Hybrid implementation of a compact 2-way Wilkinson power divider/combiner for applications in the low RF band

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Abstract—**This paper presents the design and manufacture of a compact 2-way Wilkinson power divider/combiner intended to work in the low RF frequency band. A hybrid of 3D printing, copper electroplating, and PCB technologies is used to implement the Wilkinson prototype. A high degree of compaction is achieved using helical-microstrip transmission line segments as the basic building blocks in the design of the component. The electromagnetic performance of the compact prototype is compared with that of a reference Wilkinson device implemented using standard PCB technology and working at the same central frequency. The results show similar behavior in terms of port matching and bandwidth, with an area reduction of more than 70% in the proposed design compared to the reference Wilkinson device.**

Keywords—**Wilkinson device, 3D printing, copper electroplating, helical-microstrip transmission lines.**

I. Introduction

Delay lines, impedance transformers and power divider/combiners are examples of the variety of RF and microwave components that can be implemented using transmission line (TL) segments as building blocks. The electrical length of the segments and their characteristic impedance are the key parameters to consider in the design of such components. When designing components based on TL segments for a specific frequency range, the most important limiting factor is the required electrical length. In the low frequency band of the RF spectrum designs are not practical unless compaction is performed. The idea of this is to reduce the physical length of the TL segments while maintaining their electrical length. In planar technologies the usual way to achieve this goal is by using meanders [1],[2],[3] or reactive loading [4],[5],[6]. In the former case, the coupling between the traces of the meanders and the bends in each meander introduces discontinuities that can affect propagation along the signal path. In the latter case, reactive loading usually reduces the operating bandwidth of the TL segment. Recently [7], the use of helical-microstrip TLs has been proposed as an alternative compaction procedure to meandering and reactive loading. Helical-microstrip TL are a particular case of Helical TL. In essence, a helical TL is a coaxial TL in which one of the conductors (usually the outer conductor) is replaced by a helical spiral [8],[9]. If the cross section of the helical spiral is a rectangle, then the geometry corresponds to a helical-microstrip TL. Due to their 3D nature, the helical-microstrip TLs do not present any discontinuity in the signal path. Moreover, by adjusting the density of turns in the helicoid, a compaction factor (i.e., the ratio of electrical length to physical length) of up to 5 has been produced without significant degradation of the characteristic impedance of the line and operating bandwidth [7].

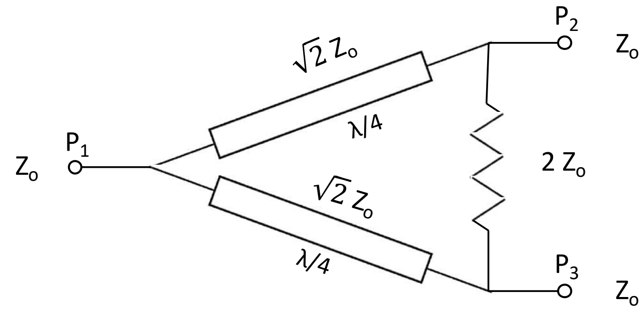

Fig. 1. Schematic view of a Wilkinson power divider/combiner

According to this, in this paper we take advantage of the improvements related to the helical-microstrip TLs to implement a compact Wilkinson device in the low RF band. We present the design, fabrication, and characterization of a compact 2-way Wilkinson power divider/combiner with a center frequency of 250 MHz. The component was manufactured using a combination of 3D printing technology and copper electroplating, to implement the helical-microstrip TL segments, and printed circuit board (PCB) technology, to implement the interconnections and access pads. The result was a compact hybrid device that also demonstrates the compatibility of these technologies.

The rest of the paper is organized as follows. Section II is devoted to the design, electromagnetic (EM) simulation, and optimization of the proposed compact Wilkinson device. In section III, we focus on the manufacturing of the diferent parts of the component and the assembly process. In this section we also present the results of the experimental characterization of the proposed device and its comparison with a classical planar implementation of a Wilkinson power divider/combiner. Finally, in section IV, we present our conclusion and consider future trends.

II. Compact Wilkinson Design

Fig. 1 is a schematic view of the Wilkinson power divider/combiner [10]. The optimum operating frequency is that for which the electrical length of the TL segments is equal to λ/4. At this frequency all the ports are perfectly matched to

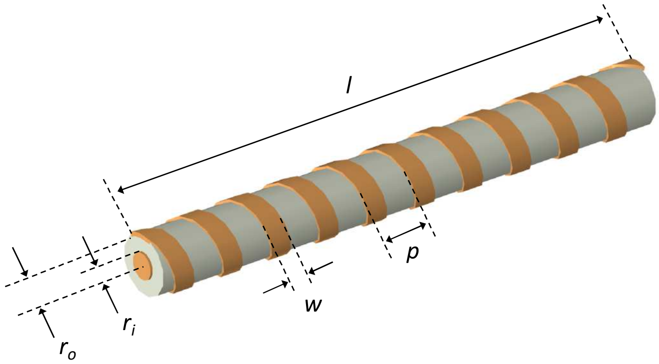

Fig. 2. 3D model of a helical micro-strip TL segment, including the main geometrical parameters.

the reference impedance Z_o, and ports 2 and 3 are perfectly isolated [11]. At microwave frequencies the required electrical lengths lead to TL segments of a few centimeters in length. Meanwhile, for operating frequencies in the low RF band (i.e., a few hundred MHz), practical designs require compaction. For this, in this paper we propose the use of helical-microstrip TL segments. Fig. 2 shows a 3D model of one of these segments. The main geometrical parameters are the physical length of the segment, l, the inner and outer radii, r_i and r_o, respectively, the number of turns, N, the width of the turns, w, and the pitch between turns, p. In this model, copper metallization is assumed. The intermetal material is a photopolymer dielectric used in stereolithographic (SLA) and material jetting (MJ) 3D printing. The relative permittivity is 2.9 and the loss tangent is 0.02.

According to [7], the characteristic impedance, Z_o, of a helical-microstrip TL can be written as follows:

$$Z_o = \frac{120\pi}{\sqrt{\varepsilon_r}} \frac{h_{eff}}{w} \quad (1)$$

where, ε_r is the relative permittivity of the intermetal material and h_{eff} is given by:

$$h_{eff} = r_o \ln\left(\frac{r_o}{r_i}\right) \quad (2)$$

Considering the 3D model shown in Fig. 2, it is straightforward to show that the total length of the helical spiral, l', can be approximated by:

$$l' = \sqrt{(2\pi r_o N)^2 + l^2} \quad (3)$$

Finally, assuming vacuum as a reference, the electrical length of the segment, l_e, can be written as:

$$l_e = \sqrt{\varepsilon_r}\, l' \quad (4)$$

According to (1) and (2), by adjusting the width of the turns and the inner and outer radii we can tune the characteristic impedance of the segment to the desired value. Furthermore, according to (3) and (4), by increasing the number of turns we can modify the compaction factor (i.e., the ratio between the physical length and the electrical length of the segment).

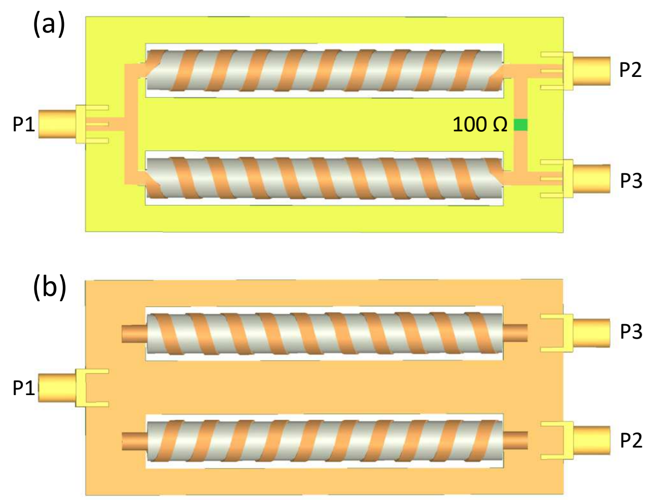

Fig. 3. Virtual top (a) and bottom (b) views of the EM model of the hybrid prototype of Wilkinson power divider/combiner.

For a given value of the characteristic impedance and compaction factor, the set of equation (1) to (4) gives a first estimate of the corresponding geometrical parameters. To increase accuracy, an EM simulation is usually required.

Fig. 3 shows a 3D EM model of a hybrid implementation of a Wilkinson power divider/combiner. The model consists of two helical-microstrip TL segments that are embedded into a PCB through two openings. To maintain a symmetrical design, the helical spiral is clockwise in one of the segments and counterclockwise in the other. The PCB is used to mount the $2Z_o$ resistor (i.e., 100 Ω) and to attach SMA connectors to the access ports P1, P2, and P3. In this design, to ensure a smooth transition between the helical microstrip and the PCB microstrip the difference between radii, r_o and r_i, is equal to the thickness of the PCB (i.e., 1.57 mm). Considering this constrain, EM simulations were performed to obtain the geometrical parameters that give a characteristic impedance of the segments equal to $2^{1/2} Z_o$ (i.e., 70.71 Ω), and an electrical length of λ/4 at an operating frequency of 250 MHz (i.e., 0.3 m in vacuum). The final optimized values are, w=2.3 mm, r_i=1.5 mm, r_o=3.07 mm, N=10, and l=60 mm. The compaction factor is about 5. In Fig. 3b, the extension of the inner ground cylinder should be noted at both sides of the TL segments. This allows the cylinder to be soldered to the PCB ground plane, ensuring electrical connectivity and mechanical fixing. Finally, the overall dimensions of the prototype including the SMA connectors are 98.5 mm x 30 mm.

III. Manufacturing and EM Characterization

A. Manufacturing Process

Once the 3D model of the prototype shown in Fig. 3 was validated, the manufacturing process began with the fabrication of the helical-microstrip TL segments. First, the dielectric base of these elements was printed using an Objet260 Connex 1 3D printer from Stratasys, Ltd. A photopolymer was used as the

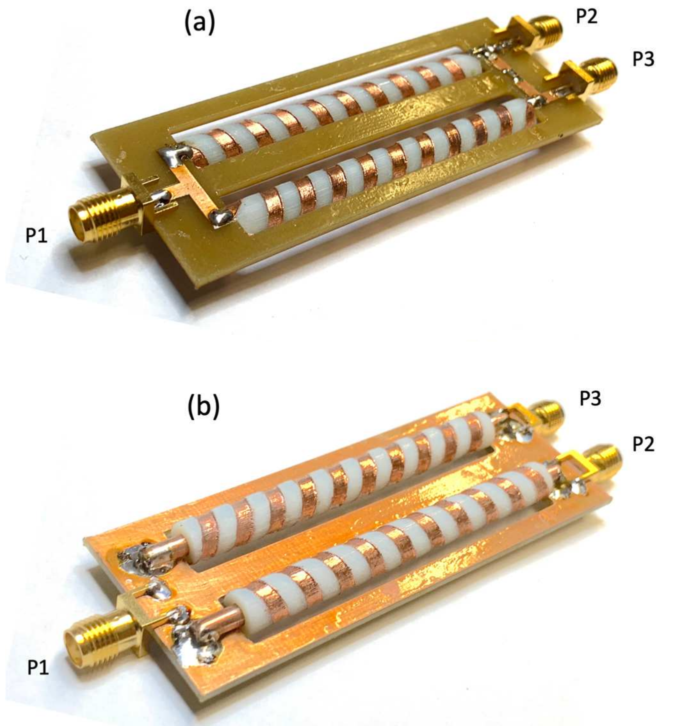

Fig. 4. Actual Top (a) and bottom (b) views after assembly of the hybrid prototype of Wilkinson power divider/combiner.

printing material, which after UV curing has a relative permittivity of 2.9 and a loss tangent is 0.02. Silver ink was then used to define the helical spiral on the outer surface of the segment. Finally, the silver ink was used as a seed to grow a layer of copper by electroplating. The same procedure has been used to implement conical inductors, 3D capacitors, broadband impedance transformers, and filters, among other components. A detailed description of the fabrication process can be found in [12]. In the current implementation the inner conductor of the TL segments was not electroplated. Instead, a 3 mm diameter copper bar was used as the ground inner cylinder.

The PCB was fabricated using a standard FR4 double-sided substrate. A Protomat S103 PCB milling machine from LPKF Laser & Electronics AG, was used to define the traces on the top surface of the PCB and the openings where the TL segments were to be located. The bottom metallization of the PCB was used as the ground plane.

The final step in the manufacturing process was to assemble the different parts. First the TL segments were placed in the openings, and both ends of the inner ground cylinder were soldered to the PCB ground plane. Then, all the required components were soldered on the top surface, and finally the SMA connectors were attached and soldered on both sides of the PCB.

Fig. 4 shows top and bottom views of the prototype obtained after assembly. For comparison purposes, a planar PCB Wilkinson power divider/combiner tuned to the same frequency of 250 MHz was also manufactured. A view of the reference device together with the hybrid prototype is shown in Fig. 5.

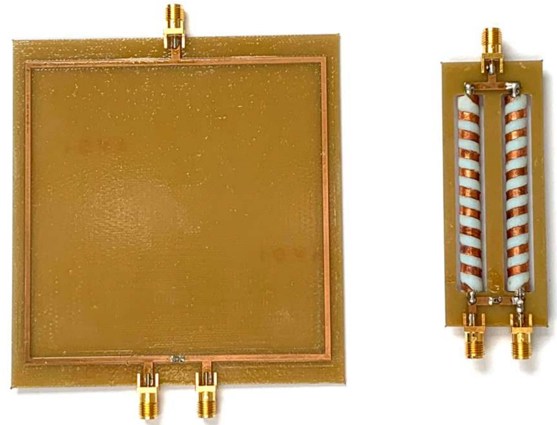

Fig. 5. Actuals views of the reference PCB Wilkinson device (left) and the hybrid prototype (right).

The reduction in surface area, including SMA connectors, is about 75%.

B. EM characterization

The S parameters of the reference device and the hybrid prototype were measured, in the frequency range from 1 MHz to 500 MHz, using an E5071C Vector Network Analyzer, from Keysight Technologies, Inc. The reflection parameters are shown in Fig.6. The transmission parameters in Fig. 7, and the isolation between ports 2 and 3 in Fig.8. Since reflection parameter S33 shows almost the same behaviour as S22, it is not plotted in the figure. The same applies to the transmission parameter S31.

From Fig.6, we can observe that there is a good port matching for both components (i.e., the reference device and the compact hybrid device). The S11 parameter is below -20 dB for frequencies from 200 MHz to 270 MHz, and S22 (thus also S33) is better than -20 dB for frequencies from 100 MHz to 360 MHz. Concerning transmission, we can observe from Fig.7 that the compact hybrid component shows a higher insertion loss than the reference component. However, the difference is less than 0.3 dB for the entire frequency band. Finally, regarding isolation we can see from Fig.8 that both components show very similar behaviour. The maximum isolation is about -33 dB at the operating frequency and is better than -20 dB for frequencies from about 200 MHz to 300 MHz.

These results are in line or outperform previous reported works [2],[4] and [6]. In addition, the proposed design incorporates high reconfigurability and technological compatibility.

IV. Conclusion

In this work we present the design, manufacture and EM characterization of a compact Wilkinson divider/combiner intended to work at a central frequency of 250 MHz. A prototype is implemented using a combination of 3D printing, copper electroplating and PCB technologies. The use of helical-microstrip TL segments as the building blocks in the design of the component, allow a high degree of compaction (up to 75% in

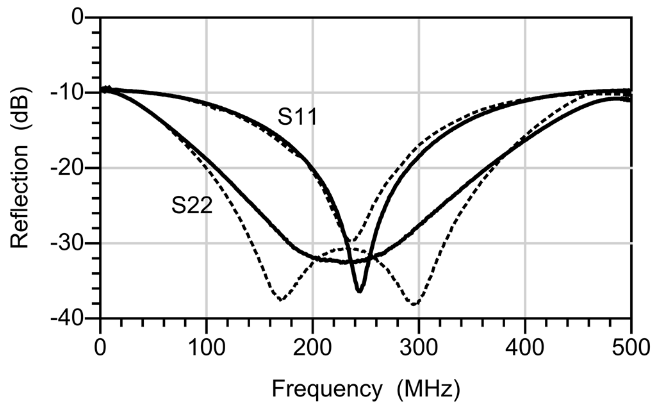

Fig. 6. Measured reflection parameters of the Wilkinson power dividers combiners. The dotted line corresponds to the reference device and the continuous line to the hybrid compact hybrid prototype.

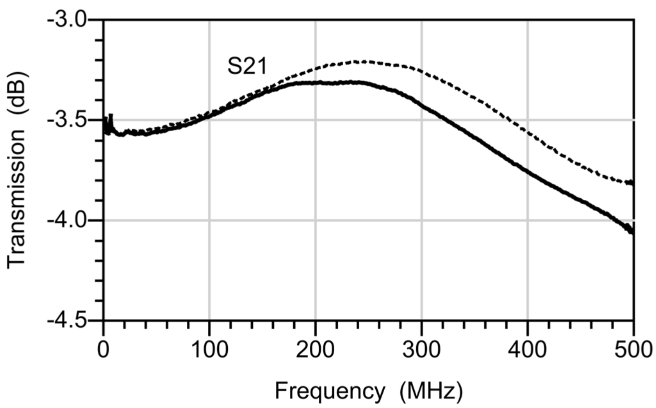

Fig. 7. Measured transmission parameters of the Wilkinson power dividers combiners. The dotted line corresponds to the reference device and the continuous line to the hybrid compact hybrid prototype.

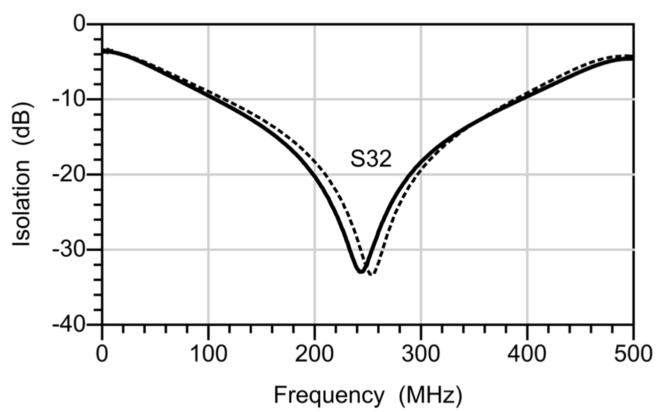

Fig. 8. Measured isolation parameters of the Wilkinson power dividers combiners. The dotted line corresponds to the reference device and the continuous line to the hybrid compact hybrid prototype.

surface area) without degrading the port matching, isolation, and bandwidth compared to a PCB reference device.

The results demonstrate the compatibility of 3D printing helical-microstrip TL technology and PCB technology for RF applications. Further work is currently underway to expand the use of helical-microstrip TL technology to other applications in the RF band.

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