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Solenoid RF Transformer and Balun

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1. Introduction

As communication systems develop, we need smaller RF circuits and devices. In many RFIC modules, the passive devices require major area of the circuits and it is very important to reduce the size. The size and performance of RF monolithic transformers should be improved because they have important roles in RF circuits such as impedance matching, balun, coupler, and others [1]. The transformer is the device which can transfer the energy using magnetic coupling without significant loss. Although many results have been reported to improve the performance of the monolithic RF transformer [2] [3], most 2D spiral type transformers on silicon substrate suffer from the substrate loss. To solve these problems and make high performance transformers, we adopt solenoid structures. The solenoid transformers on the dielectric film, UPILEX-S, have low insertion loss and high coupling coefficient (k). And the balun fabricated using two solenoid transformers requires very small area compared to spiral Marchand baluns.

2. Fabrication

The RF solenoid transformer was fabricated using the dielectric film (Upilex-50s) which was 50um thick and its dielectric constant (ε_r) was 3.5. First, the etching technology was studied to make via-holes which were required to make a solenoid structure. We used the O_2 plasma etching to make fine via-holes. To make interconnections using the via-holes, we filled the via-holes with copper using electro-plating method. Gold and nickel (about 1~2um thickness) was plated to prevent the oxidation of copper. After via-hole filling process, the front and back side signal lines were patterned and electro-plated using gold. Detailed fabrication process was shown in the reference [4]. To measure, the dielectric film on which the solenoid transformer was fabricated was attached on a Pyrex glass substrate.

3. Results and discussion of the solenoid transformers

Fig. 1 shows the solenoid transformer structures. It has four ports. For measurement of the inverting transformer the port 2 and port 4 were shorted to the ground and non-inverting transformer was measured when the port 3 and 4 were shorted to the ground. The fabricated solenoid transformer has 30x50 μm^2 via-holes, 300x50 μm^2 core area, 15 μm signal line spacing, 4 μm metal thickness, and 16 turns.

Fig. 2(a) and (b) show the S-parameter, high power transfer efficiency of the solenoid transformer and its equivalent circuit model for inverting type [4].

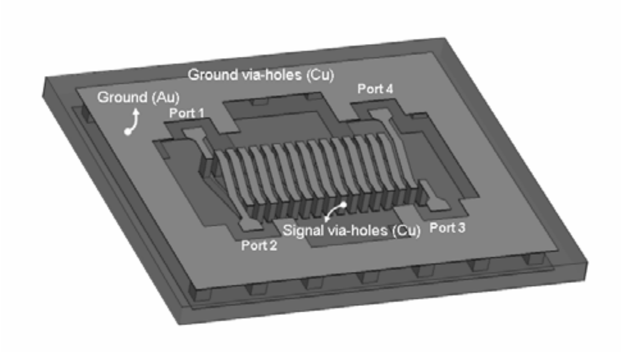


Fig. 1. Schematic of the solenoid transformer.

The S_{21} of the measured S-parameter shows this solenoid transformer has very low insertion loss and good high power transfer efficiency. To calculate high power transfer efficiency, the equation of maximum available gain (G_{max}) was used. For transformers, it has no adequate simple figure-of-merit so maximum available gain was used to describe RF transformer performance. The equations are shown below [6].

$$G_{max} = \left|\frac{S_{21}}{S_{12}}\right|(n - \sqrt{n^2 - 1}) \quad (1)$$

$$n = \frac{1 - |S_{11}|^2 - |S_{22}|^2 + |\Delta|^2}{2|S_{12}S_{21}|} \quad (2)$$

$$\Delta = S_{11}S_{22} - S_{12}S_{21} \quad (3)$$

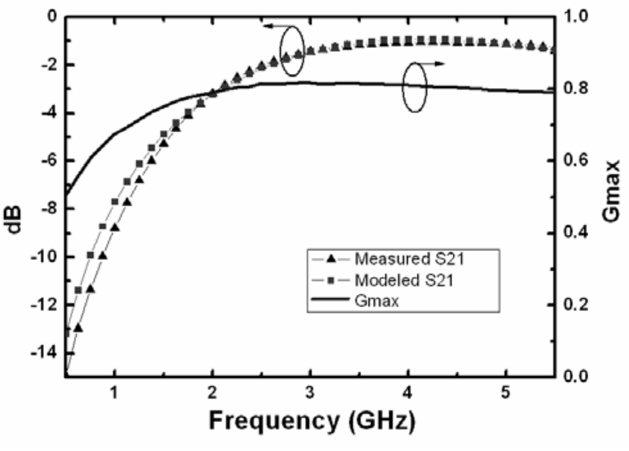
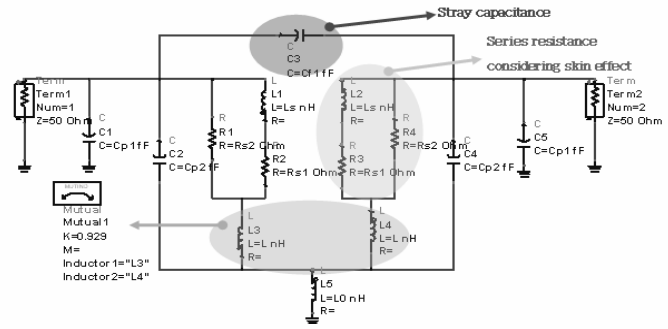


Fig 2. (a) S21 and high power transfer efficiency graph of the inverting solenoid transformer.



Cp1(fF)	Cp2(fF)	Rs1(Ω)	Rs2(Ω)	Ls(nH)	L(nH)	L0(nH)	k
312.62	5.84	0.29	3.12	0.68	2.63	0.86	0.929

Fig. 2. (b) Equivalent circuit model of the inverting solenoid transformer.

The coupling coefficient of the transformer was extracted using the equivalent circuit model and its value (k) was 0.929. Generally, it is very hard to get coupling coefficient higher than 0.9 in spiral transformer. It is because the solenoid structure has lower sensitivity to leakage and parasitic capacitance caused by substrate-contact area than spiral structures. This result means that the fabricated solenoid transformer can transfer the energy very effectively without significant loss and can be a good candidate for RF balun.

4. Results and discussion of the solenoid balun

Using good energy transfer properties of the solenoid transformer, we made solenoid balun using two solenoid transformers. Fig. 3 shows a photograph of the fabricated solenoid balun. Port 1 is input, port 2 and 3 are differential outputs, and port 4 is open because it was designed as Marchand type. To make symmetrical structures, two transformers of the balun have a common ground port and two transformers were separated by 100um distance. Fig. 5 shows that the fabricated balun has very small area compared to the early spiral Marchand balun [7]. It occupies only half area compared to spiral baluns.

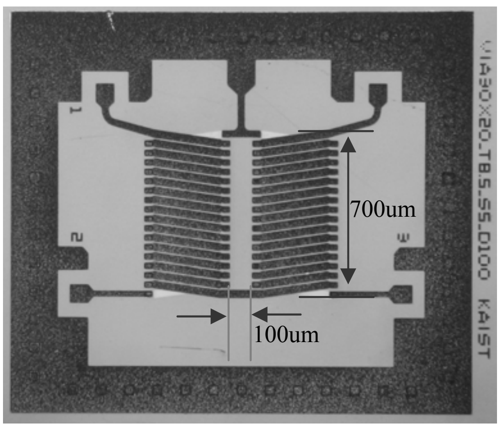


Fig. 3. Fabricated balun photograph (via-hole size= 20x30um, core area=300x50um2, signal spacing=5um, metal thickness=4um, and turns=8.5 turns for a single transformer).

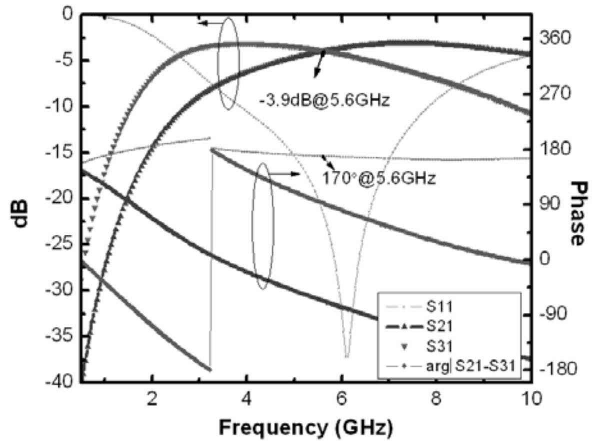


Fig. 4. Measured S-parameters of the fabricated solenoid balun.

Fig. 4 shows the measured S-parameters of the fabricated balun. This graph shows the balun has a balanced output at 5.6GHz and its amplitude of the S_{21} (or S_{31}) is -3.9dB. The phase difference of the two ports is 170°.

5. Conclusions

To improve the size and RF performance, we made solenoid transformer and balun. Because of low substrate losses, the fabricated transformer has good power transfer properties and high coupling coefficient. The balun made using two solenoid transformer shows that solenoid structure has a merit of small size for Marchant balun. However, the fabricated balun has very narrow balance frequency band and 10° phase error. We think the large phase error was caused by asymmetrical structures of three port devices. It requires large core area and optimization port location to improve the solenoid balun.

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