Design of Quad-Band Rat-Race Coupler for GSM/WiMAX/WLAN/Satellite Applications

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Abstract. *In this communication, a novel quad-band ratrace coupler (RRC) is developed for GSM/WiMAX/WLAN/Satellite applications. A conventional RRC is converted to exhibit quad-band operation by using a quad-band microstrip-line (QBML). The proposed QBML is constructed by two coupled-lines, one series transmission-line and two short-ended stubs. The ABCD matrix method is applied to develop the design formulas. Based on these formulas, a quad-band RRC operating at 1.8 GHz, 3.5 GHz, 5.4 GHz, and 7.1 GHz is designed and verified through fabrication and measurement. The measurement and full-wave simulation responses are very much consistent as expected.*

Keywords

Rat-race coupler, quad-band, coupled-line

1. Introduction

The rat-race coupler (RRC) is one of the essential and widely used components in advanced RF/Microwave system applications. Several techniques for the design of wideband RRCs have been reported [1–12]. These RRCs are suitable for single-band/broadband applications. Due to multi-standard communication systems, multi-band RF/microwave front-end components are highly desirable, which leads to reduction in both cost as well as size of the overall system. In recent years, many techniques have been employed to design dual-band [13–23], triple-band [24–28] and quad-band [29–31] components. In [14], a triple-section branch-line coupler has been employed to design a dual-band RRC. In [15], a single-band RRC has been converted into a dual-band RRC with reconfigurable power division. In [16], a dual-band RRC has been developed employing π-shaped topology based on glass-integrated passive device technology. In [17], the π-shaped stepped impedance topology has been applied for the design of a dual-band RCC. In [18], a dual-band RRC has been realized by applying two additional shunt-stubs with the conventional single-band RRC. In [20], two dual-band RRC have been realized by employing T-shaped topology and an additional open-ended stub. In [21], a modified structure with an open-ended stub has been used to develop a dual-band RRC with arbitrary power division. It is observed that design of dual-band devices are explored extensively but multi-band components are highly desirable for advanced communication systems.

In the literature, several techniques have been employed for the development of triple-band [24–28] and quad-band [29–31] devices. In [24–25], triple-band impedance transformers have been realized. In [26], a triple-band RRC has been developed using resonators. In [27], metamaterial transmission-line has been used for the design of triple-band RRC. In [28], a T-shaped stepped impedance transformer has been applied to design a triple-band RRC. In [29], a H-shaped topology has been applied to realize a quad-band transformer for ultra-high transforming ratio. In [30], laterally offset dual-ring resonator and dual-ring split-resonators have been employed for the design of quad-band RRC woth spurious response. In [31], the concept of negative refractive-index transmission-line has been applied for the development of quad-band RRC. In literature, it is found that very few multi-band RRC have been realized. Therefore, the design and validation of quad-band RRC needs to be explored further.

This paper presents a novel design procedure for development of quad-band rat-race coupler (RRC) for GSM/WiMAX/WLAN/Satellite applications. A quad-band microstrip-line (QBML) is employed in place of $\lambda/4$ microstrip-lines of the traditional RRC. The closed-form formulas are derived by applying ABCD matrices. Finally, a prototype of quad-band RRC is validated through fabrication and experimentation. The key features of the proposed quad-band RRC are summarized as follows:

1. A new quad-band microstrip-line architecture is proposed and investigated.
2. Mathematical derivations are formed using ABCD matrx method, which provides the benefit of flexibility of the proposed quad-band microstrip-line.
3. A simple design approach is summarized for the development of quad-band RRC.

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4. A quad-band RRC is designed and verified through the fabrication and measurement for GSM/WiMAX/WLAN/Satellite applications.

5. The fabricated prototype exhibits quad-band operation, good isolation and low magnitude and phase imbalance.

2. Mathematical Study of The Quad-Band Microstrip-Line

The topology of the proposed quad-band microstrip-line (QBML) is depicted in Fig. 1. The QBML is configured as a Π-shaped topology inserted between the coupled lines. The Π-shaped topology is composed of a series transmission-line (Z_L, $2\theta_K$) and two shunt-ended stubs (Z_M, θ_K). The even/odd-mode characteristic impedances of the coupled-line (θ_K) are Z_{Ke} and Z_{Ko}, respectively. This QBML is equivalent to the conventional microstrip-line having characteristic impedance of Z_C at four distinct frequency bands. The ABCD matrices of the proposed QBML and the conventional $\lambda/4$ microstrip-line are computed by following [29]:

$$\begin{bmatrix} A_T & B_T \\ C_T & D_T \end{bmatrix} = M_K M_L M_M M_L M_K = \pm M_C, \quad (1)$$

$$M_K = \begin{bmatrix} \cos\theta_K & j\frac{(Z_{Ke}+Z_{Ko})\sin\theta_K}{2} \\ j\frac{2\sin\theta_K}{Z_{Ke}+Z_{Ko}} & \cos\theta_K \end{bmatrix}, \quad (2)$$

$$M_L = \begin{bmatrix} 1 & 0 \\ -j\frac{cot\theta_K}{Z_L} & 1 \end{bmatrix}, \quad (3)$$

$$M_M = \begin{bmatrix} \cos 2\theta_K & jZ_M\sin 2\theta_K \\ j\frac{\sin 2\theta_K}{Z_M} & \cos 2\theta_K \end{bmatrix}, \quad (4)$$

$$M_C = \begin{bmatrix} 0 & jZ_C \\ \frac{j}{Z_C} & 0 \end{bmatrix}. \quad (5)$$

Here, M_C and Z_C are the ABCD-matrix and characteristic impedance of a traditional $\lambda/4$ microstrip-line. By setting Z_K=Z_{Ke}+Z_{Ko} and employing matrix-inverse properties, equation (1) can be expressed as:

$$M_L M_M M_L = \pm M_K^{-1} M_C M_K^{-1}, \quad (6)$$

$$\begin{bmatrix} P+\frac{2Z_M}{Z_L}R & jZ_M Q \\ \frac{jQ}{Z_M} - \frac{j2P\cot\theta_K}{Z_L} - \frac{j2RZ_M}{Z_M^2\sin\theta_K} & P+\frac{2Z_M}{Z_L}R \end{bmatrix} = \pm \begin{bmatrix} \left(\frac{Z_K}{4Z_C}+\frac{Z_C}{Z_K}\right)Q & jZ_C R - j\frac{Z_K^2}{4Z_C}S \\ \frac{jR}{Z_C} - j\frac{Z_C}{4Z_K^2}S & \left(\frac{Z_K}{4Z_C}+\frac{Z_C}{Z_K}\right)Q \end{bmatrix}, \quad (7)$$

where: $P = \cos 2\theta_K$, $Q = \sin 2\theta_K$, $R = \cos^2\theta_K$ and $S = \sin^2\theta_K$.

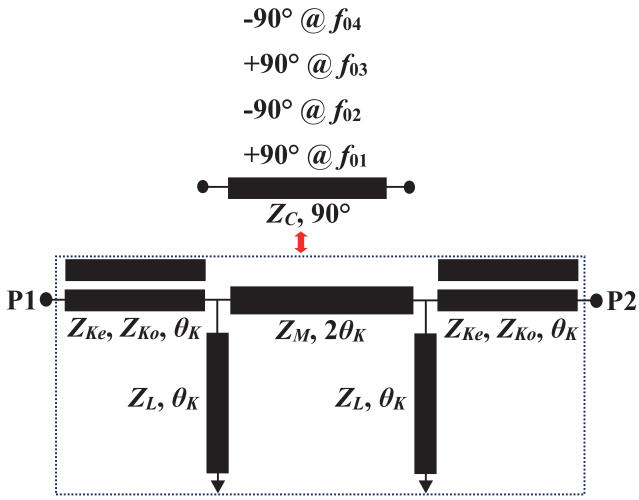

Fig. 1. Schematic of the proposed quad-band microstrip-line (QBML).

Applying ABCD matrix properties, equation (7) can be solved as:

$$P + \frac{2Z_M}{Z_L}R = \pm\left(\frac{Z_K}{4Z_C}+\frac{Z_C}{Z_K}\right)Q, \quad (8a)$$

$$jZ_M Q = \pm\left[jZ_C R - j\frac{Z_K^2}{2Z_C}S\right], \quad (8b)$$

$$P + \frac{2Z_M}{Z_L}R = \pm\left(\frac{Z_K}{4Z_C}+\frac{Z_C}{Z_K}\right)Q. \quad (8c)$$

Simplifying equation (8), we obtain:

$$\tan^2\theta_K \pm \left(\frac{Z_K^2+4Z_C^2}{2Z_K Z_C}\right)\tan\theta_K - \left(1+\frac{2Z_M}{Z_L}\right) = 0, \quad (9a)$$

$$\tan^2\theta_K \pm \left(\frac{8Z_M Z_C}{2Z_K^2}\right)\tan\theta_K - \frac{4Z_C^2}{Z_K^2} = 0, \quad (9b)$$

$$\tan^2\theta_K \pm \left(\frac{Z_K^2+4Z_C^2}{2Z_K Z_C}\right)\tan\theta_K - \left(1+\frac{2Z_M}{Z_L}\right) = 0. \quad (9c)$$

The values of $\tan\theta_K$ in equation (9) are expressed as:

$$\tan\theta_K = \pm\left[\frac{2Z_C}{Z_K}\left(\sqrt{1+\frac{\left(Z_K^2+4Z_C^2\right)^2}{64Z_C^2}} - \frac{Z_K^2+4Z_C^2}{8Z_C^2}\right)\right]. \quad (10)$$

In order to obtain quad-band operation, the proposed QBML and conventional TL must be equivalent at four different frequencies of f_{01}, f_{02}, f_{03} and f_{04}. It is considered that $f_{01} < f_{02} < f_{03} < f_{04}$. Let the electrical lengths of the microstrip-lines are θ_{K1}, θ_{K2}, θ_{K3} and θ_{K4} at the center frequencies of f_{01}, f_{02}, f_{03} and f_{04}, respectively.

Hence, the four solutions of tanθ_K are determined as:

$$\theta_{K1} = \tan^{-1}\left[\frac{2Z_C}{Z_K}\left(\sqrt{1+\frac{\left(Z_K^2+4Z_C^2\right)^2}{64Z_C^4}} - \frac{Z_K^2+4Z_C^2}{8Z_C^2}\right)\right], \tag{11a}$$

$$\theta_{K2} = \tan^{-1}\left[\frac{2Z_C}{Z_K}\left(\sqrt{1+\frac{\left(Z_K^2+4Z_C^2\right)^2}{64Z_C^4}} + \frac{Z_K^2+4Z_C^2}{8Z_C^2}\right)\right], \tag{11b}$$

$$\theta_{K3} = \pi - \theta_{K2}, \tag{11c}$$

$$\theta_{K4} = \pi - \theta_{K1}. \tag{11d}$$

Employing the (11a)–(11d), we determine:

$$f_{02} = f_{01}\frac{\theta_{K2}}{\theta_{K1}}, \tag{12a}$$

$$f_{03} = f_{02}\left[\frac{\pi}{\theta_{K2}} - 1\right], \tag{12b}$$

$$f_{04} = f_{01}\left[\frac{\pi}{\theta_{K1}} - 1\right]. \tag{12c}$$

The impedances (Z_M and Z_L) are determined by solving (9):

$$Z_M = Z_K\left(\frac{Z_K^2+4Z_C^2}{16Z_C^2}\right), \tag{13}$$

$$Z_L = \frac{Z_K^3}{8Z_C^2}\left(\frac{Z_K^2+4Z_C^2}{4Z_C^2-Z_K^2}\right). \tag{14}$$

The procedure for designing of quad-band RRC can be summarized as follows:

1. First, the impedance values of 3 dB traditional RRC are chosen as Z_A = 70 Ω and Z_B = 70 Ω. Select, $Z_C = Z_A = Z_B$.
2. The electrical length $\theta_K = \theta_{K1}$ can be determine from (11a).
3. The first operating frequency f_{01} is assumed, for a particular value of Z_K (76.5 to 111.5 Ω), other operating frequencies f_{02}, f_{03}, and f_{04} can be determined employing (12a), (12b), and (12c), respectively.
4. Applying (13) and (14), determine the values of Z_M and Z_L, if these parameters are exceeding the fabrication limit of microstrip technology, return to step-3 and choose a suitable value of Z_K.
5. Determine the dimensions of the proposed quad-band RRC at the first mid-band frequency (f_{01}).

Based on the above sythesis approach, the design parametrs (Z_M, Z_L, f_{02}, f_{03}, f_{04} and θ_K) are computed by using the equations (8)–(13). Based on the derived closed-form formulas, we have eight unknowns (Z_K, Z_M, Z_L, f_{01}, f_{02}, f_{03}, f_{04} and θ_K) and six equations to obtain solutions. Hence, two degrees of freedom are exist. Therefore, the parameters Z_K and f_{01} are chosen as free variables. Considering the fabrication limit of Z_M and Z_L (20 Ω ≤ 150 Ω), Z_K can be chosen between 76.5 Ω to 111.5 Ω. The operating frequencies (f_{02}, f_{03} and f_{04}) can be tuned by varying any one of the free variable (either Z_K or f_{01}). For example, Table 1 shows the different values of f_{02}, f_{03}, f_{04} at various f_{01} and for a fixed Z_K = 95 Ω. Similarly, Table 2 depicts the variation of f_{02}, f_{03}, f_{04} for various Z_K and at fixed f_{01} = 1.8 GHz. Hence, the operating frequencies f_{02}, f_{03}, f_{04} can be tuned by varying the free variables.

f01 (GHz)	**f02** (GHz)	**f03** (GHz)	**f04** (GHz)
0.7	1.34	2.0	2.7
0.9	1.72	2.63	3.45
1.2	2.3	3.51	4.6
1.5	2.86	4.4	5.75
1.8	3.44	5.27	6.91

Tab. 1. The values of f_{02}, f_{03}, f_{04} at various f_{01} and for a fixed Z_K = 95 Ω.

Z$_K$ (Ω)	**f02** (GHz)	**f03** (GHz)	**f04** (GHz)
80	3.0	4.41	5.63
85	3.15	4.68	6.0
90	3.29	4.97	6.46
95	3.44	5.27	6.91
100	3.6	5.58	7.38

Tab. 2. The values of f_{02}, f_{03}, f_{04} for various Z_K and at fixed f_{01} = 1.8 GHz.

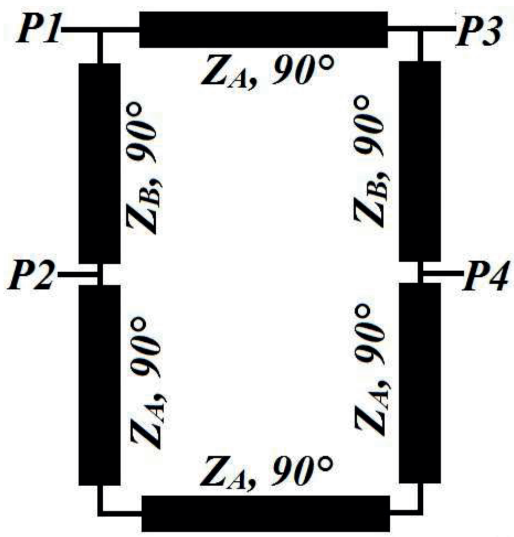

Fig. 2. Schematics of the conventional rat-race coupler.

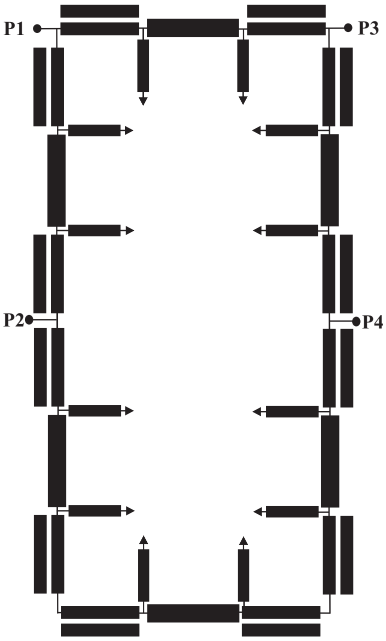

Fig. 3. Schematics of the proposed quad-band rat-race coupler.

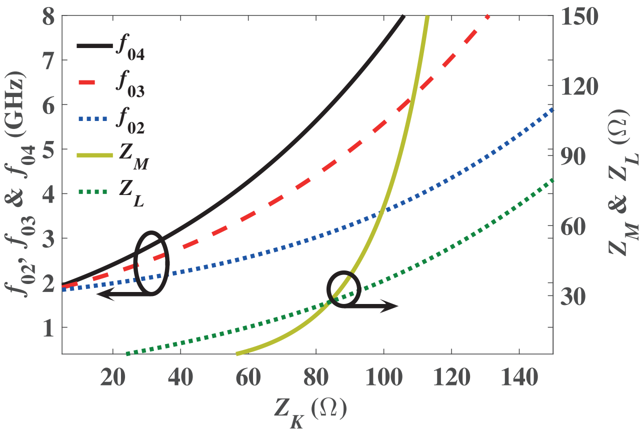

Fig. 4. Design curve for the proposed quad-band RRC.

3. Fabrication and Validation

The geometrical layout of the conventional 3-dB rat-race coupler (RRC) is depicted in Fig. 2. The characteristic impedances of the $\lambda/4$ microstrip-lines of the RRC are given as $Z_A = Z_B = 70.7\ \Omega$. These microstrip-lines are replaced by the proposed QBML to develop a quad-band RRC as illustrated in Fig. 3. Considering $Z_C = Z_A = Z_B = 70.7\ \Omega$, a design curve is plotted for the calculation of operating frequencies and impdances of the proposed QBML as illustrated in Fig. 4. Based on the above design procedure, the circuit parameters for a 70.7 Ω microstrip-line are computed as $Z_{Ke} = 59.7\ \Omega$, $Z_{Ko} = 37.3\ \Omega$, $Z_M = 35.6\ \Omega$, $Z_L = 63.4\ \Omega$ and $\theta_K = 36.4°$. Using these parameters, the physical dimensions are computed at f_{01}. To verify the concept, a quad-band 3-dB RRC is fabricated for GSM/WiMAX/WLAN/Satellite applications operating at 1.8, 3.5, 5.4, and 7.1 GHz, respectively.

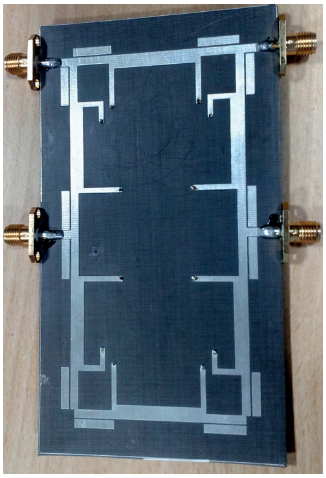

Fig. 5. Fabricated prototype of the proposed quad-band rat-race coupler.

A Rogers RT/Duriod 5870 substrate (ϵ_r = 2.33, thickness = 0.787 mm, $\tan\delta$ = 0.0009) is employed for fabrication. The fabricated prototype of the proposed quad-band RRC is illustrated in Fig. 5. The circuit size of the quad-frequency RRC is $0.40\lambda_g \times 0.80\lambda_g$ mm^2, here λ_g is the guided wavelength at f_{01}.

The Circuit, full-wave simulated and tested magnitude responses are depicted in Fig. 6 and Fig. 7. The return loss ($|S_{11}|$) and isolation ($|S_{41}|$) are greater than 20 dB and 27 dB, respectively. From measured results, the magnitude at transmission ($|S_{21}|$) and coupling ($|S_{31}|$) ports are found as ± 0.5 dB deviation from the ideal value of 3 dB. Fig. 8 and Fig. 9 depict the in-phase and out-phase responses of the proposed quad-band RRC, respectively. Considering the magnitude imbalance of ΔM ($|S_{21}|-|S_{31}|$) = 0.5 dB and phase imbalance of $\Delta\Phi(\angle S_{21}-\angle S_{31})$ = 5°, the bandwidth is greater than 200 MHz at all the operating frequency. The experimental performances of the fabricated quad-band RRC are summarized in Tab. 3.

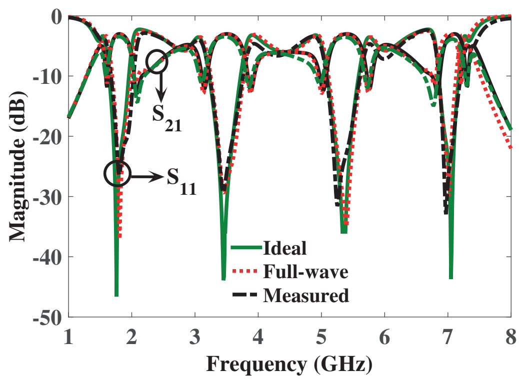

Fig. 6. Simulated and measured S-parameters response (S_{11} and S_{21}).

Ref.	**Techniques**	**Operation**	**RL** (dB)	**ISL** (dB)	**MI** (dB)	**Size** (λ_g^2)
[26]	π-shaped resonator	Tri-band	< -10	< -22	≤ 1.4	NR
[27]	MTM TL	Tri-band	< -10	< -20	≤ 2.0	0.063
[28]	T-shaped stepped impedance	Tri-band	< -20	< -20	≤ 0.6	0.26
[30]	LODR+CDSR slots	Quad-band	< -15	< -29	≤ 3.3	0.27
[31]	GNRI-TL unit	Quad-band	< -10	< -10	≤ 3.4	0.02
This Work	**Coupled-line, transmission-line & shunt-stub**	**Quad-band**	$< \mathbf{-20}$	$< \mathbf{-27}$	$\leq \mathbf{0.9}$	**0.32**

Tab. 3. Comparative analysis of the proposed and existing multi-band RRC. (RL: Return Loss; ISL: Isolation; MI: Magnitude Imbalance; PI: Phase Imbalance; NR: Not Reported).

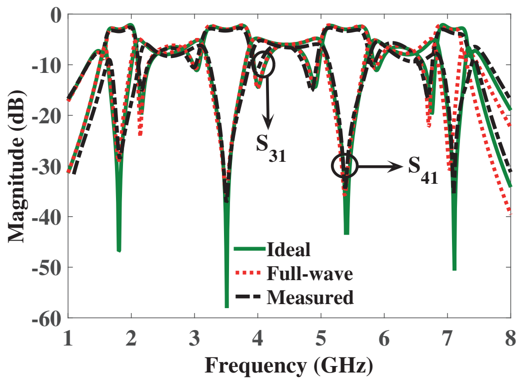

Fig. 7. Simulated and measured S-parameters response (S_{31} and S_{41}).

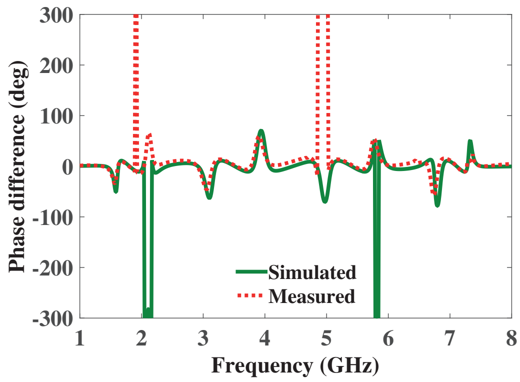

Fig. 8. Simulated and measured in-phase response $\angle S_{21} - \angle S_{31}$.

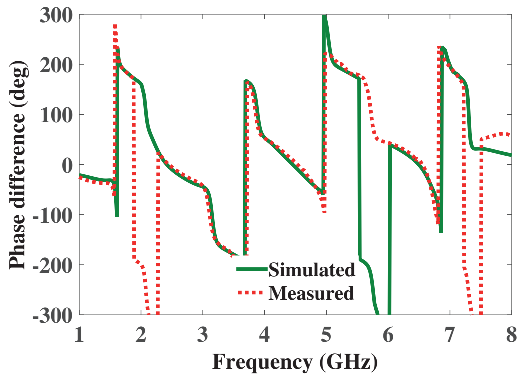

Fig. 9. Simulated and measured out-phase response $\angle S_{24} - \angle S_{34}$.

Freq. (GHz)	**1.8**	**3.6**	**5.4**	**7.1**
$\lvert S_{11} \rvert$ (dB)	−26.3	−26	−22.6	−19.1
$\lvert S_{21} \rvert$ (dB)	−3.46	−3.49	−3.56	−3.91
$\lvert S_{31} \rvert$ (dB)	−3.4	−3.28	−3.47	−3.79
$\lvert S_{41} \rvert$ (dB)	−27.34	−37.13	−32.58	−35.38
In-phase (deg)	0.6	2.4	3.1	1.06
Out-phase (deg)	180	182.5	181.7	180.1

Tab. 4. Experimental performance of the quad-band RRC.

Table 4 depicts the comparative analysis of the proposed and existing multi-band RRC. The proposed quad-band RRC exhibits greater return loss, isolation and magnitude imbalance when compared to [26–31]. The size of the proposed quad-band RRC is larger than the existing multi-band RRC but provides a simple mathematical analysis to achieve quad-band operation.

4. Conclusion

In this article, design of a novel quad-band rat-race coupler (RRC) has been reported for GSM/WiMAX/WLAN/Satellite applications. The conventional RRC has been converted to provide quad-band characteristics by employing a novel quad-band microstrip-line (QBML). The proposed QBML has been configured by using two coupled-lines, one series microstrip-line and two short-ended stubs. The design formulas are derived by applying ABCD matrix method. Based on these formulas, a quad-band rat-race coupled has been designed and verified through fabrication and experimentation. The full-wave simulation and experimentation results show good agreement as expected.

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