Multi-Material Inkjet-Printed Power Dividers for Antenna Array Feed Networks

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***Abstract*—This paper explores the potential of a two-material piezo drop-on-demand process for the realization of monolithic four-way power dividers. Integration concepts using grounded coplanar waveguide transmission lines with different geometrical profiles, i.e. solid- and dielectric-filled conductors, are examined to observe their suitability for the power divider realization. For proof-of-concept validation purposes a prototype of the four-way power divider was manufactured and tested at Ku-band. It demonstrated a reflection coefficient $|S_{11}| \leq$ -10 dB from 11 GHz to 14.9 GHz that corresponds to a fractional bandwidth of 30.46%. The proposed solution has an average insertion loss of 5.2 dB that includes the loss of the coaxial connectors.**

***Index Terms*— Additive manufacturing, antenna feed networks, power dividers, 3D printing.**

I. INTRODUCTION

The next generation (5G+/6G) of wireless networks are pushing modern communication systems towards high-speed and multi-standard communication demands. To achieve better spectral efficiency and highly-reliable communication links within the upcoming FR3 band (7.125-24.25 GHz), multiple-input multiple-output (MIMO) antenna systems are increasingly being explored [1], with their performance and size relying heavily on the power distribution network. The realization of power dividers is typically performed using printed circuit board (PCB) microstrip (MS) techniques [2]-[4]. They are simple and easy to integrate with planar antenna arrays. However, they are limited by narrow fractional bandwidth (FBW) to around 7-11% and operating frequencies lower than 6 GHz. At higher frequencies, miniaturization becomes a challenge as the MS lines become very thin, complicating the manufacturing process. In [4] a modified MS gap waveguide technique is proposed for the realization of a power divider at 10 GHz with FBW of 21% but its complex geometry makes integration cumbersome.

Substrate integrated waveguide (SIW) concepts using PCB techniques have also been considered for the realization of power dividers with higher power handling capabilities and lower loss [5]-[7]. While wideband matching (FBWs ~39-47%) was achieved in [5] and [6], the circular power divider topology in [5] can only be used in radial antenna array arrangements, and the multi-layer implementation in [6] requires mechanical assembly that is prone to alignment errors. Furthermore, the power divider concepts in [5]-[7] were realized using many large metallized vias with wide hole sizes and were manufactured using PCBs with discrete thicknesses limiting the design flexibility and applicability to generalized antenna solutions.

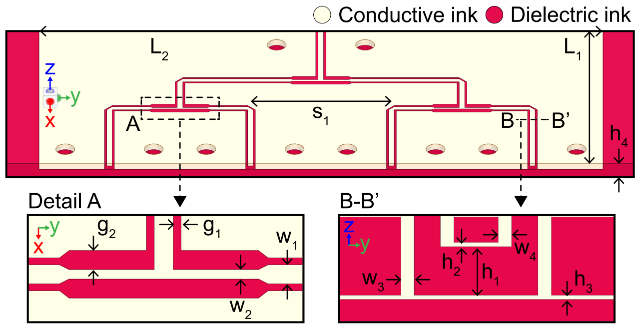


Fig. 1. 3D model of the proposed inkjet-printed power divider (top) including a top view of its T-junction (Detail A) and a cross-section of its GCPW lines (B-B' cut plane). Dimensions are in mm. $S_1 = 15.2$, $g_1 = 0.22$, $g_2 = 0.6$, $W_1 = 0.6$, $W_2 = 0.3$, $W_3 = 0.1$, $W_4 = 0.1$, $h_1 = 0.4$, $h_2 = 0.035$, $h_3 = 0.035$, $h_4 = 1.32$, $L_1 = 25.8$, $L_2 = 60.8$.

Advancements in additive manufacturing (AM) or 3D printing technologies such as fused deposition modeling (FDM), stereolithography (SLA), direct metal laser sintering (DMLS) are being explored [8] to circumvent the manufacturing, integration, and performance limitations of conventional PCB technologies or CNC machining. However, they often lead to multi-part integration solutions that are prone to manufacturing and assembly errors. Multi-material AM technologies based on inkjet printing have recently been proposed as a monolithic integration alternative for RF passive components [9], [10], and antennas [10] that comprise both conductive and insulating materials leading to smaller size and advanced functionality.

Taking into consideration the advantages of multi-material piezo drop-on-demand inkjet printing, this paper explores the potential of a two-material inkjet printing manufacturing process for the realization of a four-way power divider using a highly-conductive ink (CI) and a low loss UV-curable dielectric ink (DI). A detailed design analysis is presented taking into consideration the manufacturing and material capabilities of the two-material inkjet process. Two grounded coplanar waveguide (GCPW) transmission lines using solid- and dielectric-filled conductors are explored for the realization of high-performing couplers while minimizing CI consumption to reduce manufacturing costs.

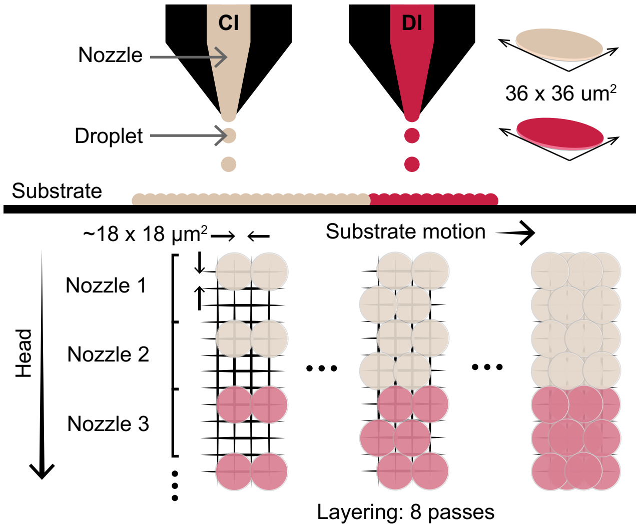


Fig. 2. Conceptual diagram of the two-material inkjet-printing process [11].

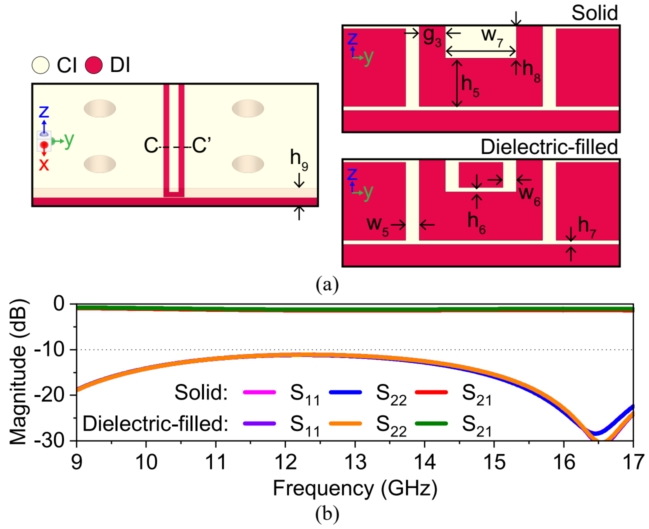


Fig. 3. GCPW transmission lines. (a) 3D model (left) with two variations in the implementation of the center conductor (right) – solid and dielectric-filled – seen across C-C' plane, and (b) their corresponding EM-simulated S-parameters.

II. Inkjet-Printed Four-way Power Divider

A. *Four-way Power Divider Configuration*

Fig. 1 shows the geometrical details of the proposed four-way power divider. It consists of three identical T-junctions to ensure equal power distribution between the input port and all the four output ports. To facilitate the design of the four-way power divider, a symmetric configuration is used with respect to the center of an array with an assumed spacing s_1 of 15.2 mm (~0.66λ_0 at 13 GHz).

The design aims for fully-monolithic integration while taking into consideration the manufacturing capabilities and constraints of a Lights-Out Digital Manufacturing (LDM) two-material piezo drop-on-demand inkjet manufacturing process [8] based on a UV-curable acrylate DI that has a relative permittivity of ε_r= 2.8 and loss tangent tanδ =0.02, and a AgCite CI with a conductivity of σ = 2.21x10^7 S/m. The details of the LDM two-material inkjet process are shown in Fig. 2. Specifically, the inkjet printer converts the 3D model to multiple layers through slicing, and each slice is converted to pixels of approximately 18x18 μm^2 each. To construct a structurally sound slice, eight printing passes are required as shown in Fig. 2 while dispensing 36x36 μm^2 CI and DI droplets simultaneously for rapid manufacturing.

Taking into consideration the thin layer capabilities of the LDM process and the ability to create very thin vertical fully-metallic interconnections, the thickness of the side metallic walls (W_3), the dielectric height of the GCPW (h_1), and the ground metallic layer thickness (h_3) can be made substantially thinner than in conventional PCB manufacturing, reducing the manufacturing cost of the inkjet printing process and freeing up space for other RF components. In the proposed design, W_3 is selected equal to 100 μm and h_3 equal to 35 μm, which are much larger than the skin depth (≈0.6 μm) at 13 GHz. The dielectric height h_3 is set to 0.4 mm, and the overall height of the proposed power divider is h_4 = 1.32 mm.

B. *GCPW Transmission Lines and T-junctions*

Two different configurations for the center conductor of the GCPW are considered in Fig. 3(a) for the 50 Ω lines. The design starts with the solid inner conductor configuration [Fig. 3(a), upper right], where the conductor is filled with CI for homogeneity and the gaps g_3 are filled with DI instead of air in conventional PCB GCPW lines. The design also considers a thicker center conductor of height h_8 to increase the width of the gaps g_3 and ease manufacturing. For example, with a height h_8 = 35 μm the gap is 64 μm. By increasing the height to 285 μm, the optimized gap g_3 widens to 220 μm which appears to have good impedance matching within the X- and Ku- bands as seen in Fig. 3(b). Specifically, the transmission line has a total length of 12 mm with an average insertion loss (IL) of 1.2 dB (i.e., attenuation factor = 1 dB/cm). The design procedure of increasing the center conductor thickness to widen the GCPW gaps underscores the advantage of the inkjet-printing technology in achieving design flexibility, easing the manufacturing process. However, increasing the conductor height will require a larger metallic area, which has the potential to increase the manufacturing costs due to the need for more CI, which is the key driving cost.

In an alternative approach the center conductor is filled with DI [Fig. 3(a), bottom right]. Furthermore, a minimum side metallic wall thickness W_5 = 100 μm and upper and lower metallic cover thickness h_6 = 35 μm were used leading to a 50% CI volume reduction while still maintaining good performance as evident in Fig. 3(b). As such, to reduce the cost of manufacturing, the dielectric-filled conductor is used in the design of the power divider.

To evaluate the capabilities of the inkjet printing process a T-shaped three-port power divider was designed to have equal power split at the output ports with its input matched at Z_0 = 50 Ω over the X- and Ku- bands. The configuration is shown in Fig. 4(a). The input port 1 and the output ports 2 and 3 adopt

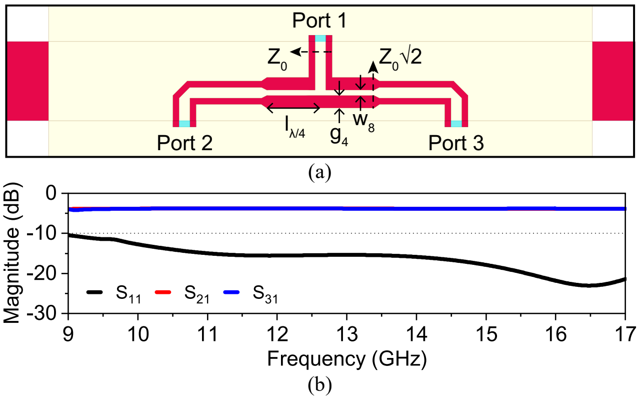


Fig. 4. T-junction power divider. (a) Top view, and (b) EM-simulated S-parameters.

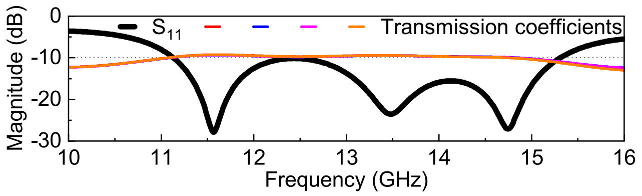


Fig. 5. Simulated reflection coefficient ($|S_{11}|$) and transmission coefficients ($|S_{21}|$, ($|S_{31}|$), ($|S_{41}|$), ($|S_{51}|$)) of the proposed four-way power divider.

the previously optimized 50Ω GCPW transmission lines to connect to coaxial-based end-launch connectors. It is important to note that, since no straightforward analytical computation exists for the quarter-wavelength GCPW line with DI-filled gaps, its length $l_{\lambda/4}$, width W_8, and gap g_4 are optimized using full-wave analysis with the goal of achieving good input reflection and transmission coefficients. The resulting S-parameters of the T-junction power divider are given in Fig. 4(b) and good impedance matching from 9 GHz to 17 GHz is seen with an average IL of 0.8 dB.

Afterwards a four-way power divider was designed for a center frequency of 13 GHz and the widest possible BW. The final dimensions of the proposed power divider are given in Fig. 1. For clarity, the 3D models of coaxial connectors are hidden in Fig. 1 but are included in the full-wave simulations. The corresponding full-wave simulated results are shown in Fig. 5. They demonstrate a reflection coefficient $|S_{11}| \leq -10$ dB from 11.1 GHz to 15.3 GHz (Ku-band) that corresponds to a FBW of 32.23%, and an average IL of 3.5 dB attributed to the losses from the embedded coaxial connectors and the finite material properties of the conductive and dielectric inks.

III. Experimental Validation

To validate the proposed inkjet-printed concept, 12 mm-long prototypes of the two different types of the GCPW transmission lines and a prototype of the four-way power divider were manufactured and tested. Fig. 6(a) shows the manufactured GCPW transmission line with a solid center conductor and Fig. 6(b) shows the details of its cross-section. The prototype with the dielectric-filled center conductor is not shown here since it looks identical. Instead, a cross-section of the dielectric-filled center conductor is provided in Fig. 6(c).

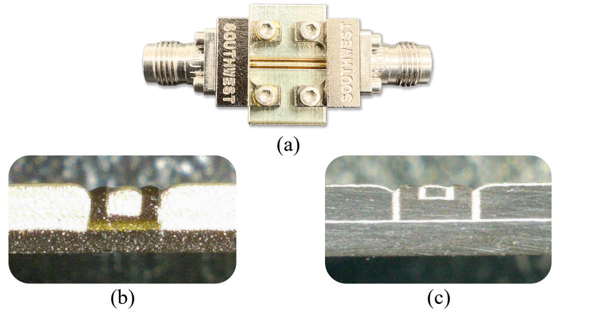


Fig. 6. Manufactured transmission line. (a) Prototype, and cross-section of the GCPW variant with (b) solid and (c) dielectric-filled center conductors.

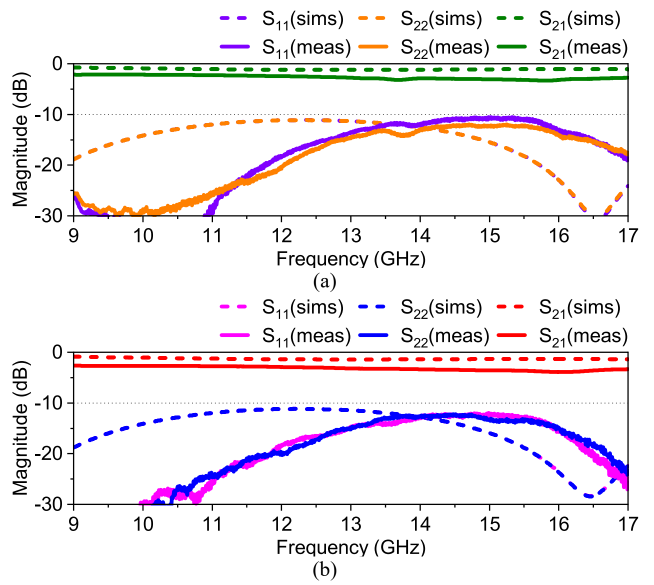


Fig. 7. Simulated and RF-measured S-parameters of the manufactured GCPW transmission lines with (a) solid, and (b) dielectric-filled center conductors.

A good correlation between the RF measured performance of the solid [average IL of 2.7 dB (2.25 dB/cm)] and the dielectric-filled [3.2 dB (2.67 dB/cm)] GCPW transmission lines is obtained successfully verifying the manufacturability of the dielectric-filled center conductor concept that demonstrates good impedance matching from 9 GHz to 17 GHz. A comparison with the EM simulations is also provided in Fig. 7 and appears to be in good agreement. Both the EM-simulated and RF-measured results include the coaxial connector losses. The difference in the average IL of 1.5–2 dB between measured and simulated results is due to manufacturing imperfections in the GCPW lines as seen in Fig. 6 (b)-(c) that resulted in uneven top surface, and coaxial connector setups.

The prototype of the proposed inkjet-printed four-way power divider is shown in Fig. 8, with an overall size of 26 x61x1.32 mm^3 and a weight of only 4.1 grams. Its measured RF performance is summarized in Fig. 9 as follows: center frequency of 13 GHz, 10-dB return loss BW from 11 GHz to 14.9 GHz that corresponds to a FBW of 30.46%, and an average IL of 5.2 dB that includes the loss of the coaxial end-launch connectors. A comparison with the EM simulations is

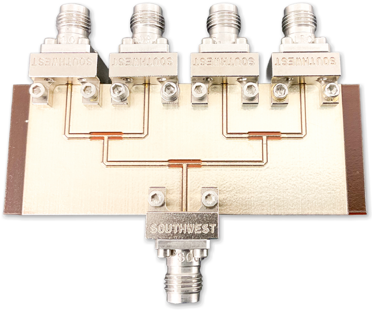
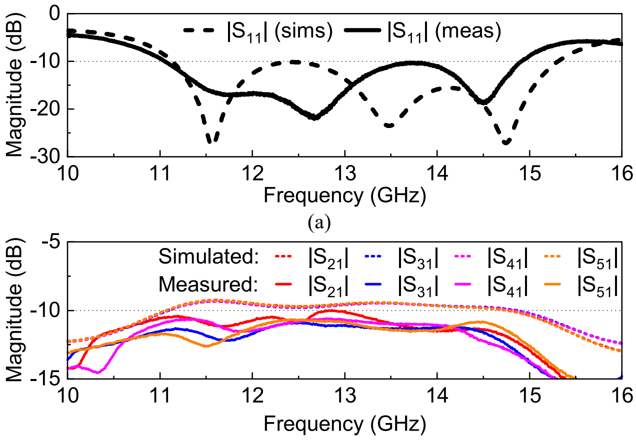


Fig. 8. Manufactured prototype of the proposed inkjet-printed four-way power divider when fed with coaxial end-launch connectors.



(a)

(b)

Fig. 9. RF-measured and EM-simulated performance of the proposed inkjet-printed four-way power divider. (a) Reflection coefficient of the input port, and (b) transmission coefficients $|S_{21}|$, ($|S_{31}|$), ($|S_{41}|$), ($|S_{51}|$).

also provided in Fig. 9 and appears to be in a reasonable agreement, successfully validating the inkjet-printed concept. The shift in S_{11} can be attributed to manufacturing inaccuracies of the lines and gaps, and the inexact values of the relative permittivity of the DI used in full-wave simulations. The increased IL in the manufactured prototype is most likely due to the compounded losses from the interconnecting lines between T-junctions, the conductive and dielectric inks, and the inaccuracies in modeling the embedded coaxial connectors. The proposed power divider is compared with other state-of-the-art planar power dividers in Table 1. As evidenced, the proposed inkjet-printed power divider exhibits wider FBW than most of the approaches. Furthermore, this is the first time that an inkjet-printed power divider has been implemented using a two-material inkjet process and at such a high frequency demonstrating its potential for a large variety of applications within the upcoming FR3 band (7-24 GHz).

IV. Conclusion

This manuscript presented a new design and integration concept for the realization of highly-miniaturized power dividers. A two-material piezo drop-on-demand inkjet process was used for the realization of the proposed four-way power divider, and its performance was investigated at Ku-band. It demonstrated $|S_{11}| \leq$ -10 dB between 11-14.9 GHz (FBW = 30.46%) and an average IL around 5.2 dB including the loss of the end-launch connectors.

TABLE I. Comparison with State-of-the-Art Planar Power Dividers

Ref.	T.W.	[2]	[3]	[4]	[5]	[6]	[7]
Tech.	AM	PCB	PCB	PCB	PCB	PCB	PCB
Structure	GCPW	MS	MS	MS	SIW	SIW	SIW
I/O ports	1x4	1x3	1x4	1x16	1x4	1x4	1x4
f_0 (GHz)	13	5.8	5	10.4	2.4	32	9.8
FBW (%)	30.46	6.9	10.8	21[a]	39.3	46.7	18
IL (dB)	5.2	N.A	2.38	1	0.8	1.2	2

a. Simulated

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