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Ultra-wideband GCPW-MS-GCPW transitions on Si wafers for microwave photonic components

Mohammed El-Gibari, Dominique Averty, Cyril Lupi, Hongwu Li and Serge Toutain

Abstract — **We present back-to-back GCPW-MS-GCPW (Grounded Coplanar Waveguide-Microstrip lines) transitions on substrates in thin film on cheap silicon wafers, constituted of a 1-cm microstrip line and pads or stubs compatible with CPW probes. Their bandwidth can cover the frequency range between 180 MHz and 60 GHz. These performances are obtained without making via-hole in the substrate and patterning the bottom ground plane. These transitions using the electromagnetic coupling between the bottom and top ground planes simplifies the manufacturing and facilitates the characterization, by means of coplanar probes, of microwave photonic devices realized from materials in thin film and whose driving electrode is a microstrip line, such as electro-optic modulators based on polymer poled by Corona effect.**

Keywords — **electro-optic modulators, GCPW-MS-GCPW transitions, ultra-wide bandwidth, microwave photonic devices, polymers, thin film.**

I. Introduction

THE characterization of microwave circuits and microwave photonic components on wafer requires the use of probe stations for reason of convenience [1]-[3]. Most of these test systems are equipped with probes compatible with coplanar transmission lines of type GSG (Ground-Signal-Ground) insuring a good reliability of the electrical contact. A transition between coplanar and microstrip lines (CPW-MS) is thus indispensable to characterize components driven by microstrip lines with CPW probe station.

Generally, in electro-optic modulators based on polymer, the chromophores responsible for the electro-optic effect are oriented perpendicularly to the substrate by corona effect. The driving signal must be applied using a microstrip line. One solution for their characterization with CPW probes is to physically connect the coplanar ground planes to the bottom ground plane of microstrip line with a via-hole, which is complicated and difficult to achieve especially when the polymer is crosslinked. It is in this context that we conducted a comprehensive study of transitions between coplanar and microstrip lines on substrate in thin film, to find a simple and efficient method for the characterization of components driven by microstrip line with CPW probes. As one of the key advantages of electro-optical modulators is their very board bandwidth, the transition used for their characterization and realization must therefore have the bandwidth as wide as possible to cover that of the modulators.

To characterize their modulators based on electro-optic polymer driven by microstrip line with CPW probes, R. Michalah *et al.* [4] studied transitions between microstrip and coplanar transmission lines with a radial stub to avoid physical connection between ground planes by via-holes. Their GCPW-MS (Grounded Coplanar Waveguide-Microstrip lines) transition with a 5-mm microstrip line presents certainly a bandwidth up to 45 GHz, but its lower limit is about 2 GHz even with a radial stub diameter of 3 mm, which is very disadvantageous because they do not provide access to modulators' performance on the frequency range below 2 GHz.

In this paper, we present a theoretical study and an experimental validation of back-to-back GCPW-MS-GCPW transitions with an ultra-wide bandwidth without making via-holes in the substrate and patterning the bottom ground plane, so the transitions can be realized on cost-effective Silicon wafers independently of their resistivity and an additional alignment of mask for the bottom ground plane is avoided. These transitions are made on dielectric substrates of thickness h = 8 µm with a bandwidth exceeding 60 GHz, their 180-MHz low frequency limit makes them suitable for applications in radio over fiber [5]. To our best knowledge, such bandwidth has never been achieved so far by via-free GCPW-MS-GCPW transitions. These transitions will greatly facilitate the characterization of microwave photonic components on thin film materials and their packaging.

II. Simulations and measurements

The two structures of GCPW-MS-GCPW transitions studied in this paper are shown in Fig. 1. These transitions are built on a substrate deposited on a Silicon wafer. The experimental validation has been carried out with a 8-µm resin SU8. The thickness of the resin has been determined in the study of the optical single-mode waveguide of a modulator based on the electro-optic polymer PIII (PGMA/DR1) [6] to obtain a maximum confinement factor and minimum driving voltage, using SU8 as optical cladding. Due to its thermal crosslinking ability, the polymer PIII has an improved stability of its electro-optic effect. From this thickness and the dielectric constant of the resin SU8 (ε_r = 3.55), we used the software Linecalc

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Agilent Advanced Design System (ADS 2006 version) to determine the dimensions of the transitions in order to have a characteristic impedance of 50 Ω for both the microstrip section and the CPW section: the width of the central strip W = 17 µm, the coplanar gap G = 13 µm. The length of the microstrip line L is 1 cm.

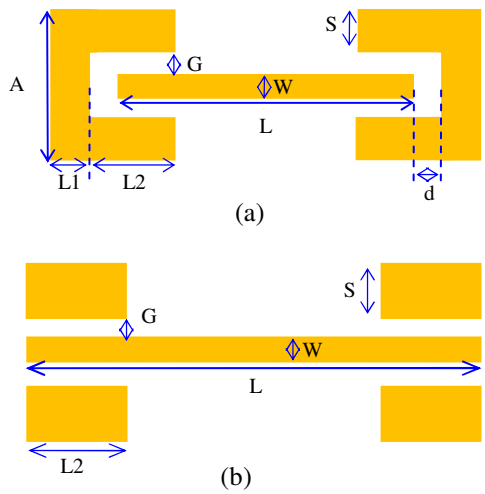

Fig. 1. The two structures of back-to-back GCPW-MS-GCPW transitions. (a) The first structure with rectangular stubs; (b) The second structure with CPW pads.

A. *Transitions with rectangular stubs*

The lower frequency limit of the bandwidth depends upon the surface of the stub, to reduce it as low as possible without affecting significantly the higher frequency limit, we take the length of the stub L_1 = 1 mm and the width of the stub A = 2.043 mm (A = W + 2xG + 2 mm). For the distance d between the end of the microstrip line and the inner part of the stub, we take 100 µm to avoid harmful influence of parasitic capacity between signal and ground strips (in Fig. 1-a). The condition d > (W +2 x G) should be satisfied to get rid of this parasitic capacity according to [7]. The length of the coplanar ground plane L_2 has been fixed to 1 mm so CPW mode can be stabilized and converted to MS mode.

Figure 2 shows the simulation results with HFSS of a back-to-back GCPW-MW-GCPW transition on SU8 resin directly deposited on a low resistivity silicon (LRS, resistivity = 0.001 Ω.cm) wafer, the aluminium thickness is 4 µm. The loss tangent of the SU8 resin is estimated between 0.043 and 0.078 according to [8] and [9]. We have chosen the value of 0.043 for all our simulations because this value gives the best correlation between measurements and simulations. As one can see, a very wide bandwidth is obtained when the dielectric losses are negligible. Not only the bandwidth exceeds 40 GHz, but also, what is even more remarkable, the lower limit frequency goes down to 180 MHz, against 2 GHz for the transition with radial stub proposed by R. Michalah *et al.* under conditions similar to ours in terms of thickness and permittivity of the substrate [4]. When the dielectric losses of SU8 are taken into account, the bandwidth is limited to 20 GHz without affecting its lower frequency limit.

For experimental realizations, we have, on a 380 µm thick LRS wafer used as ground plane, deposited by spin coating two layers of 4 µm polymer SU8; the first layer having been crosslinked before depositing the second layer. To measure S-parameters of our realized structures, we used a network analyzer Agilent E8364B with probes Cascade I40AGSG250 (bandwidth of 40 GHz, inter-probe distance of 250 µm and probe width of 12 µm). The calibration method used is the LRM (Line-Reflect-Match) method with a calibration substrate Cascade AE-101-190. The whole system is controlled by the software Wincal Cascade.

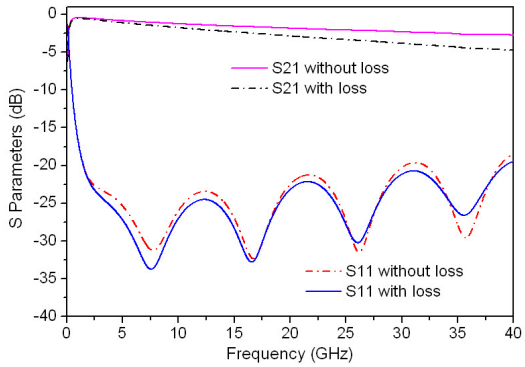

Fig. 2. Simulation results of a transition on SU8 with and without taking into account the dielectric losses, the aluminum thickness is assumed to be equal to 4 µm.

Due to bad adhesion of the aluminum to the SU8 resin, we had to limit the thickness of the aluminum layer to 370 nm. This small thickness is responsible for the insertion loss of -4.3 dB. Nevertheless measurements and simulations (cf. Fig. 3) are in perfect agreement in terms of the S21 parameter and in less good agreement for the S11 parameter due to impedance mismatch caused probably by a poor uniformity of the strip width. The measured bandwidth of the GCPW-MS-GCPW transition covers the frequency range between 420 MHz and 8.95 GHz.

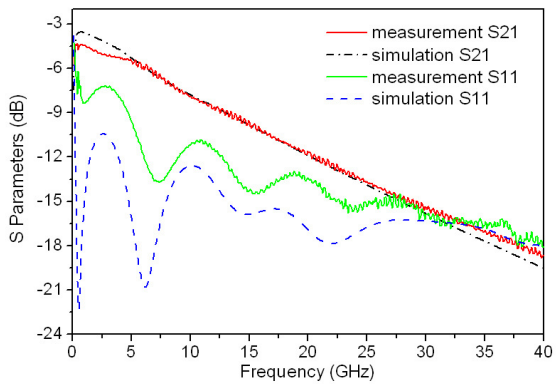

Fig. 3. Simulation and measurement results of a GCPW-MS-GCPW transition with rectangular stubs on SU8 resin with 370-nm aluminum metallization.

Thanks to their board bandwidth and their exceptional lower frequency limit, the GCPW-MS-GCPW transitions with rectangular stubs are very useful for characterization of components driven by MS electrode with CPW probe station. But they are not suitable to connecting the driving MS electrode to electrical connectors due to their "closing" stubs. That's why we also studied transitions with simple

CPW pads which permit both characterization and connecterizing of MS-electrode driven components.

B. Transitions with CPW pads

The structure of this type of GCPW-MS-GCPW transitions studied in this subsection if shown in Fig. 1-b. This open structure permits the signal strip to be connected to the center conductor of a V-connecter. The bandwidth of the transition is limited in high frequency by the CPW pad length L_2 in the transition due to the propagation of electromagnetic energy between the bottom and top ground planes, called CPM mode by Raskin [10] as coplanar microstrip mode. Shorter this length is, higher the high cut-off frequency is.

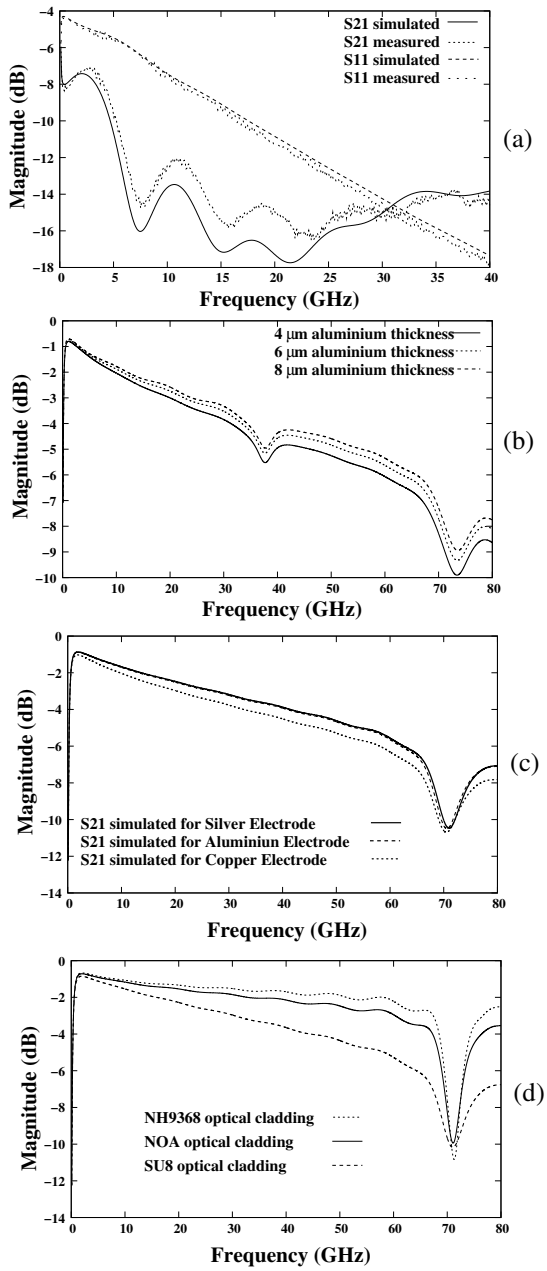

Fig. 4. S-parameters of a transition with CPW pads on 8-µm thick SU8 (except d). (a) 370-nm thick aluminum metallization and L_2=1 mm; (b) different thicknesses of aluminum metallization and L_2=2 mm; (c) different electrode metals and L_2=1 mm; (d) different substrate materials with 6-µm silver metallization and L_2=1 mm.

We have studied the performances of transitions with 370-nm thick aluminum metallization on 8-µm thick SU8 first deposited on a Silicon wafer, the CPW pads length L_2 is fixed to 1 mm to obtain board bandwidth. The measured and simulated results in good agreement are presented in Fig. 4 (a). The low metallization thickness is one more the main responsible for the losses observed in the transitions under test. Actually, simulations with different aluminum metallization thicknesses (SU8 substrate and L_2=2 mm) are presented in Fig. 4 (b), the results show that the transition with a 6-µm thick aluminum metallization gives a [210 MHz-30.75 GHz] bandwidth. So, the bandwidth features of the GCPW-MS-GCPW transition are closed to those required for various applications of electro-optic modulators, radio over fiber particularly [5].

Then a simple analysis shows that, to decrease the low cut-off frequency we can enlarge the area of the CPW ground pads, by increasing either the ground pads' length L_2 or their width S. But, as shown previously, that results in decrease of the high cut-off frequency, so a trade-off must be found. In order to increase the high cut-off frequency, metals with higher conductivity than the aluminum can be used, as an example we compare in Fig. 4 (c) the bandwidths of the transitions with three standard metals on SU8 thin film for L_2=1 mm. In this simulation the use of silver or copper metallization allows to extend the -3 dB high cut-off frequency to 30 GHz. Another parameter responsible of the limited bandwidth is the dielectric losses of the substrate (tanδ value) in which the wave is propagating. For our experimental study we used the SU8 resin because it resists well to chemical etching but it has a large loss tangent tanδ, other dielectric materials are commercially available with lower tanδ. For example the NOA polymer has a permittivity equal to 3.22 with tanδ = 0.013, less than one third of that of SU8. The Fig. 4 (d) gives the S21 parameter for two standard commercial polymers which can be used as substrate (tanδ= 0.013 for NOA and tanδ=0.043 for SU8).

In order to draw some synthetic conclusions and trends from our results, we put together in Table 1 the bandwidths calculated with HFSS software for different thicknesses and types of metallization for two lengths L_2.

Table 1: -3 dB bandwidth of the transition with CPW pads

Substrate	Metal	L_2 (mm)	Metal thickness	Bandwidth (GHz)
SU8	Al	1	4 µm	0.42 -20.45
SU8	Cu	1	4 µm	0.42 -26.70
SU8	Ag	1	4 µm	0.42 -27.60
SU8	Ag	1	6 µm	0.42 -30.75
SU8	Ag	1	8 µm	0.42 -31.80
SU8	Ag	2	8 µm	0.21 -31.56
NOA	Ag	1	6 µm	0.42 -60.35
NOA	Ag	2	6 µm	0.21 -36.71
NH9338	Ag	1	6 µm	0.42 -67.39

According to the results in Table 1, it is possible to achieve to a [420 MHz-60.35 GHz] bandwidth with appropriate dielectric materials from the point of view of microwave loss, with L_2=1 mm and a 6 µm thick silver metallization. To reach the widest bandwidth possible for

radio over fiber communication, it would be very important to synthesize transparent dielectric materials with electrical losses similar to those of the commercial PTFE/glass/ceramic substrate NH9338 (tanδ= 0.0047, ε_r=3.41): in this case a [420 MHz-67.39 GHz] bandwidth would be achievable (cf. Fig.4 (d) and Table 1).

III. Analysis of the Resultas

The small thickness of the dielectric substrate is a double advantage for a good transition without via-holes. On the one hand, it can easily create an electromagnetic coupling between the bottom ground plane of microstrip line and coplanar pads by capacitive effect. On the other hand, the low ratio of thickness h and the gap G of the coplanar line promotes the conversion of the field between the coplanar and microstrip modes.

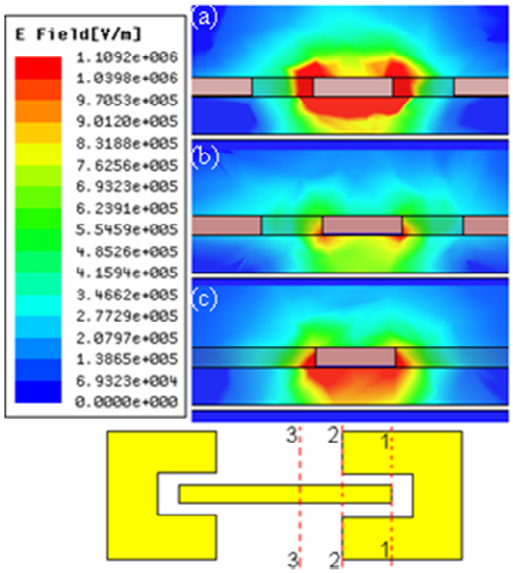

Fig. 5. Electric field in several transverse planes of a transition with rectangular stub. (a) entry of the transition (plane 1) (b) at the end of the stub (plane 2) (c) on the microstrip line (plane 3).

The second effect is very visible on the electric field distribution in plane 1 at the entrance to the transition in Fig. 5 (a). The evolution of the coplanar mode, rather hybrid from the beginning, towards to the microstrip mode is done very quickly as can be seen in Fig. 5 (b). The microstrip mode well established along the microstrip line, cf. Fig. 5 (c). This explains why the insertion losses are low (0.3 dB) in our simulations with a 4 µm aluminum metallization in Fig. 2.

For a better electromagnetic coupling between the CPW pads and the bottom ground plane, the surface of the CPW pads should be as large as possible, especially for the lower cut-off frequency of the bandwidth of the transition. However the increase of this area has drawbacks at high frequencies. Indeed resonance modes appear at frequencies inversely proportional to the maximum size of the CPW pads, so that increasing their size may give rise to resonance peaks in the frequency range of interest. It is hence necessary to optimize the dimensions of the pads according to the application and frequency band to cover.

IV. Conclusion

We have presented in this article two types of back-to-back GCPW-MS-GCPW transitions on substrates in thin film on LRS wafers. According to the metal utilized, its thickness and the loss tangent of the substrate dielectric materials, the theoretical bandwidth of these transitions could achieve 60 GHz. These transitions are simple to perform. They require neither the creation of via-holes for the postponement of the ground nor pattern in the bottom ground plane. If the dielectric polymer SU8 limited bandwidth transitions performed at 20 GHz with a metallization of 4 µm, use of substrate materials with lower dielectric losses allows to expect to make transitions whose bandwidth goes up to 60 GHz.

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