A quad-band branch line coupler with high frequency ratio

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Abstract In this paper, a novel quad-band branch line coupler with high ratio (from 6.27 to 14.96) of the largest operating frequency to the smallest operating frequency is presented. To realize quad-band operations, a combination of coupled lines and open stubs is proposed which can make the design flexible. By using analysis of even and odd modes, the equivalent equations for the quad-band operation are obtained. Compared to the existing quad-band branch line coupler, the proposed quad-band coupler has the highest ratio of the largest operating frequency to the smallest operating frequency, which is valuable for wideband and ultra wideband application. For practical applications, a quad-band coupler operating at 0.7, 1.64, 4.09, and 5.03 GHz which can be used for the long term evolution (LTE) and Wi-Fi is designed, fabricated, and measured. The simulated and measured results agree well with the design theory.

Key words: Branch line coupler, quad-band, coupled lines, operating frequency ratio

Classification: Microwave and millimeter wave devices, circuits, and hardware

1. Introduction

With the development of wireless communication systems, the demand for versatile devices which can cover multiple frequency application bands is increasing constantly[1-3]. The branch line couplers are essential components for constructing various microwave circuits such as modulators, balanced amplifiers, phase shifters and wireless transceivers[4-10]. Many methods for designing multi-band branch line couplers have been proposed in the past few years[10-37]. The quad-band operations have been reported including the combination of coupled lines and transmission lines[33], the T shaped coupled line sections[34], the open stubs added to the conventional branch line coupler’s ports[35], adopting to fulfill satisfactory matching within each operating band based on the single-band branch line coupler[36], and the generalized negative refractive index transmission line unit cells[37].

In this paper, a novel quad-band branch line coupler is proposed. To realize the quad-band operation, coupled lines and open stubs replacing the quarter-wave-length transmission lines are applied. For verification purposes, a quad-band branch line coupler operating at 0.7, 1.64, 4.09, and 5.03 GHz has been designed, fabricated, and measured. The schematic diagrams of the conventional single-band branch line coupler and the proposed quad-band branch line coupler are shown in Fig. 1. Here, \( Z_{E1} \), \( Z_{E2} \), \( Z_{O1} \), and \( Z_{O2} \) are the characteristic impedances of the even and odd modes of the coupled lines respectively. \( Z_{C} \), \( Z_{R1} \), and \( Z_{R2} \) are the characteristic impedances of the transmission lines and \( Z_{C} \) is 50 \( \Omega \). \( \theta \) is the electrical length of coupled lines and open stubs.

![Schematic of branch line couplers](image)

**Fig. 1** Schematic of branch line couplers. (a) Conventional single-band branch line coupler. (b) Proposed quad-band branch line coupler.

2. Proposed quad-band structure

The schematics of the conventional quarter-wave-length transmission line and the proposed quad-band structure are shown in Fig. 2. The mathematical analysis of the even, odd modes and the operation of quad-band is

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explained.

![Diagram](image)

**Fig. 2** Schematic of basic structure. (a) Conventional quarter-wavelength transmission line. (b) Proposed quad-band structure.

### 2.1 Even mode analysis

The even mode equivalent circuit of the half conventional transmission line is an open stub with electrical length 45° and characteristic impedance \( Z_c \) as shown in Fig. 3a. The even mode equivalent circuit of the half quad-band structure is two parallel open stubs connected with a transmission line as shown in Fig. 3b. The impedances \( Z_{IN1}, Z_{IN2} \) of Fig. 3 can be illustrated respectively as follow:

\[
Z_{IN1} = \pm jZ_c \\
Z_{IN2} = j -Z_c Z_R \cot \theta + Z_E (Z_E + Z_R) \tan \theta \\
Z_{IN2} = j \frac{Z_c Z_R \tan \theta + Z_E (Z_E + Z_R) \tan \theta}{Z_E + 2Z_R} \\
\]

(1)

(2)

Considering that both of the two circuits are equivalent, Eq. (3) is obtained.

\[
Z_{IN1} = Z_{IN2} \tag{3}
\]

When negative and positive signs are taken in Eq. (1), \( Z_{E1} \) and \( Z_{E2} \) are respectively derived as:

\[
Z_{E1} = -\frac{Z_c \tan \theta + Z_R - Z_R \tan^2 \theta + \sqrt{-8Z_c Z_R \tan^2 \theta + (Z_c \tan \theta - Z_R + Z_R \tan^2 \theta)^2}}{2 \tan^2 \theta} \pm \frac{\sqrt{8Z_c Z_R \tan^2 \theta + (-Z_c \tan \theta - Z_R + Z_R \tan^2 \theta)^2}}{2 \tan^2 \theta} \\
Z_{E2} = Z_c \tan \theta + Z_R - Z_R \tan^2 \theta \\
\]

(4)

(5)

### 2.3 Quad-band Operation

It is obvious that even and odd mode impedances \( Z_E, Z_O \) are determined by the open stub impedance \( Z_R \) and the electrical length \( \theta \). By selecting a suitable value of \( Z_R \), the \( Z_{E1}, Z_{O1}, Z_{E2}, Z_{O2} \) calculated respectively at \( \theta_1 \) and \( \theta_2 \) within 90° satisfy Eq. (11) and (12).

\[
Z_{E1} = Z_{E2} = Z_E \tag{11} \\
Z_{O1} = Z_{O2} = Z_O \tag{12}
\]

It means that when these values of \( Z_E, Z_O, \) and \( Z_R \) are taken, Eq. (3) and (8) are satisfied at \( \theta_1 \) and \( \theta_2 \). \( \theta_1 \) and \( \theta_2 \) are the electrical lengths at the first two operating frequencies \( f_1 \) and \( f_2 \). After \( \theta_1 \) is determined, \( \theta_2 \) can be obtained by selecting an appropriate \( Z_R \) to achieve two operating frequencies, as shown in Fig. 4.
Fig. 4 Calculated values of $Z_E$, $Z_O$, $\theta_2$, and $Z_R$ for different $\theta_1$. (a) $\theta_1 = 12^\circ$, $Z_R = 21.9\Omega$. (b) $\theta_1 = 16^\circ$, $Z_R = 35.8\Omega$. (c) $\theta_1 = 20^\circ$, $Z_R = 62.9\Omega$. (d) $\theta_1 = 24^\circ$, $Z_R = 151.6\Omega$.

To realize the quad-band operation, the electrical lengths $\theta_1$ and $\theta_2$ at the third and fourth operating frequencies $f_3$ and $f_4$ are obtained as:

\[
\begin{align*}
\theta_3 &= 180^\circ - \theta_2 \\
\theta_4 &= 180^\circ - \theta_1 
\end{align*}
\]

And there is

\[
\frac{f_3}{\theta_1} = \frac{f_2}{\theta_2} = \frac{f_3}{\theta_3} = \frac{f_4}{\theta_4}
\]

(15)

So the operating frequencies $f_3$ and $f_4$ are calculated as:

\[
\begin{align*}
f_3 &= f_2 \frac{180^\circ - \theta_2}{\theta_2} \\
f_4 &= f_1 \frac{180^\circ - \theta_1}{\theta_1}
\end{align*}
\]

(16) (17)

In the design, $\theta_1$ can be obtained by selecting $f_1$ and $f_4$ from Eq. (17). And $Z_E$, $Z_O$, $\theta_2$, and $Z_R$ can be calculated by solving Eq. (1-3, 6-8) through computer calculation.

The Fig. 5 shows the variations of $Z_E$, $Z_O$, $\theta_1$, and $\theta_2$ against $Z_R$. It should be noted that $\theta_2$ is determined by $\theta_1$ and cannot be adjusted. Under the condition of $20 \Omega < Z_R < 200 \Omega$, the range of $\theta_1$ is $11.28^\circ$-24.76° and the range of $\theta_2$ is $27.33^\circ$-57.33°, which results in the ratio of the first two operating frequencies $f_1$ and $f_2$ to 2.31-2.41 as calculated in Eq. (15). The ranges of $f_3 / f_1$ and $f_4 / f_1$ can be obtained as 4.96-13.55 and 6.27-14.96 respectively from Eq. (15-17).

3. Application and results

For further demonstration, a proposed quad-band branch line coupler operating at 0.7, 1.64, 4.09 and 5.03 GHz has been fabricated and measured. The prototype and layout of the proposed coupler is shown in Fig. 6.

The coupler has been designed and simulated with Advanced Design System and Ansys HFSS, and fabricated on a Taconic TLY-5 substrate with a thickness...
of 0.762 mm and a dielectric constant of 2.2. The component values and dimensions of the fabricated coupler are shown in Table I. The simulated and measured results of the designed coupler are shown in Fig. 7 and summarized in Table II.

The operating frequencies shift slightly due to parasitic effects and discontinuity at the component connections and the fabrication errors. For the first two operating frequencies, the amplitude imbalance ($\Delta A = |S_{21}| - |S_{11}|$) is $< 0.7$ dB and the phase difference between the two output ports is $< 3^\circ$ compared with $\pm 90^\circ$. Meanwhile, for the third and fourth operating frequencies, the amplitude imbalance ($\Delta a = |S_{21}| - |S_{11}|$) is $< 1$ dB and the phase difference between the two output ports is $< 7^\circ$ compared with $\pm 90^\circ$. The insertion losses are high for the upper frequencies because the measurement is in an open space which results in high radiation loss. Generally, it is observed that the simulated and measured results are in good agreement.

### Table I. Component values and dimensions of the coupler.

| Components | Impedance (Ω) | Width (mm) | Length (mm) | Space (mm) |
|------------|---------------|------------|-------------|------------|
| $Z_{13}, Z_{23}/\theta$ | 88.55, 48.51/21.99 | 1.26 | 19.76 | 0.25 |
| $Z_{3}/\theta$ | 62.62, 34.3/21.99 | 2.16 | 19.51 | 0.14 |
| $Z_{2}/\theta$ | 91.06/21.99 | 0.78 | 19.74 | - |
| $Z_{1}/\theta$ | 64.39/21.99 | 1.53 | 19.38 | - |

![Fig. 7 Simulated and measured results of the designed coupler. (a) Return loss $S_{11}$. (b) Insertion loss $S_{21}$. (c) Coupling coefficient $S_{12}$. (d) Isolation $S_{11}$. (e) Phase difference between $S_{21}$ and $S_{31}$.](image)

The comparison between the proposed coupler and the previous multi-band branch line couplers is shown in Table III. Compared with the coupler from reference [33-36], the proposed quad-band structure has the highest ratio of the largest operating frequency ($f_{\text{MAX}}$) to the smallest operating frequency ($f_{\text{MIN}}$) which can reach by 14.96.

### Table III. Comparison with previous works.

| Reference | [33] | [34] | [35] | [36] | This work |
|-----------|------|------|------|------|-----------|
| Tactic    | Coupled lines and transmission lines | Coupled lines | Open stubs | Matching circuitry | Coupled lines and open stubs |
| Frequency (GHz) | 0.7/1.7/2.6/ | 0.66/1.52/ | 0.7/2.1/ | 1.5/2.4/ | 0.7/1.6/ |
| $S_{11}$ (dB) | $< -11.2^\circ$ | $< -11.0^\circ$ | - | $< -16.2^\circ$ | $< -18.18^\circ$ |
| $S_{21}$ (dB) | $> -3.9^\circ$ | $> -3.71^\circ$ | - | $> -3.71$ | $> -4.83$ |
| $S_{31}$ (dB) | $> -3.91^\circ$ | $> -3.84^\circ$ | - | $> -4.00$ | $> -4.09$ |
| $f_{\text{MAX}} / f_{\text{MIN}}$ range | 8.1-11 | 1.95-7 | 5.7-9 | - | 6.27-14.96 |

* Max $S_{11}$, Min $S_{21}$, Min $S_{31}$, Max $S_{11}$ for the operating band.
# Simulation results.
^ Calculated from the figure.

### 4. Conclusion

A novel quad-band structure consists of coupled lines and open stubs has been proposed. The ratio of the largest operating frequency to the smallest operating frequency ranges from 6.27 to 14.96. The high frequency ratio supports that the coupler can be used in devices and systems with a wide frequency range, which is valuable for wideband application. For the purpose of verification, a quad-band coupler working at 0.7, 1.64, 4.09, and 5.03 GHz which can be used for LTE and Wi-Fi is designed and implemented. The simulated and measured results match well with the design theory.

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