# Vertical Balun and Wilkinson Divider[a]

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***Abstract* — We report the development of a novel broadband 3D vertical balun exhibiting superior performance due to ground plane removal and unique 3D features. The balun offers ± 5 degrees phase and ± 0.5 dB amplitude imbalance, from 2.0 – 2.7 GHz. In addition we present the performance of a 3D X-band 4-way Wilkinson Divider.**

## I. INTRODUCTION

The recent boom in wireless communications underscores the need for providing inexpensive microwave circuits and higher levels of on-chip integration. A promising approach is to build three dimensional microwave circuits by laminating multiple microwave circuit layers on top of each other while keeping all active devices on the semiconductor layer. RF Lines on the first layer are in the embedded transmission line (ETL) configuration while the upper layers are in a simple stripline configuration.

The 3D approach lowers cost by saving valuable real estate space [1]. This area is receiving increased theoretical attention [2]-[3]. Several multilevel MMIC circuits have been reported [4]-[6]. We have developed [3] a model for the effective dielectric constant and characteristic impedance. In this paper we use these models to design and build a 3D X-band 4-way Wilkinson Divider. We also utilize the unique features of the 3D environment to design a broadband vertidcal balun circuit. Both simulation and experimental results will be presented.

## II. VERTICAL BALUN DESIGN AND EXPERIMENT

We present a 3D balun with a unique concept. Normal quarter wave baluns (Figure 1a shows the schematics of a traditional balun) suffer from the absence of large impedance values in planar transmission lines (e.g. microstrip or stripline). This leads to narrow band operation. The equivalent circuit of a traditional balun is shown in Fig. 1b. The balun circuit is modelled as a pair of transmission lines, a main transmission line, with characteristic impedance $Z_o$, the impedance of the coaxial transmission line, and a shunt transmission line with characteristic impedance $Z_{shunt}$. The shunt transmission line is formed by the outer shell and the ground plane below. This shunt line is undesirable since it provides an alternate path for the signal and disturbs the signal balance away from the center frequency. The higher $Z_{shunt}$ is made, the broader the bandwidth of the balun. In practice, one way of increasing $Z_{shunt}$ is by choosing a coaxial line with a small outer diameter, but this leads to higher loss (due to the small diameter of inner conductor). The proposal we have increases $Z_{shunt}$ significantly by increasing the distance between the balun structure and ground plane and having them in perpendicular planes.

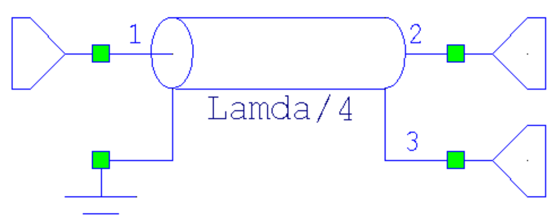


Fig. 1a: Conventional balun design configuration.

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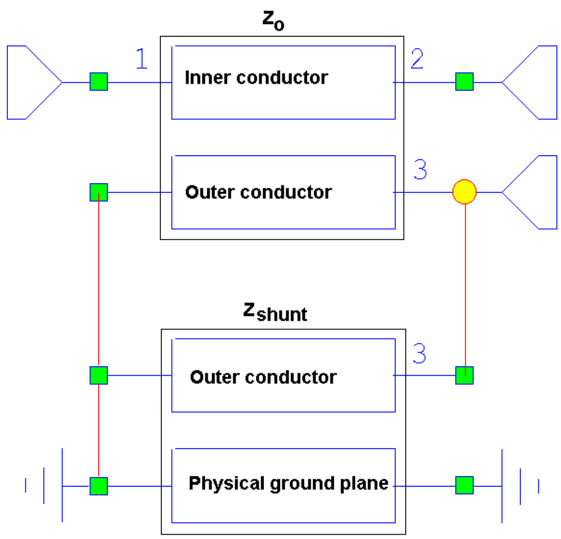


Fig. 1b: Conventional balun equivalent circuit.

We propose a vertical parallel conductor transmission line to act as the balun structure. The idea is that a vertical transmission line will have very little shunt capacitance and will exhibit large line-to-ground impedance. This should facilitate the design of broadband baluns. The layout of the proposed balun is shown in Figure 2 where we have added some microstrip matching (to 50 ohms) for all three ports of the balun. The vertical inductor-like parallel lines form a transmission line system with characteristic impedance 100 ohms and are implemented on high dielectric constant ($\varepsilon_r = 10.2$) material, Rogers 6010, to reduce radiation loss. This transmission line system is vertical with respect to the microstrip ground. This reduces any stray shunt capacitance and leads to a very high impedance between the vertical transmission line and the circuit ground and enables the design of broadband baluns. The performance of the completed balun is shown in Figure 3.

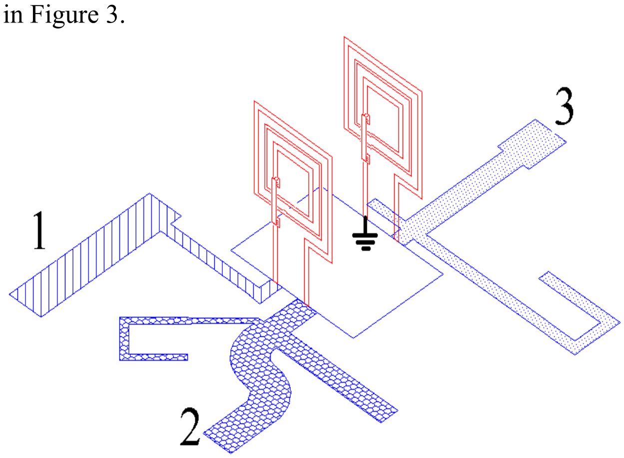


Fig. 2a: Vertical balun concept: layout of vertical balun design.

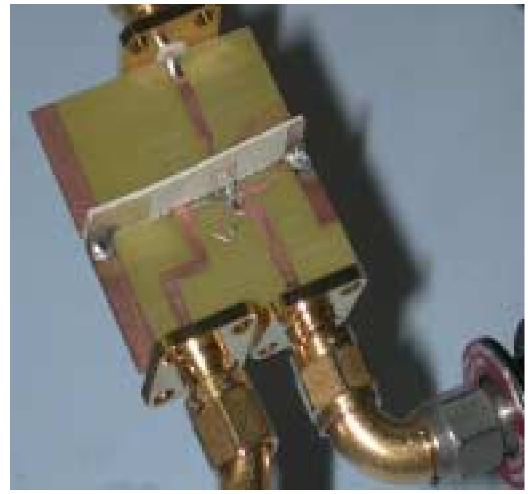

Fig. 2b: Vertical balun concept: picture of finished balun.

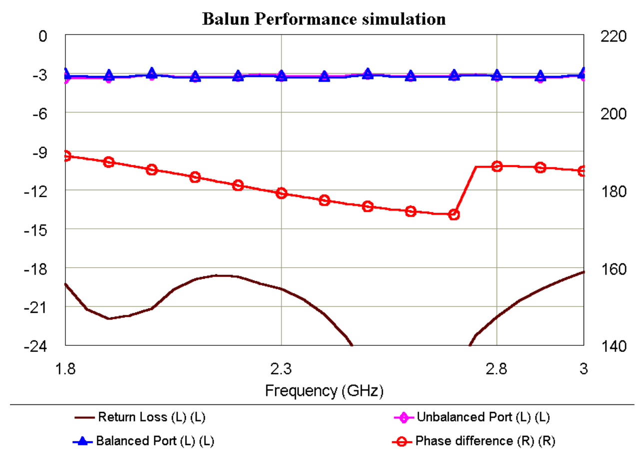


Fig. 3a: Simulated vertical balun performance. The return loss is better than –15 dB, and phase variation is –/+ 7 degrees over 1.8 GHz to 3 GHz bandwidth.

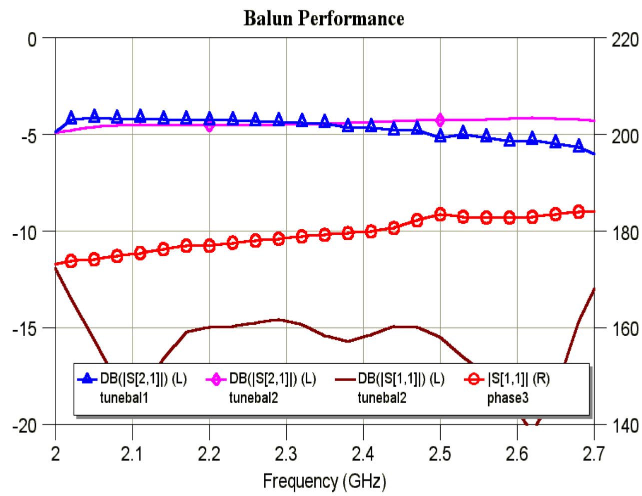


Fig. 3b: Measured vertical balun performance. The return loss is –15 dB, and phase variation is –/+ 5 degrees.

The measured balun performance shows broadband operation, 2.0 GHz to 2.7 GHz (30% bandwidth). The amplitude and phase imbalance is ± 0.5 dB and ± 5 degrees, respectively. The insertion loss is 4.5 dB, about 1.5 dB above ideal value of 3 dB, includes the SMA connector loss (about 0.4 dB), reflection loss (0.2 dB), and any potential radiation loss from the vertical structure. According to our theoretical simulation, which assumes perfect assembly and fabrication, the design should work from 1.8 GHz to 3.0 GHz (50% bandwidth). EM simulation was carried out using AWR's *Microwave Office.*

## III. 4-WAY WILKINSON DIVIDER DESIGN AND EXPERIMENT

We designed a 3D 4-way Wilkinson divider using an Alumina-Ployimide thin film process. One of the challenges of planar circuits, which is easily overcome in 3D circuits, is designing 1-to-N way combiners where the line length of each arm is kept constant. In a Wilkinson divider, all the arms are the same length and are connected together at the input and at the output (to the balancing resistors that provide isolation). The 3D environment facilitates the realization of *equal-length* arms that are connected at input and output. The schematic of a general N-way Wilkinson divider are shown in Fig. 4a. In our case, N=4. We implemented two of the arms of the Wilkinson divider on a 10-mil Alumina substrate, then added 30 microns of Polyimide ($\varepsilon_r$ = 3.2), and implemented the other two arms. The line width was selected such that each line has 100-ohm characteristic impedance and quarter wave length at 10.75 GHz. Via holes were used to connect the lines and to connect to the resistors. EM simulation was carried out using Sonnet and Ansoft's HFSS. The layout, picture and measured performance are shown in Figs. 4b, 4c, and 4d.

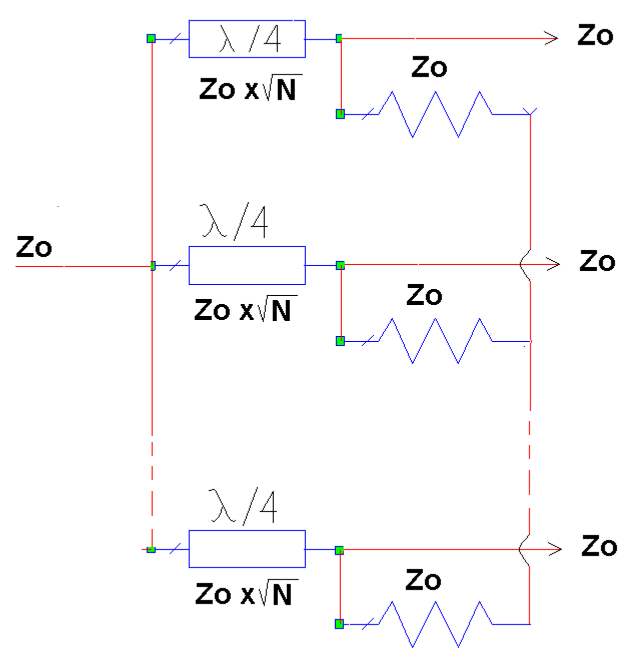


Fig. 4a. General N-way Wilkinson divider schematic. In our case, N=4.

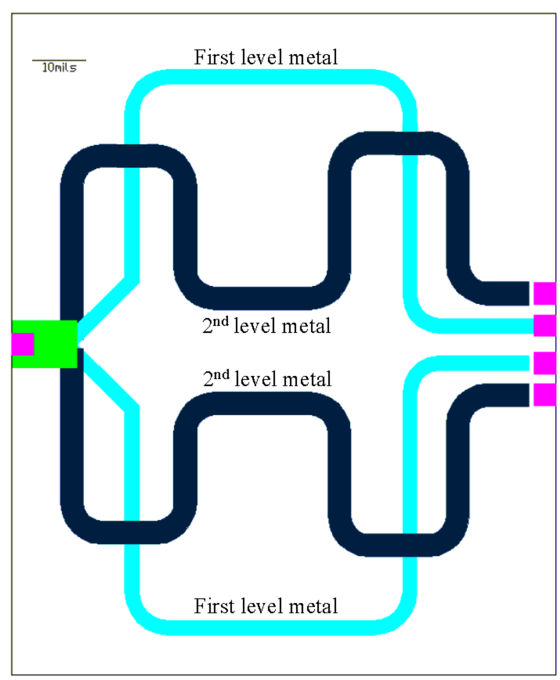

Fig. 4b. 3-layer X-band 4-way Wilkinson divider layout (the isolation resistors are hidden). Each line has a characteristic impedance of 100-ohm.

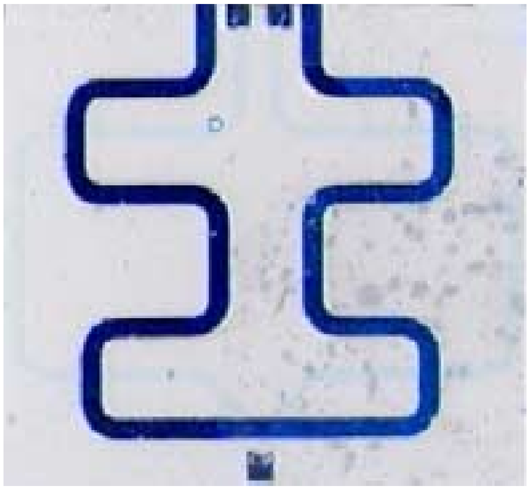

Fig. 4c. Picture of finished 3-layer X-band 4-way Wilkinson divider. Off chip resistors used are not shown.

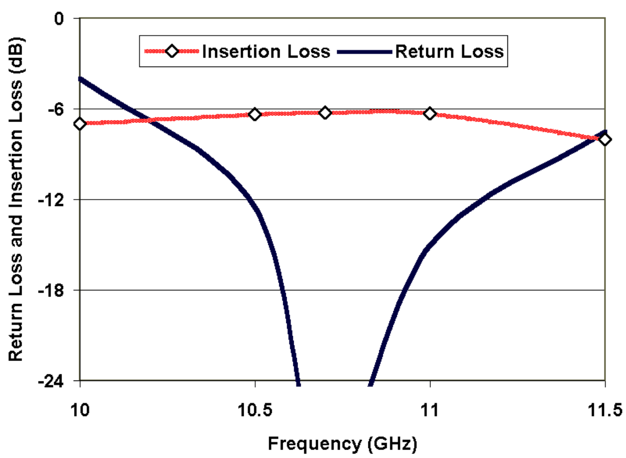


Fig. 4d. 3-layer X-band 4-way Wilkinson divider measured performance (for all arms of the Wilkinson, the insertion loss is about 6 dB, as expected from a 4-way divider, and return loss is about –15 dB).

The overall size of the Wilkinson divider circuit is 0.1" x 0.1". This is similar to the size of conventional 2-way Wilkinson divider built using planar circuit topology. A 4-way Wilkinson, built using planar topology would be difficult to build and larger in size. The 3D technology, in general, offers higher integration advantages.

## IV. Conclusion

We developed a broadband 3D balun that relies on a novel concept of vertical coupled transmission lines. The measured results confirm the usefulness of the concept and points to the need to reduce any radiation-based loss. We also designed and tested a 3D X-band, multi-layer, 4-way, Wilkinson divider. The 3D concept can be easily expanded to N-way division, where N=5, 6, 7, etc. In general, the 3D/multilayer topology offers much greater flexibility than the conventional planar topology.

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