A miniaturized and self-packaged Gysel power divider with embedded metamaterials in SISL platform

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Abstract This paper presents a self-packaged Gysel power divider (PD) with embedded metamaterials in substrate integrated suspended Line (SISL) platform. Metamaterials are formed by a periodic arrangement of I-shaped electrical resonators that can produce high dielectric constants and are encapsulated in the multi-layer SISL structure to reduce the circuit size. Fabricated by using a standard printed circuit board (PCB) process, the proposed Gysel PD is self-packaged. The structure of the meandering line introduced in the layout of PD can be downsized. The designed PD with embedded metamaterials operates from 3.3 to 3.6 GHz with a bandwidth of 14.8% for $S_{11} < -20$ dB. Compared with the case where metamaterials are not embedded, the circuit area is reduced by about 61%.

Keywords: Gysel power divider (PD), high-dielectric constant metamaterials (HDCM), substrate integrated suspended line (SISL), self-packaged

Classification: Microwave and millimeter-wave devices, circuits, and modules

1. Introduction

The power divider (PD) is an essential component in microwave systems/RF circuits and is extensively used in power amplifiers, antenna arrays, modulators, etc. The PDs have been widely studied, such as waveguide PDs [1], and planar PDs [2, 3, 4, 5]. However, the conventional Gysel PD occupies a relatively large area due to the use of the quarter or half-wavelength microstrip transmission line. Therefore, the research on the miniaturization of the Gysel PD is significant. In [2] and [4], the Gysel PD structure is constructed by using the composite right/left-handed transmission lines (CRLH TLs), which can reduce the circuit size. In [6] and [7], a miniaturized substrate integrated waveguide (SIW) Gysel PD based on LTCC technology is proposed and designed.

In the field of radiofrequency equipment design, metamaterials have been extensively explored to achieve miniaturization [8, 9, 10, 11] and enhance performance indicators such as gain, antenna directivity [12], bandwidth [13, 14, 15] and other good properties in radio frequency devices [16, 17, 18, 19]. And various structures such as dual band branch line couplers, compact ring hybrids, zeroth order antennas, and broadband baluns have been intro-duced by incorporating metamaterial transmis-

![Fig. 1](image-url) (a) Schematic diagram of HDCM unit cell (b) variation of dielectric constant ($\varepsilon$) with frequency for the HDCM unit cell
first obtain the $S_{11}$ and $S_{21}$ parameters through electromagnetic simulation software [27, 28], and then based on Eq. (1) to Eq. (3), we use the inversion parameter method to extract effective dielectric constant $\varepsilon$ and equivalent permeability $\mu$ in [29]. The parameter $d$ represents the thickness of a single unit cell of the structure, where $n$ is the refractive index and $z$ is the wave impedance.

\[
n = \frac{1}{k \ast d} \cos^{-1} \left[ \frac{1}{2S_{21}} \left( 1 - S_{11}^2 + S_{21}^2 \right) \right]
\]

\[
z = \sqrt{\frac{(1 + S_{11})^2 - S_{21}^2}{(1 - S_{11})^2 - S_{21}^2}}
\]

\[
\varepsilon = n/z, \quad \mu = n \ast z
\]

Finally, with the help of numerical calculation and analysis software, we obtained metamaterial properties in the frequency range of 0 to 10 GHz. The result in Fig. 1(b) shows that the resonance of both electric fields and magnetic fields causes the dielectric constant to reach a peak value of 90 at 7 GHz. We verify that the 1-shaped unit has high dielectric constant characteristics.

2.2 Design of HDCM based on SISL

The multi-layer SISL structure is shown in Fig. 2. The SISL is realized by five substrates marked S1 to S5 with ten faces marked M1 to M10. We make S2 and S4 hollow into rectangles to form two cavities, which not only reduces dielectric loss and realizes suspension, but also can easily place the required three-dimensional components such as resistors in the cavity. The core circuit is designed on S3, and the designed metal patterns can be etched on M5 and M6. Each substrate can be designed and manufactured separately and then be pressed together with rivets. S1, S2, S4, and S5 are FR4 materials with a dielectric constant of 4.4 and a thickness of 0.6mm. S3 is designed on FR4 substrate with a dielectric constant of 4.4 and a thickness of 0.127mm [30]. The metamaterial layer of the metamaterial structure based on the SISL platform is separately designed in the layer below S3. For better visualization, Fig. 3 shows metamaterial layer 3-D, top, left, and front view of metamaterials. The upper and lower layers of the PCB are respectively plated with metal patches, and the middle is connected by metal through holes. The characteristics of a high dielectric constant are realized through the periodic arrangement.

Photographs of the fabricated hardware of SISL transmission lines with and without embedded metamaterials are shown in Fig. 4. The simulation and measurement results of SISL transmission lines with and without metamaterials are presented in Fig. 5 and Fig. 6, when embedding metamaterials, its resonance point is about 8 GHz. From 0 GHz to 6 GHz, insertion loss ($S_{21}$) is smaller than 0.6 dB, and return loss ($S_{11}$) is less than $-20$ dB. Electromagnetic waves can be transmitted smoothly in this frequency band, with better matching and lower loss. The measured phase change of the ordinary SISL transmission lines is 312.2 degrees, and the simulated phase change of the high dielectric constant SISL transmission lines with embedded metamaterials is 617.76 degrees from 3 GHz to 6 GHz. So its phase constant $\beta$ is increased by 1.98 times. From $V_p' = \omega/\beta$, that is to say, the slow-wave Phase velocity ($V_p'$) was reduced by 1.98 times. From this $V_p' = c/\sqrt{\varepsilon}$, it can be seen that when the electromagnetic wave propagates in the medium,
its dielectric constant is increased by 3.92 times. Due to the relative dielectric constant of the substrate is 4.4, so the relative dielectric constant of the high dielectric constant SISL is 17.25 from 3 GHz to 6 GHz, which is in line with the characteristics of the high dielectric constant.

3. Simulation and measurement of Gysel power divider with and without metamaterials

In order to illustrate that after embedding metamaterials, the relative permittivity can be increased, so that the RF circuit can be miniaturized. In this section, taking Gysel PD as an example, SISL Gysel PD and SISL Gysel PD with embedded metamaterials are designed.

The structure of the conventional Gysel PD is shown in Fig. 7, which is symmetrical and consists of five sections. Its characteristic impedance and electric length are \( Z_1 = Z_2 = \sqrt{2}Z_0 \), \( Z_3 = Z_4 = Z_0 \), \( Z_5 = Z_0/\sqrt{2} \), \( \theta_1 = \theta_2 = \pi/2 \), \( \theta_3 = \theta_4 = \pi/2 \), \( \theta_5 = \pi \), and \( R = 50 \), respectively (\( Z_0 \) is the characteristic impedance of the port).

The core circuit on the M5 layer is shown in Fig. 8, which is symmetrical. The meandering line in the layout can be downsized. Considering the effect of coupling between them and all losses of the PD, we used electronic design software for a full-wave analysis. The parameters of the Gysel PD are optimized by electromagnetic simulation software and the final values are: \( L_{11} = 22.96 \text{mm}, W_{11} = 1.01 \text{mm}, L_{22} = 24.28 \text{mm}, W_{22} = 1.72 \text{mm}, L_{33} = 22.89 \text{mm}, W_{33} = 2.74 \text{mm}, L_1 = 15.8 \text{mm}, W_1 = 0.3 \text{mm}, L_2 = 18.95 \text{mm}, W_2 = 0.8 \text{mm}, L_3 = 14.95 \text{mm}, W_3 = 2 \text{mm}, R = 50 \Omega \). The center frequency is fixed to 3.45 GHz, for the 5-G application.

Each substrate of the fabricated Gysel PD and the assembled Gysel PD are shown in Fig. 9. The simulation and measurement results are presented in Fig. 10 and Fig. 11. It can be seen that the bandwidth is about 14.8% around 3.38 GHz with \( S_{23} < -20 \text{ dB} \); the isolation and reflection values \( (S_{11}/S_{22}/S_{33}) \) are more than 20 dB around 3.45 GHz and in-band insertion loss \( S_{21} \) is no more than 0.315 dB (the fixed 3 dB insertion loss of the PD is subtracted). Since it
Photograph of the fabricated hardware of SISL Gysel PD (a) each substrate without metamaterials (b) assembled PD without metamaterials. (c) each substrate with metamaterials (d) assembled PD with metamaterials.

Simulated and measured S-parameters of SISL Gysel PD (a) $S_{11}$, $S_{21}$, $S_{23}$ (b) $S_{22}$

is a one-to-two equal power divider, the curve of $S_{33}$ is the same as that of $S_{22}$, and the curve of $S_{31}$ is the same as that of $S_{21}$. It also can be seen from the measurement that the bandwidth is about 13.2% around 3.57 GHz with $S_{23} < -20$ dB; the isolation and reflection values are more than 20 dB around 3.57 GHz and in-band insertion loss is no more than 0.891 dB. The measurement approaches the predictions. The center frequency of the test moves about 200 MHz to the high frequency compared to the center frequency of the simulation. The discrepancy between the measurement and the prediction is due to the fabrication uncertainty, material error, and system error in the test.

The core size of the SISL Gysel PD based on metamaterials is $0.15 \lambda_g \times 0.27 \lambda_g$. At the same time, it can be seen from the measurement that the core size of the SISL Gysel PD without metamaterials is $0.28 \lambda_g \times 0.37 \lambda_g$; the relative bandwidth is 26% around 3.57 GHz with $S_{23} < -20$ dB and in-band insertion loss are no more than 0.86 dB. In the case of little change in performance, the area is reduced by 61% compared with the case without metamaterials.

Table I shows the comparison between this work and some reported Gysel PDs. It can be seen that the proposed PD not only has the self-packaged property but also has a smaller size due to the addition of metamaterials. This proves that miniaturization has been achieved.

4. Conclusion

A kind of metamaterial structure by using self-packaged SISL technologies is designed. It has good transmission
characteristics in the frequency band from 0 GHz to 7 GHz, while maintaining a high dielectric constant reaching 17.25. A SISL Gysel PD base on metamaterials is designed, and the area has been reduced by 61% compared with that of the Gysel PD without metamaterial. This metamaterial based on SISL provides new ideas for the design of miniaturized circuits.

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