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Dual Band Ring Couplers Using T and Π Sections

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***Abstract*- New rat-race couplers that can be operated at two separate frequency bands are presented. The design is accomplished by transforming the lengths and impedances of the conventional rat-race into dual band T or Π shaped sections. Simple design equations are used for basic design geometries. Then the rat-race coupler geometries are analyzed using a full wave electromagnetic (EM) simulator and then realized at 0.9425 and 1.96 GHz for global system of mobile communications (GSM) bands. Excellent agreement between simulated and measured results demonstrates the performance of the proposed couplers. Both ring structures have a wide frequency operation range in addition to the significant reduced-size of the Π-section based coupler.**

***Index Terms*- Rat-race, dual band, ring couplers, T-section, Π-Section, microstrip circuits.**

I. INTRODUCTION

The hybrid-ring directional coupler is one of the fundamental passive components used in microwave circuits. It is recognized as a rat race ring when it is used for 3-dB directional coupling with normalized admittance of $1/\sqrt{2}$ on the whole circumference of the ring. Conventionally, a rat-race is composed of three sections each of $\lambda_g/4$ length and another section of $3\lambda_g/4$ length, where λ_g is the guided wavelength. This device offers both in-phase and anti-phase relationships at the designated outputs with equal power splitting as well as perfect isolation between ports. Applications of rat-race hybrids can be seen in mixers (for obtaining good spurious signal rejection), phase shifters, beam-forming networks, antenna arrays, frequency multipliers, and microwave amplifiers. The rat-race hybrid ring is widely used for power division in printed circuit array antennas because it provides good isolation between output ports, which is essential for minimizing mutual coupling between radiating elements.

Efforts have been made to size reduction, harmonic suppression [1-8], and bandwidth enhancement [9] of the rat-race hybrid, which lead to great improvements in these aspects. However, recent advances in modern communication systems impose new requirements, such as multiple-band operation, on the design of RF passive circuits. Dual-band circuits provide the benefits of reducing the overall size and the fabrication cost of radio frequency (RF) modules. Arbitrary dual band microwave components based on Right/Left Handed (RLH) transmission lines or lumped distributed elements have been described in several contributions [10-12]. Dual band branch coupler using different techniques have been also reported [13,14]. For rat-race coupler design, [15] presented a coupler operating at dual frequency bands, but with, noticeably, long circumference, because the $3\lambda_g/4$ section is replaced by a $5\lambda_g/4$ line at the two-band average frequency, so the total circumference length was $8\lambda_g/4$. Two short circuit stubs are added to that ring structure too. This contributes complexity and discontinuity to the operation of the dual band rat-race coupler. The resulted coupler is of considerable size especially if constructed for low microwave frequency operation such as for global system of mobile communication (GSM) applications. A more recent design was presented in [16] for a dual band rat-race coupler which is shorter in circumference ($6\lambda_g/4$) than the design of [15] and without the short circuited stubs.

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However the design in [16] is limited to the operation of two widely separated bands (f_2>2f_1).

In this paper, new structures of dual-band rat-race ring couplers are presented. These structures feature reduced-size planar rat-race configurations and avoid using shorted stubs or via holes. The desired dual-band operation is ascertained by using dual bands T and Π-shaped transmission line sections [13,14]. Each branch-section with $\lambda_g/4$ length is converted to its corresponding dual band T or Π-shaped section. Both designed configurations overcome the double frequency restriction imposed in [16]. The resulted coupler using Π shape has a total circumference of $6\lambda_g/4$ at average frequency which results in a considerable size reduction as compared to the $8\lambda_g/4$ circumference design presented in [15]. To provide design guidelines for the proposed ring couplers, closed forms are presented utilizing the ABCD-matrices of the $\lambda_g/4$, T and Π sections. The final layout of the couplers are designed based on these formulas and, then, analyzed using a full wave electromagnetic EM simulator. To verify the design concept and performance, microstrip ring couplers exhibiting dual-band operation are realized on RT/Duroid 5880 (ε_r=2.2, h=1.575 mm) substrate. These couplers are designed to work at the two bands of the global system for mobile communications GSM1 (925-960 MHz) and GSM2 (1930-1990 MHz). The measured results are in a very good agreement with the theoretical results and ensure the performance of the dual-band operation for the proposed ring structures.

II. DUAL BAND RING COUPLERS USING T-SECTIONS

Each quarter wave length section ($\lambda_g/4$) of the conventional rat-race coupler of Fig. 1 will be converted to a dual band T-shaped transmission line section. The equivalence between the ($\lambda_g/4$) transmission line section shown in Fig. 2a, and the T-section of Fig. 2b is investigated utilizing their ABCD matrices [14]. The ABCD matrix for the original transmission line, which has ($\lambda_g/4$) length shown in Fig. 2a is given by

$$M_1 = \begin{bmatrix} 0 & jz_1 \\ jy_1 & 0 \end{bmatrix} \tag{1}$$

where z_1 is the transmission line characteristic impedance and y_1 is its admittance.
The ABCD matrix for the T-shaped transmission line section of Fig. 2b is

$$M_T = M_2 M_3 M_2 \tag{2}$$

where M_2 and M_3 are the ABCD matrices for the series and shunt elements of the T-section and are defined as:

$$M_2 = \begin{bmatrix} \cos\theta_2 & jz_2\sin\theta_2 \\ jy_2\sin\theta_2 & \cos\theta_2 \end{bmatrix} \tag{3}$$

$$M_3 = \begin{bmatrix} 1 & 0 \\ jy_3\tan\theta_3 & 1 \end{bmatrix} \tag{4}$$

where z_i, y_i and θ_i (i=2,3) are the impedances, admittances and the electrical lengths for the series and shunt elements of the T-section, respectively. Equating the element A in both Eq. (1) and Eq. (2), results in:

$$\tan\theta_3 = 2\frac{z_3}{z_2}\cot(2\theta_2) \tag{5}$$

While equating the element B, gives that:

$$z_1 = 2z_2\sin\theta_2\cos\theta_2 - z_2^2 y_3 \sin^2(\theta_2)\tan\theta_3 \tag{6}$$

Based on substituting Eq. (5) into Eq. (6):

$$z_1 = z_2\tan\theta_2 \tag{7}$$

For the purpose of dual band operation, the necessary conditions implied by satisfying Eq. (7) are [14]:

$$z_2\tan\theta_{2f_1} = \pm z_1 \tag{8a}$$

$$z_2\tan\theta_{2f_2} = \pm z_1 \tag{8b}$$

where θ_{2f_1} and θ_{2f_2} are the electrical lengths of the series stub at the two operating frequencies f_1 and f_2 respectively, and ($f_2 > f_1$). The solution for Eq. (8) is given by:

$$\theta_{2f_2} = n\pi \pm \theta_{2f_1}, \quad (n=1,2,3\ldots) \tag{9}$$

$$\theta_{2f_2}/\theta_{2f_1} = f_2/f_1 = R \tag{10}$$

Based on Eq. (5) and Eq. (10), the following conditions can be deduced:

$$\theta_{3f_2} = m\pi \pm \theta_{3f_1}, \quad (m=1, 2, 3 \ldots) \tag{11}$$

$$\theta_{3f_2}/\theta_{3f_1} = f_2/f_1 = R \tag{12}$$

For practical size transmission line, n=m=1 is chosen. The design procedure for the rat-race coupler that operates at dual bands using T-sections can be presented as follows:

-The value of the ratio R is found from Eq. (10)

-The corresponding electrical length of the series transmission line will be:

$$\theta_{2f_1} = \pi/(R+1) \tag{13a}$$

$$\theta_{2f_2} = R.\theta_{2f_1} \tag{13b}$$

-The corresponding electrical length of the shunt stub will be:

$$\theta_{3f_1} = 2\pi/(R+1) = 2\theta_{2f_1} \tag{14a}$$

$$\theta_{3f_2} = R.\theta_{3f_1} = 2\theta_{2f_2} \tag{14b}$$

-The values of impedances z_2 and z_3 can be calculated as follows:

$$z_2 = z_1/\tan\theta_{2f_1} \tag{15a}$$

$$z_3 = 0.5z_2\tan^2(2\theta_{2f_1}) \tag{15b}$$

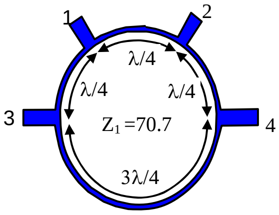

Fig. 1. The conventional ring coupler.

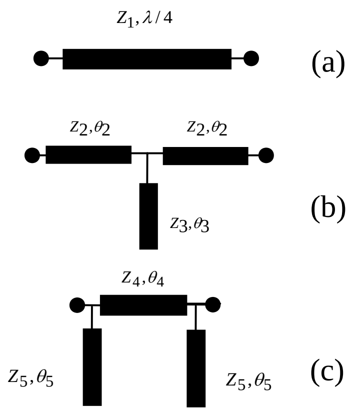

Fig. 2. λ/4 transmission line and its equivalents.
(a) λ/4 section
(b) T-shape equivalent
(c) Π-shape equivalent

Fig. 3 illustrates the variations of impedances z_2 and z_3 against the electrical length θ_{2f_1}. For practical realization of microstrip lines, the characteristic impedances should be bounded in that region (25 Ω< z <160 Ω) in most cases. Based on that, the circumference of the resulted ring coupler will be greater than that presented in [16]. Nevertheless, the operation of this ring coupler overcomes the double frequency limitation in [16] and will be valid for frequency ranges (f_2 <2 f_1) or (R<1) as shown in Fig. 4.

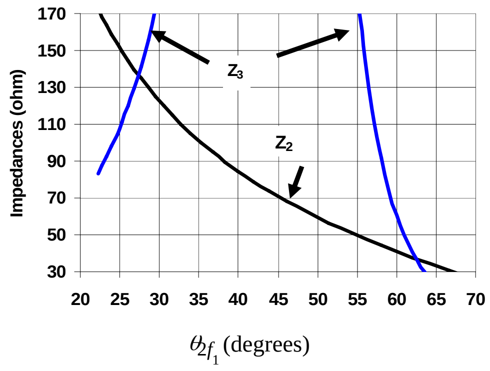

Fig. 3. z_2 and z_3 varaitoion against θ_{2f_1} .

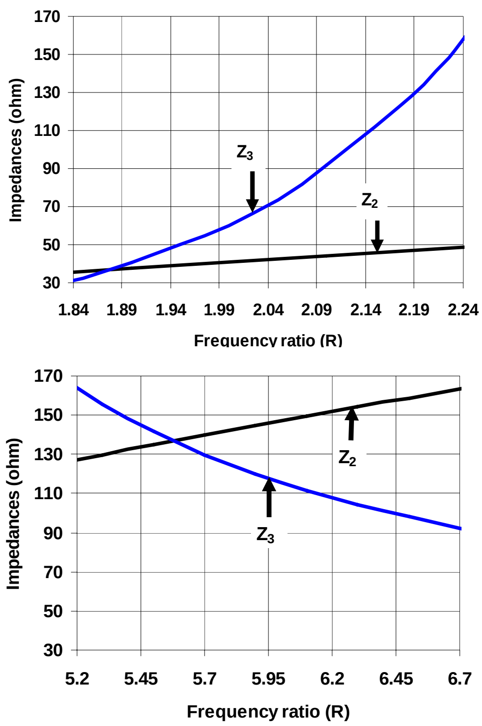

Fig. 4. z_2 and z_3 varaitoion against R.

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III. DUAL BAND RING COUPLERS USING Π -SECTIONS

Here each quarter wave length ($\lambda_g/4$) section of the conventional rat-race of Fig. 1 will be converted to a dual band Π-shaped transmission line section of Fig. 2c [13]. The ABCD matrix for the Π-shaped transmission line section of Fig. 2c is

$$M_T = M_5 M_4 M_5 \tag{16}$$

where M_4 and M_5 are defined as:

$$M_4 = \begin{bmatrix} \cos\theta_4 & jz_4 \sin\theta_4 \\ jy_4 \sin\theta_4 & \cos\theta_4 \end{bmatrix} \tag{17a}$$

$$M_5 = \begin{bmatrix} 1 & 0 \\ jy_5 \tan\theta_5 & 1 \end{bmatrix} \tag{17b}$$

Equating both of the elements A and B of the ABCD matrix of Eq. (1) and Eq. (16), the relation between the elements of the Π -shape section can be given as follows:

$$\tan\theta_5 = (z_5 / z_4)\cot(\theta_4) \tag{18a}$$

$$z_1 = z_4 \sin\theta_4 \tag{18b}$$

Following the same procedure of the previous section and after some mathematical manipulations, we obtain that:

$$\theta_{4f_2} / \theta_{4f_1} = \theta_{5f_2} / \theta_{5f_1} = f_2 / f_1 = R \tag{19}$$

$$\theta_{4f_2} = R\theta_{4f_1} = \frac{Rn\pi}{R+1} \tag{20}$$

$$\theta_{5f_2} = \frac{Rm\pi}{R+1} = R\theta_{5f_1} \tag{21}$$

For compact design, n=1 and m=1 are chosen. The electrical lengths of a practical Π -shape section are bounded in the region $(\pi/4 \le \theta_4, \theta_5 \le \pi/2)$. The design procedure for a compact rat-race coupler that operates at dual bands can be summarized as follows:

-The value of the ratio R is found from Eq. (19).

-The electrical length of the series transmission line is found from Eq. (20) with n=1 selected for compactness.

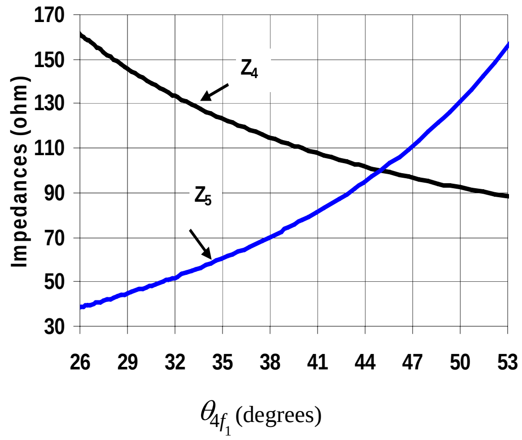
-The electrical length of the shunt stub is found from Eq. (21) with m=1 selected for compactness.

-The values of impedances z_4 and z_5 can be calculated as:

$$z_4 = \frac{z_1}{\sin(\theta_{4f_1})} \tag{22a}$$

$$z_5 = z_4 \tan(\theta_{5f_1}).\tan(\theta_{4f_1}) \tag{22b}$$

Fig. 5 illustrates the variations of impedances z_4 and z_5 against the electrical length θ_{4f_1} and frequency ratio variation (R). For the practical realization of microstrip lines, the characteristic impedances should be bounded in that region (25 Ω< z <160 Ω) in most cases. The circumference of the resulted Π-section-based ring coupler will be smaller than that presented in [15]. In addition to that advantage, the operation of this ring coupler overcomes the double frequency limitation in [16] and will be valid for frequency ranges (f_2<2f_1) or (R<1). The Π-section based ring coupler occupies area that only one-forth of the T-section based ring coupler and has the benefit of wider frequency operation range as well.



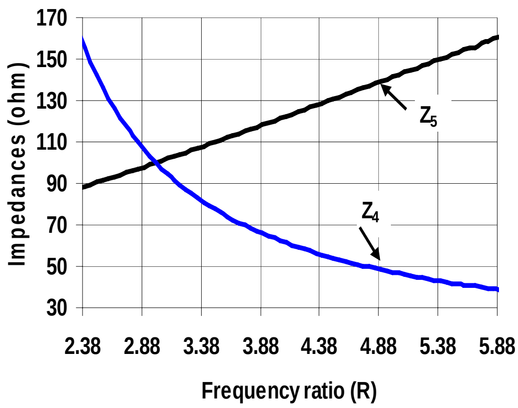


Fig. 5. z_4 and z_5 varaitoion against θ_{4f_1} and R.

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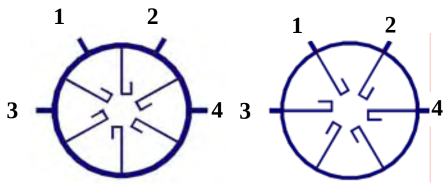
IV. SIMULATION AND MEASUREMENT OF THE DUAL BAND RING COUPLERS

Two rat-race ring couplers are designed for dual band GSM1 (925-960 MHz) and GSM2 (1930-1990 MHz) operation. The dual band center frequencies are 0.9425 GHz and 1.96 GHz respectively. Based on the above design procedure, with $z_1 = 50\sqrt{2}\,\Omega$, the design parameters for both of T-based and Π-based dual band rat-race couplers will be R=2.0769, (θ_2= θ_4= θ_5= 58.45°), θ_3=116.9°, z_2= 43.42 Ω, z_3= 84.35 Ω, z_4= 82.97 Ω and z_5= 220.1 Ω. In fact due to the Π configuration, each two shunt stubs, of 220.1 Ω impedance will be combined in parallel, so the impedance of the resulted stub will be 110.05 Ω which is easier to be realized by microstrip technology. Both of the designed dual band rat-race ring couplers (using T and Π–sections) are simulated using a full wave electromagnetic EM simulator, and then realized on RT/Duroid 5880 substrate (ε_r=2.2, h=1.5748 mm). Fig. 6 illustrates the configurations of the realized dual band rat-race couplers using T-shape and Π-shape sections. The open circuited stub lines are folded to fit inside the inner space of the ring coupler to have a better space utilization in both configurations.

The measurements of the realized dual band rat-race (using T-sections) are compared with the simulation results as shown in Figs 7-9. For the case of the in-phase outputs, the measured reflection (S_{11}) is less than (-18 dB) and (-15 dB) for the two GSM bands, respectively. The coupling coefficients (S_{21}) and (S_{31}) are equal to (-3 dB) with a deviation less than (0.36 dB) in both GSM bands. The phase shift between the coupling output ports (2 and 3) does not exceed (4.5°) for both GSM bands. For the case of out-of-phase outputs, the measured reflection (S_{33}) and isolation (S_{23}) are less than (-15 dB) and (-24 dB), respectively, for both GSM bands. The coupling coefficients (S_{13}) and (S_{43}) are equal to (-3 dB) and deviate by less than (0.4 dB) in both bands. The phase shift between the coupling output ports (1 and 4) does not exceed (5.15°) for the two GSM bands.

The measurements of the realized dual band rat-race (using Π-sections) are compared with the simulation results; both are shown in Figs 10-12. For the case of in-phase outputs, the measured reflection coefficient (S_{11}) is less than (-16.5 dB) for the two GSM bands, while the isolation (S_{41}) is less than (-31 dB). The coupling coefficients (S_{21}) and (S_{31}) are equal to (-3 dB) with a deviation less than (0.59 dB) in both GSM bands. The phase shift between the coupling outputs ports (2 and 3) does not exceed (3.8°) for the two bands. For the case of out–of-phase output, the measured reflection (S_{33}) is less than (-17dB) and the isolation coefficient (S_{23}) is less than (-25.7 dB) in both GSM bands. The coupling coefficients (S_{13}) and (S_{43}) deviate from (-3 dB) by less than (0.6 dB). The phase shift between the coupling outputs port (1 and 4) deviates by less than (3°). The above observations demonstrate the dual band superior operation of the presented designs of the rat race coupler.



(a) (b)

Fig. 6. The realized ring coupler.
(a) T-shape coupler (b) Π-shape coupler

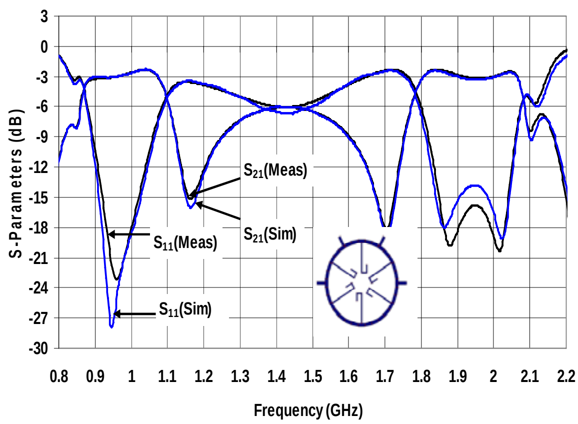


Fig. 7. The S-parameters (S_{11}) and (S_{21}) against frequency for the T-based rat-race coupler.

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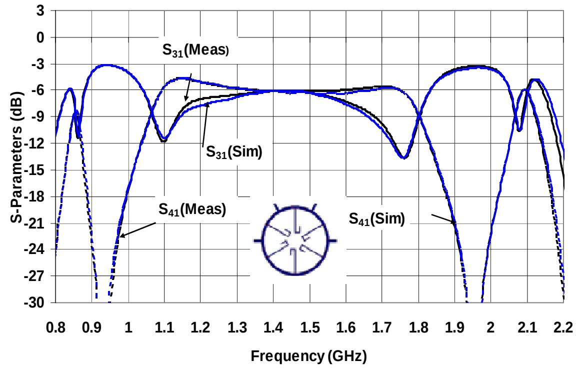

Fig. 8. The S-parameters (S_{31}) and (S_{41}) against frequency for the T-based dual band rat-race coupler.

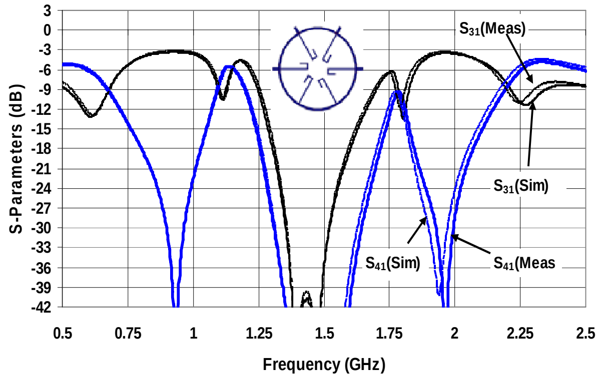

Fig. 11. The S-Parameters (S_{31}) and (S_{41}) against frequency for the Π-based rat-race coupler.

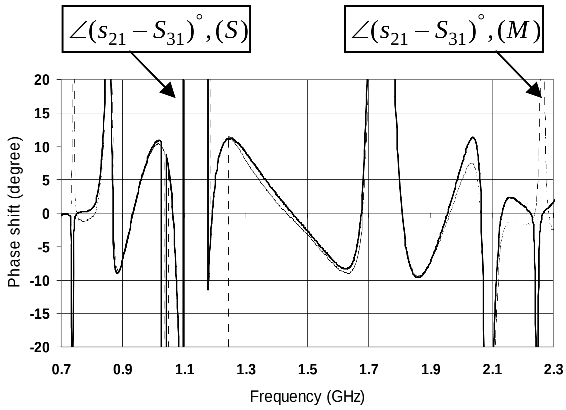

Fig. 9. The phase shift of ports (2 & 3) against frequency for T-based rat race coupler.

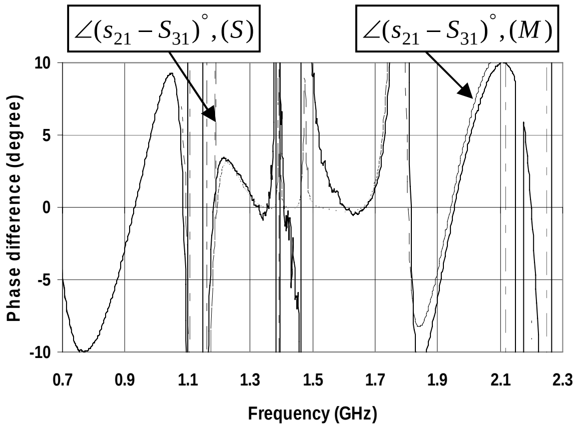

Fig. 12. The phase shift of ports (2 & 3) against frequency for Π-based rat race coupler.

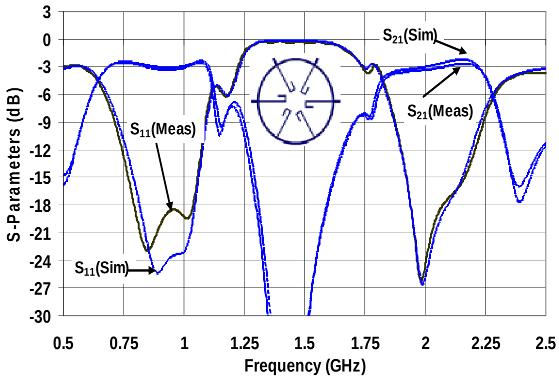

Fig. 10. The S-Parameters (S_{11}) and (S_{21}) against Frequency for the Π-based rat-race coupler.

V. CONCLUSIONS

This paper presents analysis and design of dual band rat-race couplers using T-sections and Π-sections. The basic dual band structure designs use T-section and Π-section transformation of the $\lambda_g/4$ sections of the conventional single frequency ring coupler with no short circuit stubs or via holes. Practical design equations are presented in simple forms. Dual band GSM rat-race couplers are designed and analyzed using a full wave EM simulator and then realized on RT/Duroid 5880 substrate (ε_r=2.2, h=1.5748 mm). The measurements of the realized dual-band rat-race

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couplers are in excellent agreement with the simulated results. The measurements have been carried out for both cases of in phase and out-of-phase ring dividers. The simulation and experimental results for both types of the dual band rat-race coupler for each of the in-phase or out-of-phase outputs demonstrate the superior performance of the proposed ring couplers. The designed couplers frequency-operation is limited only by the branch impedance ratio and hence by the microstrip transmission line realization technology. In addition to that, the Π-section-based ring coupler has the advantages of compactness and wider frequency-operation range which are proper for RF/microwave circuit modern applications.

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