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Nanowire-Based 3-D Transmission-Line Transformer for Millimeter-Wave Applications

Tadeu M. Frutuoso¹, João Lé², Yoann Berthoud³, Julio M. Pinheiro⁴, Marc Margalef-Rovira⁵, Philippe Ferrari⁶, *Senior Member, IEEE*, Gustavo P. Rehder⁷, and Ariana L. C. Serrano⁸, *Member, IEEE*

Abstract—In this letter, 3-D transformers based on transmission lines (TLs) working at mm-wave frequencies are presented. They were realized in a low-cost technology based on metallic-filled nanoporous membranes. Several transformers were designed and measured with different numbers of turns, from 1 to 6 turns. They exhibit working frequencies from 14.5 up to 110 GHz. The 1-dB bandwidth (BW) of the realized transformers is better than 12 GHz, and the insertion loss (IL) is between 1.1 and 1.6 dB, thus demonstrating a high efficiency at mm-waves. Transformers could be further improved by better optimizing the TLs and their return current path, which is a key parameter to be considered, given the distributed nature of the proposed transformers.

Index Terms—3-D circuits, millimeter-wave circuits, system integration, transformer.

I. INTRODUCTION

TRANSFORMERS play an important role in microwave and mm-wave circuits' and systems' design. Their main applications concern matching and biasing networks [1], poly-phase networks [2], signal generation [3], baluns [4], and power divider/combiner [5]. Their implementation in monolithic low-cost integrated technologies such as (Bi)CMOS at mm-wave frequencies is very common today. Most of the works refer to traditional transformers that use two windings (primary and secondary) aiming at low loss and high magnetic coupling coefficient. The primary and secondary spirals can be placed in the same layer [6], [7] or in different layers [8]–[10]. Using different layers with the spirals vertically aligned has shown better performance and size/cost reduction [11].

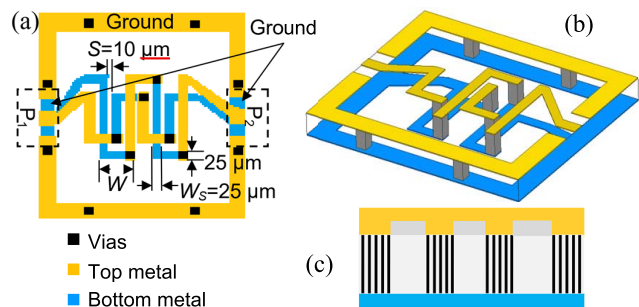
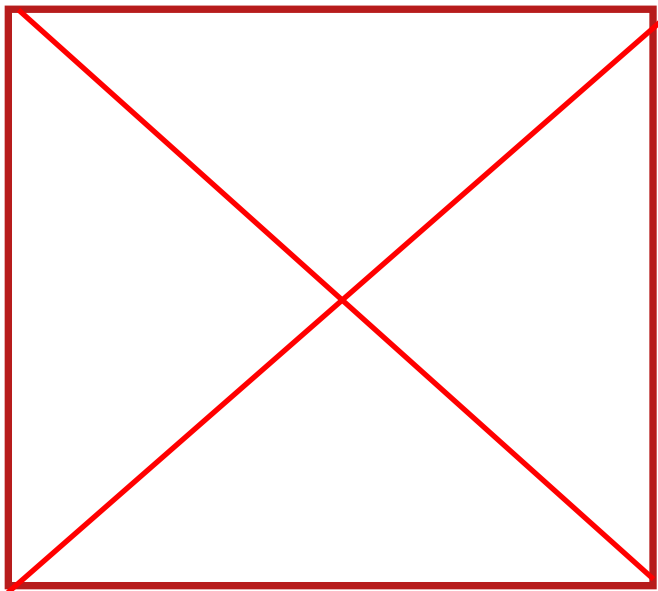


Fig. 1. (a) Illustration of the 2:2 3-D transformer. (b) Three-dimensional view of the 2:2 transformer. (c) Side view of the transformers.

Some other CMOS works refer to transmission-line transformers (TLTs) [12], [13]. TLTs consist of one or more pairs of transmission lines (TLs) interconnected in a way to provide a specific impedance ratio and have been widely studied in the whole frequency spectrum since their publication [14], [15]. In this case, evaluating the transformer performance based on the spirals' performance and their magnetic coupling factor is no longer valid. A more suitable manner to compare the performance of all types of transformers is the power transfer from the input to the output, in terms of the insertion loss (IL).

No matter which topology, (Bi)CMOS transformers are built as far as possible from the lossy silicon substrate [16], reducing eddy current and parasitic capacitances, and preferable at the top thick layers, reducing losses due to series resistance. Despite the good performance, the maximum impedance ratio is limited by the technology considering the limits of the strip width allowed [10]. Their size is still large compared with the rest of the system [17], [18] easily reaching $100 \times 100 \mu\text{m}^2$, when considering not only the spirals but also the required outer spacing from other metals. For instance, removing the power amplifier input and output transformers in [17], it would be possible to reduce the size (and therefore the cost) by half.

Heterogeneous 3-D integration (off chip solution) is an interesting alternative solution that brings flexibility and performance to the transformer design, addressing the issues related to monolithic integration. Transformers have been presented in high-resistivity silicon substrate in lower microwave frequencies [19]–[23], but the numerous vias necessary for their fabrication increases significantly the loss, becoming not suitable for mm-wave applications.

In this letter, we propose TLT transformers operating at mm-waves with broadband characteristic. The TLT is formed by two TLs 3-D meandered around each other forming a

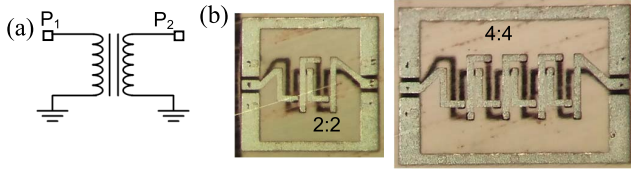


Fig. 2. (a) Transformer schematic. (b) Photographs of the fabricated 3-D transformers (4:4, right; 2:2, left).

solenoid-like topology, as shown in Fig. 1. Since they are TLs, they require return current paths, formed by the metallic rings (one for each layer) drawn around the “solenoids.” The transformers were built using a cost-effective technology based on an alumina metal-filled nanoporous membrane (MnM), where vias can be very easily realized, since the fabrication of the vias enters a standard fabrication process flow, with outstanding form factors and performance [24]. The advantage of the MnM technology is its low cost and good performance. The technology has been first introduced in [25] for the realization of slow wave TLs, with its electrical model presented in [26]. The availability of small vias allowed the development of compact 3-D inductors with high-quality factor at mm-waves, as shown in [27]. Therefore, the MnM technology is a high-performance interposer very suitable for heterogeneous 3-D integration [28], embedding passive components and circuits into the membrane.

II. MNM TRANSFORMERS’ PRINCIPLE, MODEL, AND DESIGN

The proposed 3-D transformer is formed by two 3-D meandered TLs, referred as primary and secondary, both fabricated in two metal layers, at the top (blue) and at the bottom (yellow) of a 50- μm -thick nanoporous alumina membrane. These layers are interconnected by vias realized by a forest of metallic nanowires, which are grown inside the nanopores electrochemically as described in [27]. The vias used here are $25 \times 25 \mu\text{m}^2$ to follow the width of the TLs, but smaller vias and lines could be fabricated if needed.

The relative dielectric constant ϵ_r and loss tangent $\tan\delta$ of the porous alumina substrate are 6.7 and 0.01, respectively, as determined in [25]. Since the membrane used as substrate is translucent, the bottom layer of the 3-D transformers can be as seen in Fig. 2. The end of each TL was grounded to simplify the measurement to a two-port setup, as indicated in Fig. 2(a). The return current paths required for the TLs have a strong impact on the transformer response and must be considered from the earliest stages of design. An asymmetric TL topology was used to show impedance matching flexibility in the design when compared with the symmetric layout in [19].

The model of an $N:N$ transformer is shown in Fig. 3, showing the access lines and the transformer core. Despite the similarity to the traditional transformer model, the proposed model deals with distributed capacitances and inductances related to the coupled TLs. All the values of the model parameters can be extracted from simple capacitance and inductance simulations. The relevance of such an approach is that it is physically related, and therefore, the designer can change any dimension of the TLs to obtain the desired

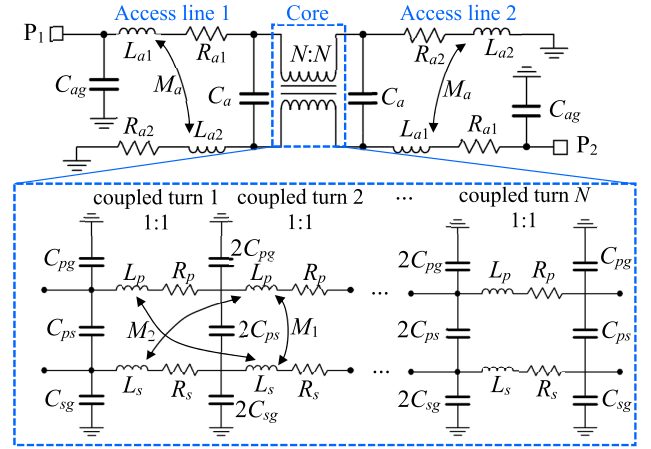


Fig. 3. Model of the $N:N$ 3-D transformers including access lines and transformer core.

response. The model is also scalable, so it can be used for TLs with any number of turns.

The access lines are modeled by the series inductance L_a and resistance R_a , the shunt capacitance C_{ag} , and the capacitance between access C_a . As the lengths of the two access lines of a TL are not symmetrical, in one end we have L_{a1} and R_{a1} and in the other end L_{a2} and R_{a2} . The magnetic coupling between accesses is modeled by the mutual inductance M_a . Regarding the transformer core, the variables for the primary TL (L_p , R_p , C_{pg}) and the secondary TL (L_s , R_s , C_{sg}) were defined for each turn of the coupled TL (1:1). The electric coupling between the two TLs is modeled by C_{ps} . Due to its asymmetry, we have included in the model the coupling between adjacent turns, which is not used in the symmetrical case. Each coupled turn is magnetically coupled through two mutual inductances, M_1 and M_2 , representing the mutual inductance of the coupled turn and between adjacent turns, respectively.

The model uses the following equations:

$$L_{(p \text{ or } s)\text{tot}} = N \cdot L_{(p \text{ or } s)} + L_{a1} + L_{a2} \quad (1)$$

$$C_{(p \text{ or } s)\text{gtot}} = N \cdot C_{(p \text{ or } s)g} + C_{ag} \quad (2)$$

$$C_{ps \text{ tot}} = N \cdot C_{ps} + 2C_a \quad (3)$$

$$M_{\text{tot}} = N \cdot M_1 + 2(N - 1) \cdot M_2 + 2M_a \quad (4)$$

where N is the number of turns.

The transformers’ accesses and TLs were simulated in ANSYS Maxwell for different numbers of turns without connections to the return path. The values of L_p , L_s , C_{pg} , C_{sg} , and C_{ps} were extracted from the slope of their curves and the values of C_a , L_{a1} , and L_{a2} by the value where their curves intercept the y-axis following (1)–(4). C_{ag} and M_a were extracted from the simulation of the accesses alone. Then M_1 and M_2 were calculated from (4). The TLs and access lines’ resistances were calculated using the dimensions of each strip, the copper conductance, and a simple skin effect model. As an example, the extracted parameters for each element of the model of a 2:2 transformer are presented in Table I and its comparison with a full-wave 3-D electromagnetic (EM) simulation and its measurement is shown in Fig. 4.

TABLE I
2:2 TRANSFORMER MODEL PARAMETERS

L_{a1}	L_{a2}	C_{pg}	C_{sg}	C_{ps}	C_{ag}
93.5 pH	89.4 pH	3.7 fF	0.75 fF	23.6 fF	5.7 fF
C_a	L_s	L_p	M_1	M_2	M_a
0.3 fF	316 pH	222 pH	101 pH	46 pH	20 pH

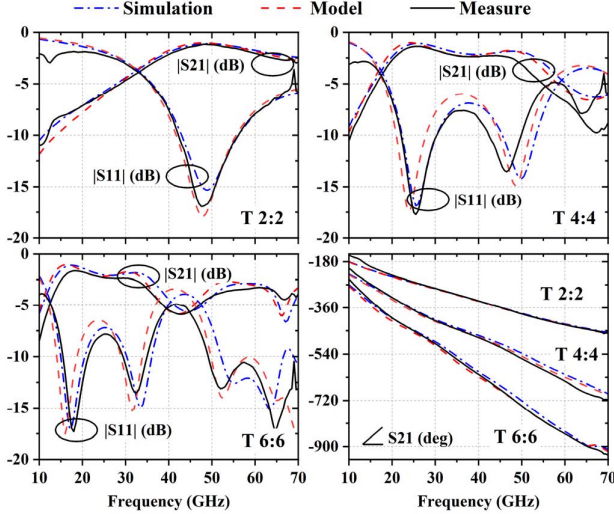


Fig. 4. Comparison between measurement, model, and simulation results for the 2:2, 4:4, and 6:6 3-D transformers.

TABLE II
COMPARISON OF MM-WAVE TRANSFORMERS

Ref.	Technology	Min. IL [dB]	Min. MAG* [dB]	1-dB BW [GHz]	Area [mm ²]	
[29]	65nm CMOS	1.5	-	56-64	0.032	
[20]	HR silicon	0.24	-	6.26-12.25	0.997	
[9]	65nm CMOS	-	0.5	45-90	0.017	
[10]	130nm SiGe BiCMOS	-	0.8	10-80	0.02	
[5]	180nm BiCMOS	-	2.5	45-50 ⁺	0.08	
[17]	90nm CMOS	5	-	55-65	0.01	
This work	MnM	1:1	1.2	0.6	15.5-103	0.24
		2:2	1.1	0.8	19.5-70 ⁺	0.39
		3:3	1.2	1.1	18-70 ⁺	0.456
		4:4	1.4	1.2	14.8-48.5	0.54
		6:6	1.6	1.3	12.8-33	0.671
	1:1 WB	1.5	0.4	15.3-110 ⁺	0.116	

*MAG defined in [31]

⁺ upper boundary limited by the measuring equipment

III. FABRICATION AND MEASUREMENT

The fabrication of the 3-D transformers follows the same steps as the 3-D inductors presented in [27]. The 3-D transformers were characterized up to 110 GHz using ground-signal-ground (GSG) probes (MPI Titan probes with 100 μm -pitch) in a cascade manual probe station (EPS-150MMW) and a Keysight PNA 5227B vector network analyzer. A line-reflect-reflect-match (LRRM) calibration was performed. To prevent short-circuiting the bottom of the transformers with the metallic chuck of the probe station, a 5-mm-thick ROHACELL 51 IG foam was used as spacing.

Six different transformers were designed, simulated, fabricated, and tested with different numbers of turns: 1–6 turns,

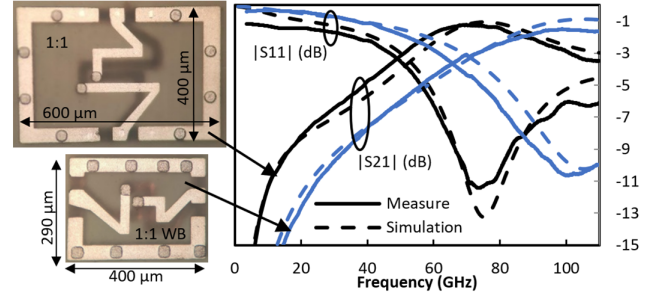


Fig. 5. 1:1 3-D transformers. The 1:1 WB has shorter TLs and the return current path is closer, resulting in higher frequency operation and larger 1-dB BW.

i.e., 1:1–6:6 ratios. The circuit model and the simulations performed in Keysight Advanced Design System (ADS) were compared with the measurements in Fig. 4 and are in very good agreement. The frequency where the circuit presents the minimum IL is inversely proportional to the number of turns, and hence, to the TLs' length, as expected. The summary of the measured performance is given in Table II showing that the proposed transformers have a performance similar or even better than those manufactured using CMOS technologies. The transformers show working frequencies up to 110 GHz, with BWs wider than 12 GHz and IL better than 1.6 dB.

The model is proven to be scalable, which provides a powerful tool for the design of new and improved TLTs. All the dimensions provided in Fig. 1 can be modified according to the model to reach the designer's needs, being the minimum distance between lines and minimum linewidth of 5 μm . Moreover, any topology with TLs with any number of turns can be easily designed using this model. For high impedance ratios, different connections between the TLs can be designed as indicated in [30], giving a high degree of freedom for the designer. By considering an effective dielectric constant equal to 3.5, which is almost the average between the air and the dielectric constant of the nanoporous membrane, it can be noted that each TL has half-wavelength in average, which corroborates the resonant frequencies observed in the return loss presented in Fig. 4. This can be used to understand how to optimize transformers. To illustrate this, two different 1:1 transformers were fabricated with different dimensions: smaller turns (shorter TL) and closer return current path, to increase the frequency and enlarge the 1-dB BW, as shown in Fig. 5.

IV. CONCLUSION

In this letter, a cost-effective technology has been proposed for the realization of 3-D mm-wave transformers. Measurements showed working frequencies from 14.5 to 110 GHz and IL between 1.1 and 1.6 dB. To our knowledge, the presented result at 110 GHz is the highest in a low-cost, interposer technology. The circuit elements of the proposed model are physical related to layout features, allowing an accurate insight of its frequency response and performance. It has also been shown that each TL's length leads to half-wavelength resonances, and their characteristic impedance limits the transformer 1-dB BW to around 20 GHz. Future work will be focused toward the development of a baluns and high ratio impedance transformers.

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