quadrature one as imposed by the design and can be integrated in dual band

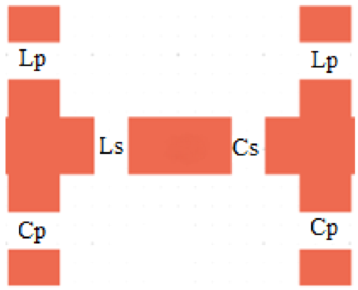

Fig. 5. The implementation with lumped elements (surface mounted passive devices/components) and microstrip technology of the miniaturized impedance inverter unit cell.

measurement instruments, working with similar performances at both imposed frequencies 0.7 GHz and 5.8 GHz, respectively. Next, the coupler will be considered for physical implementation and measurements. The results will be discussed in the next section.

4. Results and Comparative Analysis

Based on the ideal model proposed in the previous section, the next step is to implement the coupler using real components. For the lumped elements, Surface Mounted Devices (SMDs) are chosen to have a high-quality factor at high frequencies and low parasitic elements. The selected packages are chip, 0603 type, with the following dimensions: length-1.55±0.05 mm, width-0.85±0.05 mm, height- 0.45±0.05 mm (60 x 30 x 20 mil, in Imperial System). The small size chip passive components help to minimize the overall circuit.

The laminate used for the Printed Circuit Board (PCB) of the coupler is a special RF & microwave one, RT/duroid 5880 from Rogers Corporation, which is a PTFE Random Glass Fiber material. The dielectric substrate has a relative electrical permittivity (named in literature also "dielectric constant") of 2.2 at 10 GHz, a loss tangent (named in literature also "dissipation factor") of 0.009 at 10 GHz, a thickness of 1.6 mm, a thermal coefficient of the relative permittivity of -125 ppm/°C (in -50...150°C range), and a coefficient of thermal expansion of dielectric of 48 ppm/°C (in -55...288°C range). High purity Cooper foils, with a thickness of 35 µm, are placed on both sides. The manufactured PCB is basically a dedicated passive component; therefore, its layout is extremely important to be designed as to preserve the minimum/maximum parameters of the electronic circuit. The pads on which the components are placed and soldered are represented in Fig. 5.

As shown in Fig. 5, the passive components are arranged in a shape which minimize possible couplings between pads and traces, keeping a "π" symmetry. The values for the lumped elements obtained after computations differ from the standardized ones. To obtain values as close as possible to the computed ones, parallel and/or series configurations must be considered when designing the final coupler.

Choosing the type of lumped elements to be used involves determining the minimum/maximum parameters of the components so that the minimum/maximum parameters of the electronic circuit are achieved. The choice of types of lumped elements must be made at the same time as the electrical design of the electronic circuit, considering the parameters imposed on the circuit, the real conditions in which the circuit must operate, the reliability and cost price, the manufacturing and testing technologies. Considering the multitude of types of electronic components available on the market, it results that a lot of combinations can be used in the respective circuit. The combination that best corresponds to our specific application was chosen considering various considerations like cost, purchasing possibilities, size, weight, frequency behavior, mounting technologies, etc. Also, the packages used were measured and selected based on their real values and quality. Nevertheless, a trade-off between good performances at both frequencies has been considered in the design.

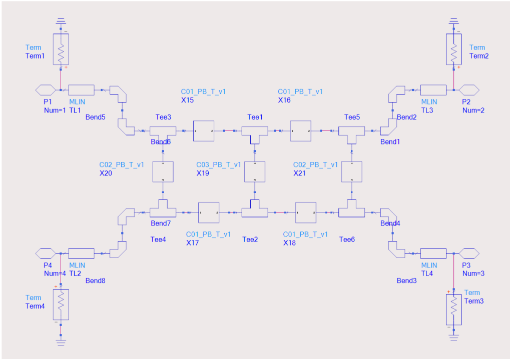

Fig. 6. The circuit/schematic diagram of the proposed dual band branch-line coupler.

The schematic diagram of the final circuit/design for the dual band branch-line coupler is given in Fig. 6. The dual band impedance inverter unit cells, as the one depicted in Fig. 5 were replaced by black boxes, of the form C_01_PB_T1 in the circuit from Fig. 6. In the schematic presented in Fig. 6, all microstrip components such as “Bends” of all shapes, “Tee” Sections and microstrip access transmission lines, “MLIN TL” have been represented. Also, the terminations, Term, for each port have been added and the ports have been numbered, P Num.

The layout of the final design based on the circuit in Fig. 6 is given in Fig. 7 a) and the legend for the layers is given in Fig. 7 b). The details of the stack-up structure and acronyms in Fig. 7 b) are presented, as follows: “Ground_Plane”- conductor/plane (Copper) layer on Bottom layer, “cond” - conductor (Copper) layer on Top layer, “cond2” - conductor (Copper) layer on an internal layer (not used), “resi”- resin layer (not presented in the figure), “diel”- dielectric layer (not presented in the figure), “Sel”- selection of the layer, “Vis”- visibility of the layer. The manufactured prototype of the coupler is presented in Fig. 7 c). The final prototype has a physical dimension of $0.45\lambda g \times 0.23\lambda g$, for a wavelength corresponding to an average frequency of 3.25 GHz [10]. The manufactured prototype was assembled using lead-free solder paste, a pick-and-place equipment, a convection oven and a soldering station with a consistent and controlled heat source. The measurements were carried out with Agilent Technologies E5071C vectorial analyzer, after performing a SLOT calibration.

The results of the measurements, compared to the simulated ones, are given in Fig. 8. Analyzing the results in Fig. 8, one may observe that the measurements are in very good agreement with the simulations. Both the return loss and the isolation loss are better than 30 dB for both frequencies.

A small shift in frequency can be observed regarding the return loss and the isolation loss at higher frequencies. A return loss and an isolation loss higher than 40 dB can be observed at around 6 GHz. The insertion loss and the coupling loss are around 3.5 dB for both frequencies,

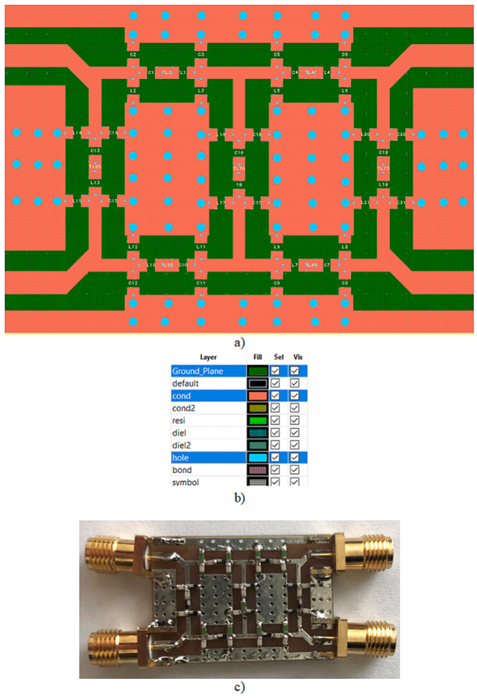

Fig. 7. The proposed dual band branch-line coupler: a) the virtual PCB layout – top view; b) legend of the layers; c) the manufactured prototype.

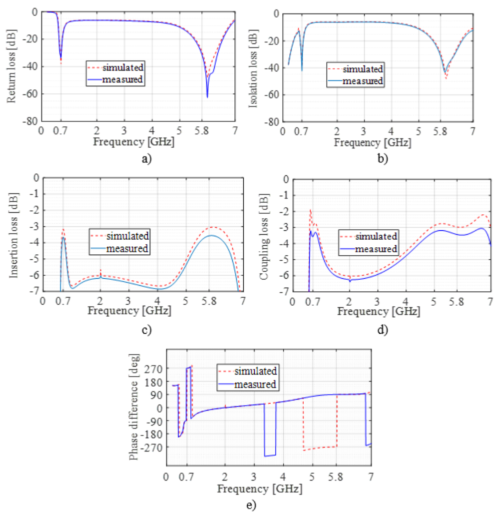

Fig. 8. Measurement and simulation results for: a) return loss; b) isolation loss; c) insertion loss; d) coupling loss; e) phase difference.

while the phase difference is 269^o and -89^o, respectively. To determine the relative bandwidth, it will be imposed for the return loss to be larger than 15 dB, for the isolation loss to be larger than 20 dB, an imbalance of ±1.5 dB for the insertion and coupling loss, respectively a phase difference imbalance of 5^o. A relative bandwidth of around 20 % for the return loss, isolation loss, insertion loss and phase difference are measured at both frequencies. A relative bandwidth of 58 % and 49 % is measured for the coupling loss.

The measurement results for the proposed coupler, as well as the ones obtained for similar couplers in literature [8], [9] are synthesized in Table 1.

Table 1. Comparison table for the dual band branch-line couplers

Reference/Parameter	[9]	[11]	This paper
Techniques	π shaped dual lines	Short-ended	**miniaturized impedance inverter cells**
Frequency [GHz]	0.85/1.8	0.9/1.8	**0.7/5.8**
Frequency ratio	2.11	2	**8.28**
Return loss [dB] BW [%]	26/21 9/10	$\sim$20/$\sim$20 9/13	**31/30** **24/24**
Isolation loss [dB] BW [%]	34/20 9/10	$\sim$14/$\sim$14 14/39	**39/31** **18/21**
Coupling loss [dB] BW [%]	3.6/3.9 –	4.07/3.6 14/38	**3.6/3.4** **21/21.4**
Insertion loss [dB] BW [%]	3.3/3.1 –	3.4/3.5 14/38	**3.5/3.5** **58/49**
Phase difference [deg] BW [%]	89/91 –	90/90 21/6	**270/90** **22/24**
Physical dimensions [mm^2]	31×31 $0.2\lambda_g \times 0.2\lambda_g$	80×36 $0.6\lambda_g \times 0.27\lambda_g$	**20×12** $\mathbf{0.45}\lambda_g \times \mathbf{0.23}\lambda_g$

Analyzing the results extracted from other literature references and presented in Table 1, one may first observe that the coupler proposed in this paper has the largest frequency ratio reported in literature so far, based on authors' knowledge.

The return loss for the coupler proposed in this paper is around 30 dB, and it is higher than the ones in [8] and [9]. The relative bandwidth for the return loss is the same for both frequencies, around 24% for the novel proposed coupler. The coupler proposed in this paper has the best values for isolation in comparison to other couplers reported in literature. They are 39 dB, respectively 31 dB, larger than 34 dB, respectively 14 dB reported in [8] and [9].

A relative bandwidth of 55% has been reported in [9] for the second frequency, but of only 9% for the first frequency, making the proposed coupler not working with similar performances at both frequencies.

For the coupling loss and insertion loss, the performances are similar for all couplers reported in [8] and [9], being around 3.5 dB.

Another improvement observed for the proposed coupler is the large relative bandwidth for the phase difference at higher frequencies, which is 24 %. The greatest value is reported in [9], which is 72 % for the second frequency, but this is for the coupler with the smallest frequency ratio considered. Nevertheless, in the design carried out in this paper, the dimensions of the overall coupler are the smallest. The coupler can be easily implemented in planar technology, using microstrip access lines and lumped elements/components

In conclusion, the coupler proposed, implemented and tested in this paper has better performances than similar couplers. Another important feature of the proposed coupler is that it works with almost similar performances at both frequencies, not like the one in [9].

Last, but not least, the proposed miniaturized cell for the implementation of the coupler can be used to transform any single band microwave circuit into a dual band one, if impedance inverter unit cells are needed.

5. Conclusions

A branch-line coupler with very high frequency ratios of 8.28 has been designed using miniaturized impedance inverter unit cells, performing very good at both frequencies and proving the novelty and efficiency of the design.

The coupler operating at two WLAN frequencies, 0.7 GHz and 5.8 GHz, having the frequency ratio of 8.28 is proposed, implemented, and manufactured using lumped elements and microstrip technology, allowing an easy integration with other components of the measurement setup. Each classical transmission line used in the branches of the coupler was replaced by dual band miniaturized impedance inverter unit cells, allowing the miniaturization of the coupler, while keeping very good performances.

The relative bandwidth is around 20 % for all parameters, while the insertion loss has a relative bandwidth of 50 % for both frequencies, the largest one reported for similar high frequency ratio couplers. Compared with the existing dual band branch-line couplers, the proposed coupler offers dual band operation with the highest band ratio, reported so far to authors' best knowledge and very good performance for all parameters, keeping reduced dimensions.

The proposed miniaturized dual band impedance inverter transmission lines with large frequency ratio can be considered to replace the classical single band impedance inverter transmission lines which are used to design passive microwave circuits such as: Wilkinson power divider, rat-race coupler or coupled-line couplers.

On the other hand, this solution cannot be extended to implement triple band couplers because the transmission lines proposed in Fig.1 are only dual band ones. They can be designed to work at two arbitrary frequencies and not at three arbitrary frequencies.

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