Compact Inductors and Baluns Using Multilayer Technology

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Abstract

Newly developed miniaturized CPW inductors and spiral baluns using the great flexibility of three-dimensional multilayer technology have been designed and fabricated. Their measured performances are presented by on-wafer RF measurements from 45MHz to 40GHz. The area of the multilayer inductor is almost four times smaller than that of planar design while maintaining the same performance. The multilayer spiral baluns are very compact and have amplitude and phase imbalance within 1dB and 10° in a frequency band from 14GHz to 28GHz with the insertion loss about 1dB. A 2.5 D simulator ADS Momentum and a true 3D simulator Ansoft HFSS were used for EM simulation of which results are compared with the measured data. These miniaturized inductors and baluns are constructed using a combination of three metal and two polyimide dielectric layers on semi-insulating GaAs substrates.

Keywords: Spiral inductors, Baluns, MMICs, Multilayer Circuits

1. Introduction

Planar spiral inductors are widely used in monolithic microwave integrated circuits (MMICs) for commercial wireless communications. However, these inductors often take up a large portion of the chip area, far more space than the active devices. In a typical amplifier MMIC up to 80% of chip area is occupied by inductors. This is why the compact miniature inductors are highly desirable for low-cost, highly integrated MMICs.

Thin-film multiplayer technology has shown to be very effective in realization of miniaturization and high level integration which results in reduction of chip size and thus low cost. Multilayer MMIC technology employing multilevel of dielectrics and metals are finding increasing applications in compact and high-performance circuits [1,2,4,5,8,9,10]. In order to utilize the chip area in more efficient manner, we present in this paper a newly developed two metal level spiral inductor structures, in which a planar spiral stacked on top of the other, separated by a polyimide layer as the dielectric layer and joined in the centre by a via hole through the polyimide layer. The stacked spiral inductors were originally analyzed by M.W. Geen et al [1], but only 50% size reduction was achieved. The multilayer structures in this work have been designed and fabricated using three layers of metals and two layers of sandwich polyimide. Their performance such as resonant frequency and quality factor are comparable to that of each other. The results show that the offset and the directly overlayed stacked spiral inductors have shrunk to 1/4 the size of the conventional planar design while maintaining similar performance. In this paper we describe the modelling, design and fabrication of multiplayer CPW inductors. The performance of both planar and 3-D inductors are analysed and compared.

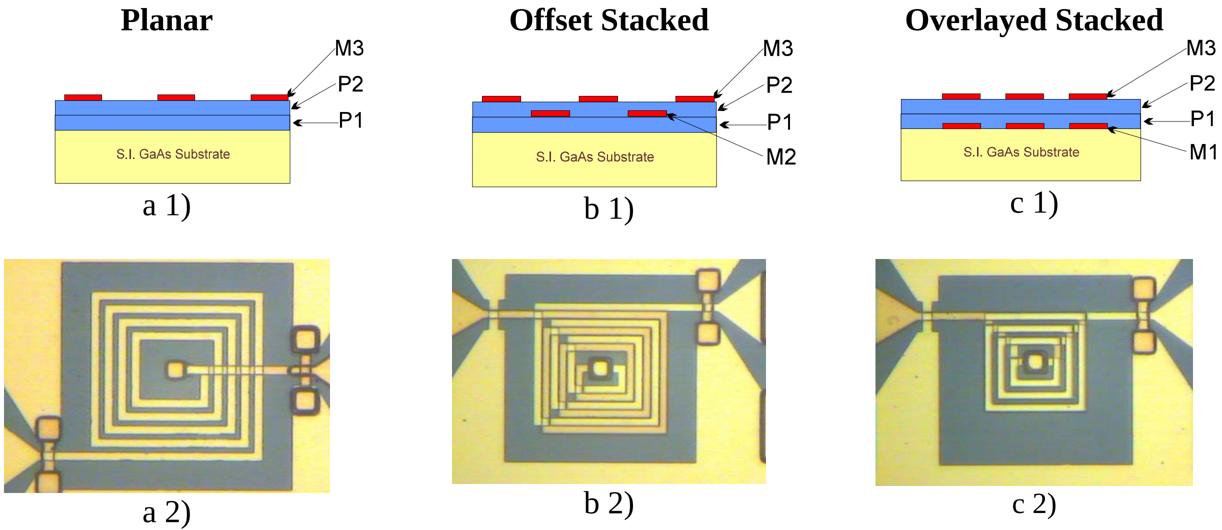
Baluns are very important components and widely used in balanced microwave circuit topologies such as push-pull amplifiers, balanced mixers, and antennas. It is used to convert an unbalanced input signal into two or more balanced output signals, or vice versa. Baluns can be classified into active balun and passive balun. Active baluns can be constructed by active FET components with common source transistor or common gate transistor to achieve impedance matched [11]. The output gain from active balun can reduce the oscillator's input gain for mixer applications. However, the dc dissipation and high noise level have to be carefully treated. Passive baluns are preferred due to their low power consumption. However the ring and Wilkinson power divider based baluns are not suitable for MMIC applications due to their large size [12]. Recently, compensated Marchand baluns have received a great attention due to its compact size, good balance performance, and wide operating frequency range [13]. Planar baluns can be made of normal microstrip and Lange typed couplers [14]. The main disadvantages of these planar baluns are their relatively large size, and poor coupling factor due to the applied edge coupling. Spiral couplers based baluns show good output imbalance in a narrow frequency band, but the substrate used is not suitable for MMICs [15].

In this paper, we present the design, fabrication and characterisation of a spiral Marchand balun with 20 GHz centre frequency using CPW multilayer technology. Very compact size was realized while maintaining good amplitude and phase imbalance over a wide frequency band from 14 to 28 GHz. The measured results were compared the simulated results using a 2.5D simulator ADS Momentum and a true 3D modular Ansoft HFSS. These data provide a design guide for optimization of spiral Marchand baluns.

The three dimensional inductors and baluns in this work have been fabricated using three layers of metals and two layers of sandwich dielectrics. In realising these multilayer structures, several processing steps have been studied including polyimide spin, curing, etching and metal contact formation. In these structures, different layers need to be interconnected properly through the etched windows of the polyimide insulating layers. The thickness of Au layers (M1, M2 and M3) was about 0.8μm. The isolating polyimide layers between metal layers were 2.5 μm thick, and the semi-insulating GaAs substrate was about 600 μm. The polyimide used in this work has a dielectric constant of about 3.7. The polyimide interconnection windows were formed by oxygen plasma reactive ion etching (RIE) through a photoresist protecting layer patterned using the photolithography process.

2. CPW Multilayer Inductors

Cross sections of three different inductor structures are shown in Figures. 1a1, 1b1 and 1c1. Two different types of stacked inductors were studied, one is directly overlayed and the second type is offset stacked. Offset stacked spiral inductors were realized on M2 and M3 layers. Their spacing are widened to 16 μm in order to reduce the inter spiral capacitance. Similar structures with lower spiral placed on M1 are also designed, which have higher resonant frequency due to their smaller inter spiral capacitance. The directly overlayed spirals has only 9 μm wide spacing and the lower spiral is placed on M3 layer instead of M2 to reduce the inter spiral capacitance. For the purpose of comparison, we also designed planar spiral inductors placed on polyimide layer as shown in Figure 1.a. The spiral inductors are designed with inductance estimated using expressions given in [5]



a 1) b 1) c 1)

a 2) b 2) c 2)

Figure 2. *Cross sectional view and micrograph of the three inductor designs: a) 4.5 turns planar spiral (M3), b) 3+3 turns offset stacked spirals (M2-M3), and c) 3+3 directly overlayed stacked spirals (M2-M3)*

On-wafer S-parameter measurements were carried out on the fabricated inductors over a large frequency range from 45 MHz to 40 GHz. By fitting the equivalent circuit model to the embedded S-parameters we have deducted the parameters of the inductors using Agilent ADS software.

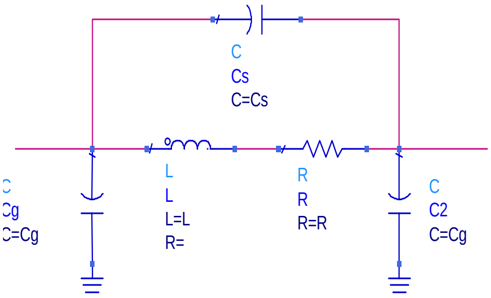


Figure 2. *Lumped-element equivalent circuit model of the inductor.*

Figure 2 shows the lumped-element equivalent circuit model of the spiral inductors on GaAs substrates. The inductance and series resistance of the track, vias, overpass and input and output are presented by inductance, L and resistance R, respectively. The series resistance, R used to model the dissipation loss due to dc resistance, skin effect and eddy current excitation and dielectric loss in the substrate and polyimide layers. Capacitance, C represents the total parasitic capacitance.

Figures 3 and 4 shows the area of the multilayer inductors and the resonant frequency as a function of inductance and for comparison also the area and resonant frequency of conventional planar inductors. factor. These results were extracted by fitting the equivalent circuit model to the embedded S-parameters. Note that the dash line represents the estimation for planar inductors. From Figure 3 it is clear that for a given inductance value a significant reduction can be achieved using multilayer inductors. The directly overlayed stacked spiral inductors take up only a quarter the space of conventional planar inductors while providing almost similar performance such as inductance, resonant frequency and Q. For example the planar inductor with 280 x 280 μm^2 area provides L = 4.7 nH, Q = 4.4 at 3.8 GHz, and f_{res} = 7.4 GHz, while similar performance can be achieved by using directly overlayed stacked spiral inductors, but with only 25% area. The directly overlayed inductors have the highest value of quality factor, because their resistances are the smallest due to the shortest track length. Also from Figures 1b1 and 1c1 it can be seen that higher resonant frequency can be achieved by increasing the thickness of polyimide layer between the two spirals reducing the inter capacitance.

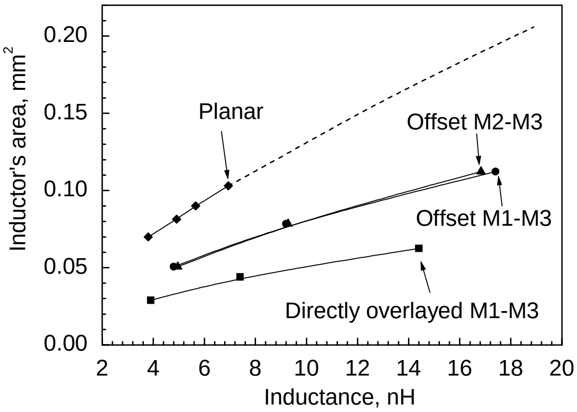


Figure 3. *Variation of inductor's area with inductance for the four spiral inductors.*

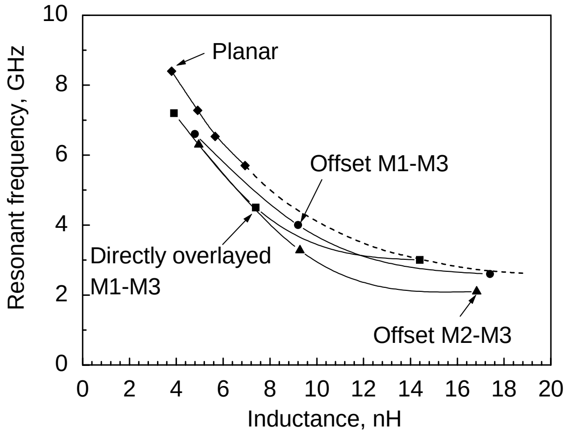
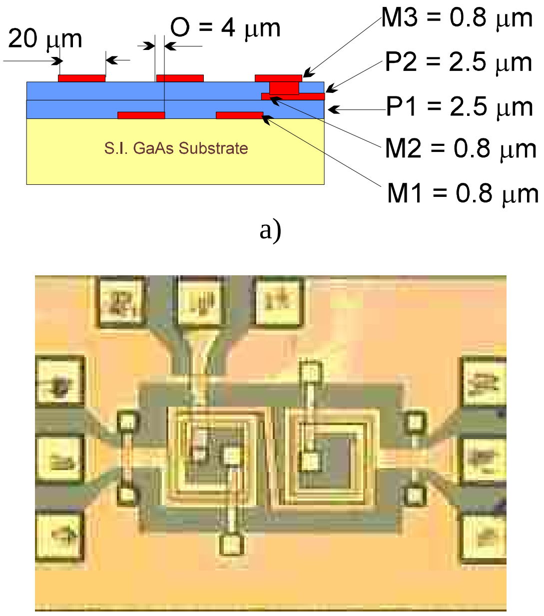


Figure 4. *Variation of resonant frequency with inductance for the four spiral inductors.*

Stacked spiral inductors can be employed in bias circuits of MMICs where the slightly higher loss and relatively low resonant frequency are little importance. They are well suited to use in applications such as lumped element matching networks for the input and output of amplifiers at lower microwave frequencies, also filter structures, which incorporate series capacitors at the centre of the spirals to produce compact L-C-L combinations.

3. CPW Multilayer Spiral Baluns



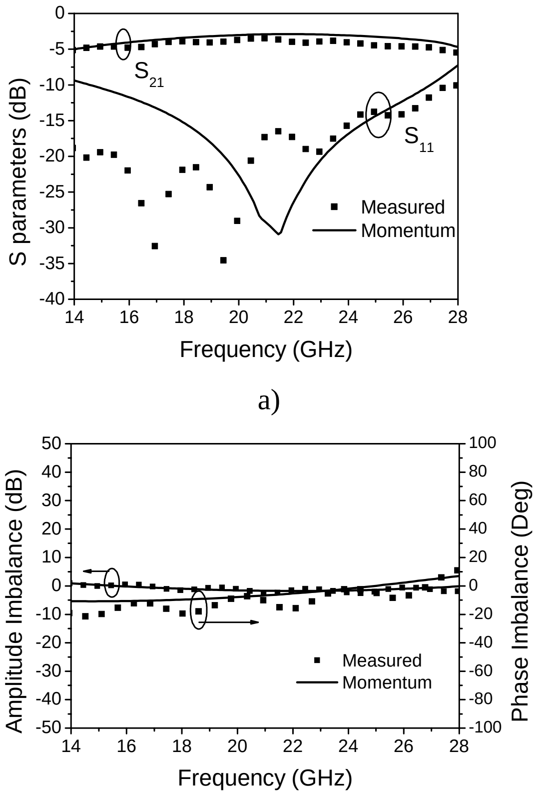
a)

b)

Figure 5. *A CPW multilayer spiral balun:*
a) cross-sectional view
b) micrograph of a fabricated, and

Spiral type baluns has the advantages of compact layouts and increased mutual coupling. Multilayer CPW spiral balun was designed to have centre frequency around 20 GHz. Figure 5a shows the cross-sectional view of the CPW multilayer balun. The balun is formed by three-metal and two polyimide layers in sandwiched structure. The present baluns were designed based on the results of our recent study on spiral couplers [16].

The designed multiplayer baluns were fabricated on 600μm thick semi-insulating GaAs substrate. On-wafer S-parameter measurements were carried out on the fabricated baluns over a frequency range from 45 MHz to 40 GHz.

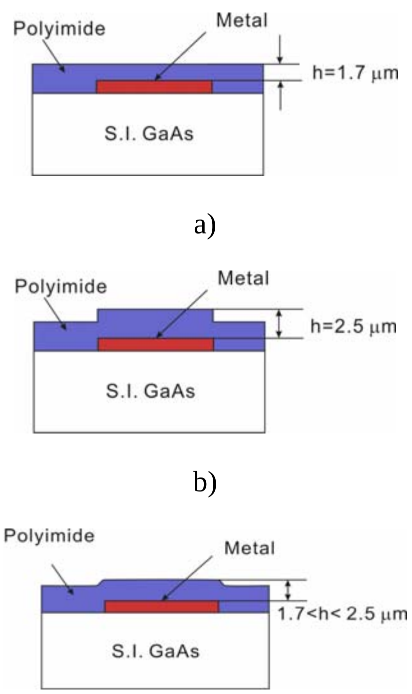


a)

b)

Figure 6. *Simulated and measured results of the spiral balun: a) S parameters, and b) Amplitude and phase imbalance*

Figures 6. shows the measured results of the fabricated spiral balun. The performance simulated using ADS Momentum also can be found in the same figures. From S_{11} it can be observed that the centre frequency is around 20GHz as designed. The output magnitude imbalance better than 1 dB was achieved within a frequency band from 14 to 28GHz. Also a good phase imbalance of ±10° can be seen. The insertion loss excluding 3dB power splitting loss at 20 GHz are about 1dB. This loss is mainly due to the resistance of the long tracks and can be improved by plating them up. In overall this 3D spiral balun provides good performance over the frequency band from 14 to 28 GHz with very compact size of 0.67 mm x 0.38 mm. Compared to the size of planar balun it is a great improvement. Figures 6 show a good agreement between simulated and measured performance apart from a little difference of the centre frequency. This difference can be explained by different polyimide thickness of the overlap area between two spirals in practical and in Momentum. We have investigated this effect with the aid of HFSS and ADS Momentum simulators. Figure 7 shows the step coverage in practical and in the two simulators. In HFSS the planarization is assumed to be perfect, e.g. there is no step above metal track resulting thinner polyimide of the overlap area (1.7μm). In contrast ADS Momentum considers 2.5μm uniform polyimide layer (see Figure 7b) in whole structure due to its 2.5 dimension nature. However experimental data shows that the polyimide thickness is between these two values (1.7μm<h<2.5μm) as shown in Figure 7c, and particularly about 2.1μm.



a)

b)

c)

Figure 7. *Cross-sectional views of step coverage in: a) HFSS, b) Momentum, and c) Fabricated circuit.*

Figure 8 show a comparison between measured and simulated S_{11}. As expected the measured centre frequency is located between simulated ones. As well known the wavelength is determined by the effective dielectric constant. In multilayer structures polyimide thickness has strong effect on the effective dielectric constant. Thicker polyimide layer in Momentum results in lower dielectric constant and thus longer wavelength and higher centre frequency as shown in Figure 8.

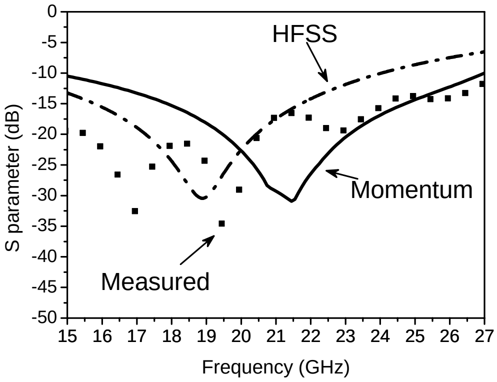


Figure 8. *Comparison between measured and simulated S_{11} of the spiral balun.*

5. Conclusion

Newly developed miniaturized spiral inductors and baluns are designed, fabricated, tested, analysed and compared. The results demonstrate that these compact structures are well suitable for low-cost, highly integrated MMICs as their occupied area are smaller than that of conventional equivalents while maintaining the same performance and thus making efficient use of MMIC chip area.

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