60GHz Coplanar Waveguide Couplers and Slotline Transition on Polished Beryllium Oxide

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ABSTRACT

This paper presents results for mm-wave coplanar waveguide couplers and a low loss slotline transition that are printed on polished beryllium oxide (BeO). BeO offers excellent microwave properties including a low loss tangent (0.0003) and high thermal conductivity. Included is the design of an optimized quadrature coupler with insertion loss around ~3.7 dB at 60 GHz.

I. INTRODUCTION

Coplanar waveguide (CPW) - slotline transitions and CPW couplers are important building blocks in MMIC circuits, particularly those involving frequency translation and/or antenna integration. The design of these components at high frequency (> 50GHz) becomes difficult due to exaggerated parasitic effects such as those associated with air-bridges and tee-junctions. In the mm-wave band, accurate full-wave simulation and effective parasitic compensation techniques are critical to achieving first-pass success.

In this paper we report on designs for a CPW - slotline transition and CPW couplers designed to operate from 58 - 64GHz on a Beryllium Oxide (BeO) substrate. BeO (ε_r=6.6, tanδ=0.0003) has excellent material properties that include low substrate loss, high thermal conductivity (~7x better than Alumina), good corrosion resistance, and chemical inertness. Major markets for BeO ceramic include several nuclear applications, microwave tube parts and similar high-temperature environments (e.g. automotive sensors). To the best of the authors' knowledge, these are the first reported results for 60 GHz thin-film circuits on BeO.

In the following sections, the design approach, full-wave simulations and experimental results for the circuits are described. These designs form the building blocks for a 60 GHz proximity sensor that is currently under development.

II. CIRCUIT CHARACTERISTICS

The circuits were fabricated on 635μm-thick polished BeO. The air-bridges used for ground plane equalization are located 6μm above the first metal layer and supported by circular pedestals on both the ends of the bridge (the width of the air-bridges is 30μm). The center of the pedestals is located 28μm into the ground plane with the pedestal diameter of 35μm. All metal lines have a thickness of 1μm, fabricated using 99.99% gold.

One drawback to BeO is relatively high surface roughness. As shown in Figure 1, the surface is still somewhat rough after polishing, and pull-outs are a risk during the polishing process. In spite of the potential problems, the circuit yield was greater than 95% and all capacitors and resistors behaved as anticipated. As an example, the measured response of a 10-dB T-circuit attenuator are shown in Figure 2 (the resistors are fabricated using TaN with a resistivity of 50Ω/square.). The measured attenuation of a CPW line with a center conductor spacing of 80μm and slot widths of 20μm was 0.7dB/mm at 60 GHz.

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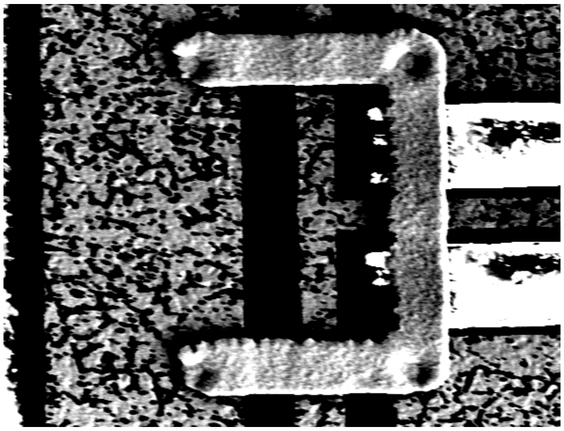

Figure 1: SEM photograph of polished Beryllium Oxide (BeO) substrate with an airbridge.

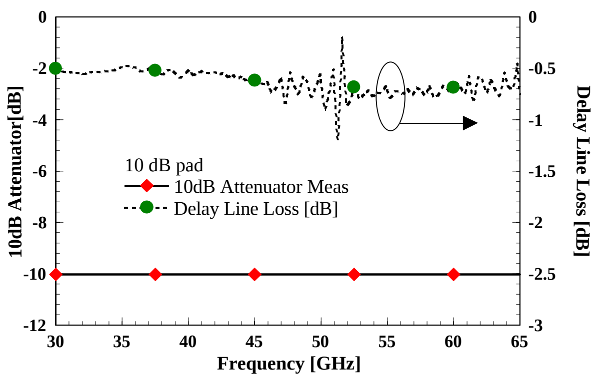

Figure 2: Measured attenuation of a 10dB T-circuit pad and measured insertion loss of a 1mm delay line.

III. QUADRATURE HYBRID COUPLER

Quadrature hybrids are 3dB couplers with 90° phase difference in the outputs of the thru and coupled arms. Figure 3 shows a typical quadrature hybrid coupler (also known as branch-line coupler) realized using CPW geometry [3]. Since it is difficult to fabricate reasonably dimensioned low impedance lines on BeO, the reference impedance for the coupler is chosen to be 100 Ω. A quarter wave transformer section is included on all ports to transform the 100Ω impedance to 50Ω.

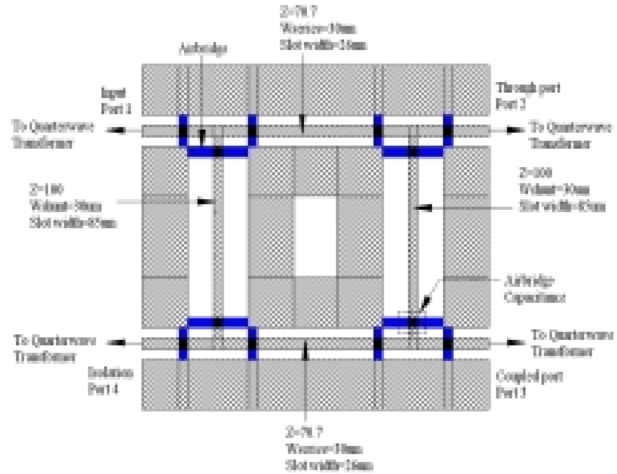

Figure 3: Geometry of a quadrature hybrid coupler implemented using CPW. Z_{ref}=100Ω; center frequency = 60GHz.

There are two basic problems with the simple coupler design. First, the capacitance introduced by the air-bridges will cause the frequency response to shift downward. Second, the tee-junction at each corner is an appreciable portion of the overall branch length, which introduces additional parasitic effects and makes the electrical length of the branches difficult to estimate. In fact, inductance associated with the tee-junction may dominate the air-bridge capacitance. The result of the non-idealities is that the input power will not be equally divided at the coupled and thru ports, and the desired 90° phase difference at the output will not be achieved.

In [4], the use of a high-impedance section in the vicinity of the air-bridges was used to compensate for excess capacitance. This method was employed here, and the simulated results predicted good return loss (S11 < -20 dB) and isolation (S41 < -20 dB). However, the center frequency was below the target of 60 GHz.

The shortcoming of the air-bridge compensation method can be traced to the difference between BeO and the silicon-based lines studied in [4]. Due to the lower dielectric constant, the inductance per unit length is greater for lines on BeO than on silicon. As a result, the parasitic inductance at the tee-junction is more significant than the added capacitance of the air-bridges. Therefore, to improve the performance a different compensation method was applied in which the characteristic impedance of the series arms was reduced (to 65 Ω versus 70.7 Ω) to lower their inductance. It is expected that similar corrections would be required for substrates such as glass and quartz.

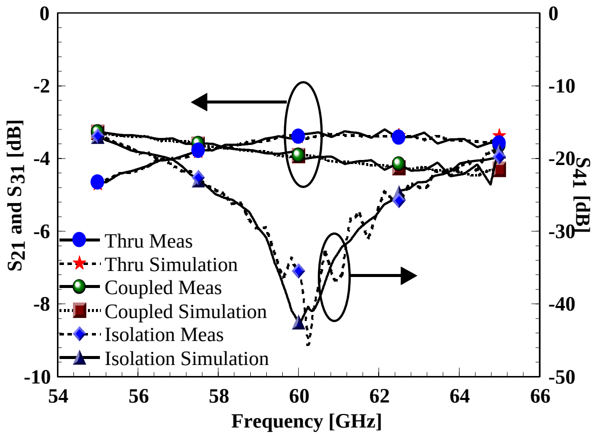

Figure 4: Comparison of coupling (thru and coupled port) and isolation between simulation (*IE3D*) and measurements of a CPW quadrature coupler.

A comparison between measurements and simulation results in given in Figure 4. The simulations were performed using Zeland's *IE3D*™. Measurements were performed using a Wiltron 360B vector network analyzer and 100μm-pitch GGB microwave probes. A Thru–Reflect–Line (TRL) calibration was performed using calibration standards fabricated on the wafer. The coupling at port 2 and 3 is approximately 3.5dB and 3.9dB, respectively.

IV. COUPLED LINE COUPLER

In this work a CPW coupled-line coupler was also developed with a target coupling value of 12 dB (Figure 5). For a narrow-band application such as the one being addressed, significant size reduction can be realized by utilizing the coupler below its quarter-wavelength frequency ($f_{\lambda/4}$), without significant degradation in the isolation and return loss. The minimum coupling length is achieved by designing to the maximum coupling at $f_{\lambda/4}$.

Initial design of the coupler was performed with the transmission line calculator *Linpar*. Using the polished BeO substrate, the minimum feature size that can be repeatedly reproduced is approximately 20 µm. Based on this limitation, the maximum (quarter-wavelength) coupling value achievable with the CPW configuration was predicted to be around 10 dB. In order to meet the 12 dB requirement, the length of the coupling section could be reduced to 200 µm (~28 degrees at 60 GHz). No correction for discontinuity reactance was included in this design, as the inductance at the entrance to the coupling section was expected to balance the excess air-bridge capacitance.

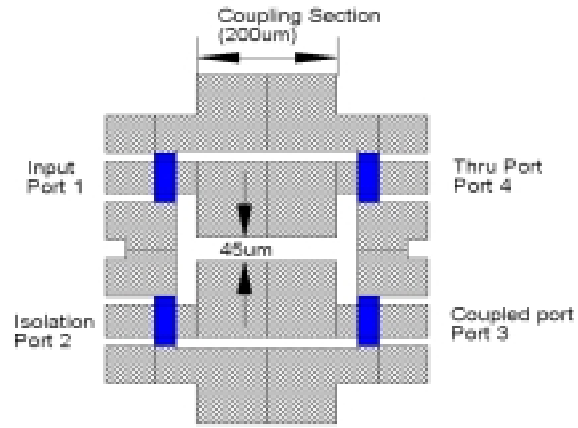

Figure 5. CPW coupled-line coupler. The length of the coupling section is ~28 degrees at 60 GHz.

A comparison between simulated and measured results for the coupled line coupler is given in Figure 6. The isolation is 25 dB or greater across the band of interest and the 60 GHz coupling value is approximately 13 dB. The insertion loss is within 0.2 dB of the ideal value.

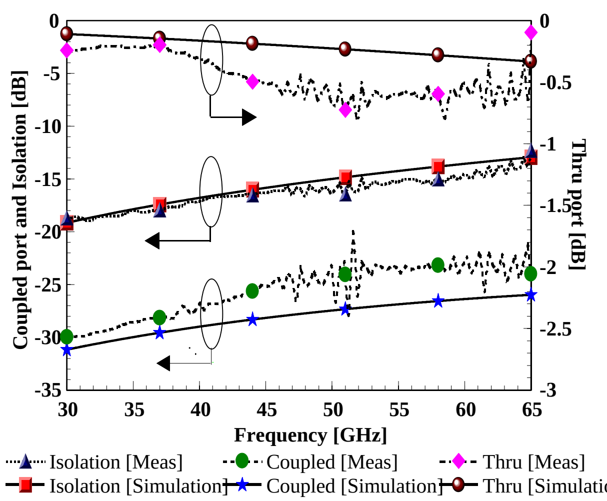

Figure 6: Measured and simulated performance of the CPW coupled line coupler.

V. CPW TO SLOTLINE TRANSITION

The proximity sensor being developed is coupled to a tapered slot antenna, necessitating the use of an efficient transition between CPW and slotline [5]. The design given in Figure 7 adopts the technique described in [1] and [2].

The shorted slot stub, comprised of two stubs arranged in series, provides a high-impedance open at the transition junction; this configuration has proven to yield lower radiation loss than similar approaches using radial stubs. Quarter-wave impedance matching sections are used on either side of the transition.

A comparison between measured and simulated results for the (back-to-back) transition is given in Figure 8. The one-way insertion loss at 60 GHz is ~1.9 dB. The noticeable radiation near 55 GHz is believed to be occurring in the slot-line section, as this is near its λ/2 frequency.

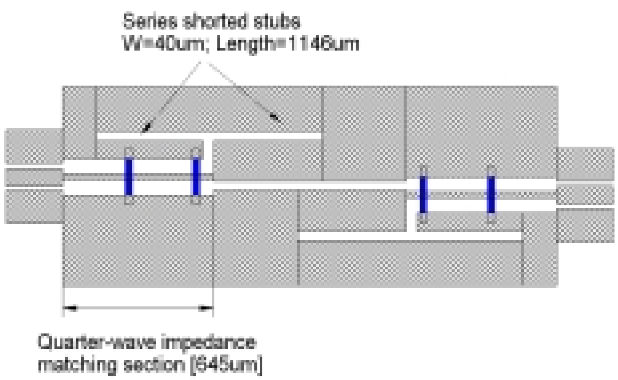

Figure 7. Back-to-back CPW to slotline transition.

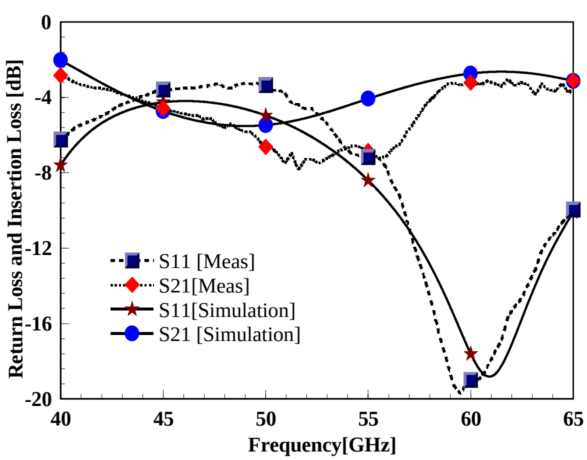

Figure 8. Measured and simulated results for the back-to-back CPW to slotline transition.

VI. SUMMARY

This paper has reported theoretical and experimental results for a variety of mm-wave CPW circuits printed on polished BeO. Despite the relatively rough surface finish of the substrate, predictable and low loss performance has been realized. Due to its high thermal conductivity, BeO is advantageous for a variety of applications where high temperature (and high power levels) are a concern.

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