A miniature TSV-based branch line coupler using π equivalent circuit model for transmission line

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Abstract A miniaturized lumped element branch line coupler with π-type equivalent circuit is proposed, the design of branch line coupler has been carried out for S-band. The lumped element in the branch line coupler is realized by TSV, and the coupler is simulated and verified by industrial simulation software HFSS. The results show that the return loss is greater than 19 dB, the isolation is better than 20 dB, and the insertion loss is less than 1.53 dB at the frequency of 2.1-2.4 GHz. The size of the miniature TSV-based branch line coupler is only 0.660×0.630mm²(0.018×0.017λ²).

key words: Branch line coupler; miniaturization; lumped element; Through-silicon via (TSV)
Classification: Electron devices, circuits and modules (Silicon)

1. Introduction

With the development of modern communication technology, the demand for miniaturization and lightweight of communication components is increasing [1], so the study of microwave passive device miniaturization has important significance. As a key element in RF microwave system, branch line couplers are used for power distribution and combination [2-4]. At the lower frequency of the microwave band, the size of a conventional branch line coupler is too large for practical use [5]. Such as in S-band, the disadvantages of traditional branch line couplers with large size are more prominent, while S-band is widely used in communication satellites, weather radars and other fields, and the size requirements are more stringent. By using the method of lumped components can significantly reduce the size, low-temperature co-fired ceramic (LTCC) and integrated passive device (IPD) technology have been introduced recently to achieve a reduction in circuit size[6], but it is difficult to improve the performance due to parasitic effects.

TSV provides low loss vertical electrical connection, so it has been widely studied in recent years [7-11], and it has the advantages of lower loss, smaller size, integrability and good transmission characteristics [12-18], which makes it not only was used as a vertical interconnect in 3D-IC, but also widely used in the passive device manufacturing [19-23]. In this paper, a miniature TSV based branch line coupler for S-band is proposed.

2. Design of TSV-based branch line coupler

The design method of TSV-based branch line coupler was described in this section. Fig.1(a) shows the structure of a branch line coupler consisting of four λ/4 transmission lines [24]. The λ/4 transmission line can be equivalent to a π-type circuit model as shown in Fig. 1(b) [25]. The lumped element value corresponding to the transmission line can be obtained by Eqs. (1) ~ (4).

\[ L_1 = L_2 = \frac{Z_0 \sin \theta}{\omega} e^{\frac{-\theta}{2}} \Rightarrow Z_1 = \frac{Z_0}{2\pi f_0} \] \hspace{1cm} (1)

\[ L_3 = L_4 = \frac{Z_0 \sin \theta}{\omega} e^{\frac{-\theta}{2}} \Rightarrow Z_3 = \frac{Z_0}{2\pi f_0} \] \hspace{1cm} (2)

\[ C_a = \frac{1}{\omega Z_1} \] \hspace{1cm} (3)

\[ C_b = \frac{1}{\omega Z_3} \] \hspace{1cm} (4)

the characteristic impedance of transmission line \( Z_1 = 47.57\Omega \), \( Z_2 = 150.15\Omega \) is obtained by odd even mode analysis theory, and the electric length \( \theta = 90° \). The inductance \( L_1 = L_2 = 3.155\mu H \), \( L_3 = L_4 = 9.95\mu H \) and the capacitance \( C_1 = C_2 = C_3 = C_4 = 1.84pF \) were calculated. Thus, the equivalent circuit diagram of the branch line coupler is obtained, as shown in Fig.1(c). The inductor is a spiral structure formed by connecting

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TSV and Redistribution Layer (RDL), as shown in Fig. 2(a). And the capacitor is a double layer interfinger structure implemented by RDL, with two layers interlaced and connected by contact, the number of the fingers in each layer is 28, as shown in Fig. 2(b). According to the design theory above, the coupler is realized by TSV technology, and it has four layers of RDL at the top and one layer of RDL at the bottom, as depicted in Fig. 3.

In this work, the substrate material of TSV is high-resistivity silicon. The dielectric constant of high-resistivity silicon is 11.9, and the resistivity is 1000 \( \Omega \cdot \text{cm} \). RDL is made of copper and embedded in silicon dioxide with a dielectric constant of 3.9.

![Fig. 1 The circuit model.](image)

(a) Traditional branch line coupler (b) \( \pi \)-Equivalent-Circuit Model (c) Circuit model of branch line coupler

![Fig. 2 Models of inductor and capacitor](image)

(a) The model of inductor (b) The model of capacitor

![Fig. 3 The model of TSV-based branch line coupler.](image)

(a) S-parameter simulation of the coupler (b) Phase difference between port 2 and port 3

**Fig. 4** The S-parameter and phase difference of the coupler

### 3. Simulation Results and comparison

The structural parameters of the branch line coupler based on TSV proposed in this paper are listed in Table I. The S-parameter simulation results and the phase difference of the model are shown in Fig.4. According to the results, when the frequency is 2.1-2.4 GHz, the return loss of the coupler is greater than 19 dB, the insertion loss is less than 1.53 dB, and the isolation is greater than 20 dB. The isolation can reach 57.62 dB at the frequency is 2.22 GHz, the bandwidth of 15 dB isolation/return loss is about 30.3%. The simulation results show that the phase imbalance at operating frequency is within 8.5°, and the phase imbalance is mainly caused by parasitic parameters. The proposed branch-line coupler is compared with four conventional structures in Table II. By comparison, the proposed coupler greatly reduced the size, at the same time it has low insertion loss and high isolation.

| Couplers \( f_0 \) (GHz) \( f_0 \) (GHz) Range (GHz) RL (dB) IL (dB) Isolation (dB) Size | \( \lambda_s \) (\( \lambda_s \)) |
|---|---|---|---|---|---|---|
| [27] | 2.5 | 2.30-2.83 | >15 | 4.17 | >14 | 1.47×1.53 | 0.012×0.013 |
| [28] | 28 | 25-30 | >14 | 3.86 | >14 | 1.15×0.98 | 0.164×0.164 |
| [29] | 2.4 | 2.15-2.47 | >15 | 4 | >15 | 4.216×3.835 | 0.079×0.071 |
| [30] | 24 | 23-25.5 | >13 | 4.7 | >15 | 8.5×8.5 | 0.197×0.197 |
| This work | 2.4 | 2.1-2.4 | >19 | 1.43 | >20 | 0.660×0.630 | 0.018×0.017 |

### 4. Conclusion

In this paper, a compact and miniaturized TSV based branch line coupler for S-band is proposed. This structure greatly reduces the size of branch line couplers and ensures low insertion loss and high isolation. The proposed design method can also be extended to other
lumped parameter passive devices.

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