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Impact of metallization layer structure on the performance of G-band branch-line couplers

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***Abstract*—Five different versions of grounded coplanar waveguide (GCPW) branch-line couplers on GaAs were EM simulated, processed and investigated for operation in G-band (140-220 GHz), based on different layer structures (including 2 or 3 metallization layers) and layouts. The best results have been obtained with the structures based on a continuous galvanic metal in the central conductor line and ohmic connections between top ground planes, reducing the insertion losses by 0.8 dB. A measured amplitude imbalance less than 0.5 dB from 160 to 200 GHz (22 %), with a coupler insertion loss lower than 1.3 dB was achieved for a 3 metallization layer branch-line coupler.**

***Index Terms*—Branch-line, hybrid, grounded coplanar waveguide (GCPW), millimeter-wave, EM (electromagnetic) simulation.**

I. INTRODUCTION

90° COUPLERS are key components for the design of image rejection mixers and balanced power amplifiers operating at millimeter-wave frequencies. These circuits are required for many applications such as high-resolution imaging radars. In comparison to other hybrids, branch-line couplers provide high port isolation as well as robust designs.

Few examples of G-band (140-220 GHz) 90° hybrids based on GCPW technology can be found in the literature ([1] presents a Lange coupler and [2] a Tandem coupler). These two research works focus on concrete designs and their performance. In this work, a comparative analysis of the impact of different technological choices is presented, to enhance performance in terms of port coupling, isolation and bandwidth. This comparison covers different metal stacks to implement the center conductor in GCPW lines, the advantages of using ohmic connections between ground planes instead of standard air-bridges and designs based on 2 metallization versus 3 metallization processes. To the authors' best knowledge, such a comparative analysis has not been published before.

In this paper, we propose and analyze novel designs of 210 GHz branch-line couplers based on different technology configurations. The paper is organized as follows. In Section II, a description of the technology is provided. Different designs are depicted in Section III. Section IV presents the comparison between the simulations and measurement results. A discussion on the benefits of the different approaches is included. Finally, some conclusions are drawn in Section V.

II. TECHNOLOGY

The couplers were manufactured in two different processes, based on 2 and 3 metallization layers. Fig. 1 shows a cross-section of the 2- and 3-layer process with the different material thicknesses and the sheet resistance values. The ohmic layer presents the highest sheet resistance, because it has a lower conductivity and thickness than the other metallization layers.

The 2-layer environment (Fig. 1, right) is characterized by the use of GaAs substrate, one layer of benzocyclobute (BCB), and on top of it a single or two metal layers. However, at very high frequencies design flexibility and layout compactness can be enhanced within a 3-layer process [3]. In this case, another BCB layer is processed on top of MET1 (BCB2), and 3 metallizations conform the signal path (Fig. 1, left). MET1 and MET2 are electron evaporated Au layers, while METG is an Au layer demonstrating higher roughness than the other two [3] and is produced by direct electrodeposition or direct galvanic metallization.

III. DESIGN DESCRIPTIONS

In order to achieve compactness, the couplers are based on GCPW lines with $14\,\mu\mathrm{m}$ ground-to-ground spacing. Table I summarizes the 5 different layouts that were processed, where C_p denotes the parasitic capacitance of the ground connection.

Couplers 1 and 2 were designed for a center frequency of 210 GHz using time-domain simulations within CST software. Fig. 2 shows the chip photograph after being fabricated in a 2-layer process (coupler 1) and 3D EM design with METG strip line (coupler 2). Air-bridges made of METG were employed in the T-junctions to eliminate parasitic modes.

Instead of galvanic air-bridges, couplers 3-5 use ohmic connections going underneath MET1. The advantage is that the central line (realized in METG) does not have to be cut before and after the T-junctions as a consequence of the overlap between the air-bridges and the central conductor galvanic

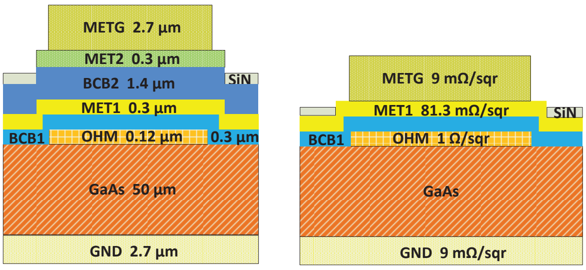

Fig. 1. Cross-section of the 3-layer (left) and 2-layer (right) technology.

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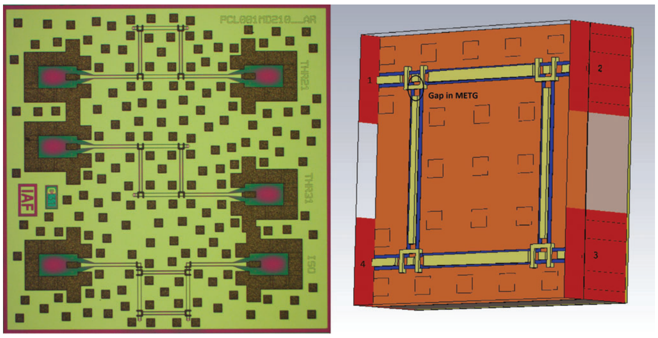

Fig. 2. Chip photo of coupler 1 and EM design of coupler 2. The coupler size (excluding probe pads and input and output lines) is 0.21x0.22 mm^2.

TABLE I

TECHNOLOGY CONFIGURATIONS FOR THE PROCESSED COUPLERS

Coupler	**Metallization layers**	**Ground connections**	**C$_P$ (fF)**	**Center conductor**
1	2-layers	Galvanic	0.5	MET1
2	2-layers	Galvanic	0.5	MET1+METG (gap)
3	2-layers	Ohmic	7	MET1
4	2-layers	Ohmic	7	MET1+METG (no gap)
5	3-layers	Ohmic	7	MET1+MET2+METG (no gap)

metal. Hereby, the discontinuity (gap in table I) is avoided and a continuous METG strip is placed.

Regarding table I, the main difference between layouts 3-5 lies on the addition of extra layers to the central conductor lines, implementing a 3-layer process for coupler 5 with the inclusion of MET2.

IV. RESULTS AND DISCUSSION

Five different configurations of branch-line couplers with the same dimensions were measured. De-embedding of the 150 µm transmission lines and probe pads from Fig. 2 have been performed by using experimentally verified Advanced Design System (ADS) models from the IAF library.

Fig. 3 (top) shows the results of coupler 1. The measurements are consistent across different wafer cells and present a reasonable agreement with the simulated S-parameters. This agreement becomes lower close to the band edges due to the low power spectral density of the Gaussian excitation (used in CST) near the band limits. The measured insertion loss and coupling at 210 GHz are 4.3 dB and 4.5 dB. Thus, a good balance is achieved. The useful bandwidth, over which the isolation is better than 15 dB and the coupling imbalance lower than 0.6 dB is about 18 % (190-228 GHz). In that frequency range S_{21} and S_{31} achieve better values than -5.1 dB.

Fig. 3 (bottom) shows the performance when non-continuous METG is added on top of MET1. The useful bandwidth is reduced (12 %) and measured S_{21} and S_{31} are -3.8 and -4.7 dB at 210 GHz. Thus, lower losses are achieved because of the inclusion of METG but the amplitude balance is better for coupler 1. Therefore, adding a non-continuous METG strip on top of the center line of the first design imbalances the insertion and coupling response of the coupler.

Loading the couplers with an additional METG layer decreases the effective dielectric constant (ϵ_{eff}). This value is 5.1 for a GCPW line with MET1, while when adding METG ϵ_{eff} is decreased to 4.4 in a 2-layer process. This causes a shift to higher frequencies as observed in Fig. 3.

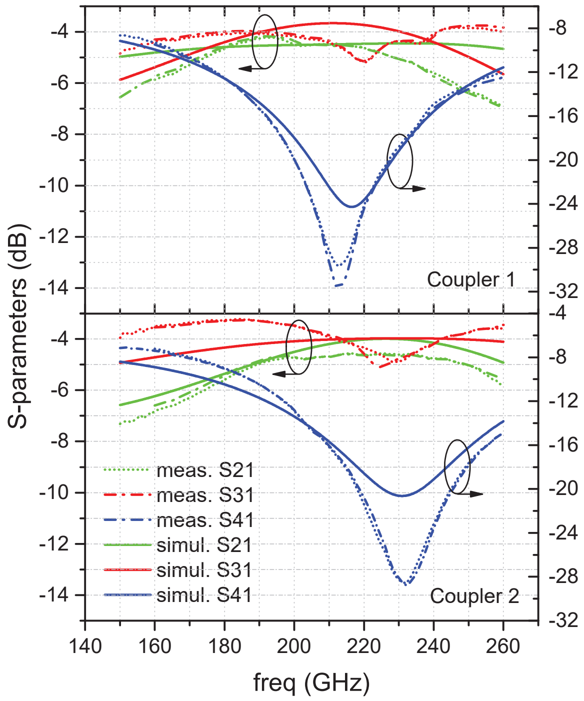

Fig. 3. EM simulation and measurements of coupler 1 and 2.

To investigate if better performance is achieved with continuous METG metallization, structures based on ohmic connections (instead of galvanic air-bridges) were processed (couplers 3 and 4). Coupler dimensions were kept as in the two previous designs and EM simulations were performed after processing. These simulations use reference values of the technological parameters, that is, no adjustment has been performed.

For the case without METG (coupler 3), Fig. 4 demonstrates higher insertion and coupling losses (lower than 5.4 dB and 5 dB between 150 and 200 GHz) than coupler 1 due to the

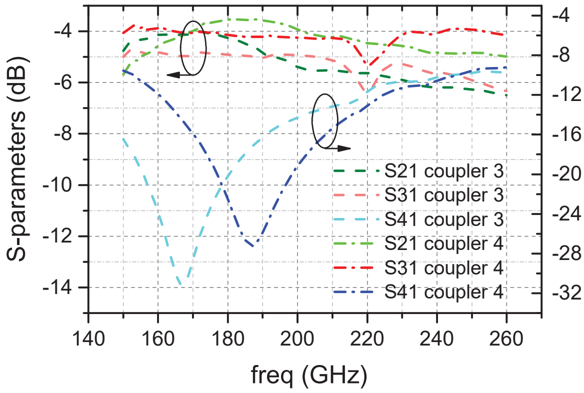

Fig. 4. Measured results of branch-line coupler 3 (MET1) and 4 (METG).

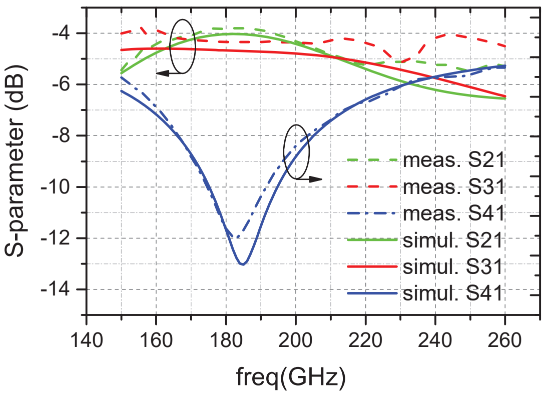

Fig. 5. EM simulation and measurements of coupler 5 from table I.

inclusion of the ohmic connections. That proves that METG air-bridges present lower losses than ohmic connections. But, when adding a continuous METG strip on top of the central line for a 2- or a 3-layer process, it is not possible to use galvanic air-bridges. Then, it is necessary to verify if losses due to the ohmic connections are compensated due to the use of a continuous METG strip.

Fig. 4 shows how the addition of METG (coupler 4) provides 0.8 dB improvement in S_{21} and S_{31} parameters compared to coupler 3, with values better than -4.3 dB and -4.2 dB and 24 % of bandwidth. Re-simulated and measured results of coupler 5 (with still the same dimensions) are shown in table II and Fig. 5, to get a similar useful bandwidth of (22 %), S_{31} better than -4.3 dB and S_{21} higher than -4.1 dB between 160 and 200 GHz, to reach -3.7 dB at 181 GHz. Thus, couplers 4 and 5 improve the previous insertion loss, bandwidth and isolation, because additional continuous layers added to the central strip line increase the conductivity.

In addition, Fig. 6 depicts better performance of the measured phase difference for couplers 3-5 (with ohmic connections). The highest phase bandwidth is achieved by coupler 5 with 92° of phase difference at 183 GHz, and a phase variation of ±3° over 160-200 GHz. However, a phase of 89° is accomplished at 230 GHz for coupler 2, with a phase variation of ±3° between 223 and 245 GHz.

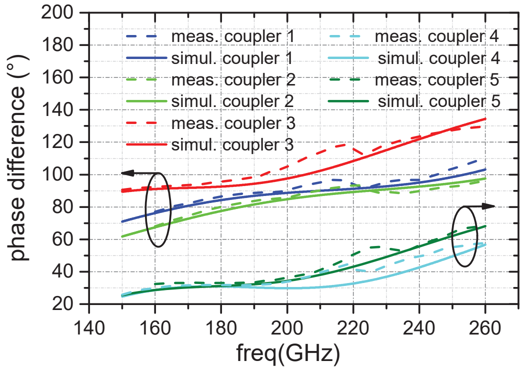

Fig. 6. Phase difference of branch-line couplers 1-5 (see table I).

TABLE II
H-BAND STATE OF THE ART POWER AMPLIFIER

Coupler	**Reference**	**Loss per coupler (dB)**	**Bandwidth (GHz)**	**Isolation (dB)**	**Amplitude Imbalance (dB)**
Lange	[1]	< 2.4	170-220 (23 %)	>15	<1
TandemX	[2]	< 1.4	190-220 (15 %)	NA	NA
Branch-Line	[4]	< 1.1	210-240 (13 %)	NA	NA
Branch-Line (This work)	Coupler 4	< 1.3	170-217 (24 %)	>15	<0.6
Branch-Line (This work)	Coupler 5	< 1.3	160-200 (22 %)	>15	<0.5

Ohmic T-junctions allow for a certain size reduction too. Table I shows the parasitic values of the ground connections. For ohmic connections this value is 7 fF, much higher than for the METG air-bridge (0.5 fF). That explains the downwards frequency shift from coupler 1 to coupler 3, so a redesign at 210 GHz would require less chip area.

Table II shows a comparison between the results achieved with the advanced branch-line configurations investigated in this work and state-of-the-art hybrid couplers. In this work the measured losses reach low values (1.3 dB at 200 GHz), amplitude imbalance is reduced and the bandwidth compared to [2] and [4] is increased, accomplishing the extraordinary value of 22 % with the novel 3-layer process configuration.

V. CONCLUSION

Different configurations of branch-line couplers have been investigated and fabricated. A reasonable agreement was achieved between measurements and EM simulations. METG layer in conjunction with ohmic T-junctions improve state-of-the art results for 2 and 3-layer processes. In a 22 % bandwidth, less than 1.3 dB losses, isolation higher than 15 dB and just 0.5 dB amplitude imbalance was obtained with a 3 layer process. Moreover, enhancement in flexibility with size reduction can be accomplished within novel 3-layer process designs.

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