Flip-chip integration of differential CMOS power amplifier and antenna in PCB technology for the 60-GHz frequency band

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Flip-chip integration of differential CMOS power amplifier and antenna in PCB technology for the 60-GHz frequency band


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Abstract—The integration of a CMOS power amplifier (PA) and antenna in printed circuit-board (PCB) technology is investigated. Both the PA and the antenna have a differential design to provide a reliable low-loss interconnect. A PCB package is proposed that enables the implementation of a high-efficiency antenna while providing mechanical rigidity. The interconnection between the PA and the antenna is realised with flip-chip technology. The performance of the package is demonstrated with measurements of the realised antenna gain and radiation patterns.

I. INTRODUCTION

The 60 GHz frequency band can be employed to realise the next-generation wireless high-speed communication. The unlicensed bandwidth of about 7 GHz allows for data rates of gigabits-per-second. Moreover, advances in silicon technology allow the realisation of low-cost RF front-end solutions. However, to utilise the potential of this frequency band, low-cost transceiver designs are needed in which antennas, RF front-end and baseband processing are fully integrated.

In this work, the integration of a CMOS power amplifier (PA) and antenna in printed circuit-board (PCB) technology is investigated. Both the PA and the antenna have a differential design to provide a reliable interconnect that is low-loss. The PA is realised in 65 nm CMOS technology, has a gain of approximately 8 dB and a 3 dB gain bandwidth that ranges from 54 to 66 GHz. The antenna is a balanced-fed aperture-coupled patch (BFACP) antenna that is optimised for bandwidth and radiation efficiency [1]. The realised bandwidth is 10-15% and the accompanying radiation efficiency is larger than 75%.

PCB technology is a mature technology that is low-cost. However, the materials that are used for the realisation of the package should be chosen carefully to obtain good performance at millimeter-wave frequencies. Moreover, the influence of etching and alignment tolerances should be taken into account to obtain a robust design. Additionally, the flip-chip interconnection between the PA and the PCB needs to be characterised to retain the performance of the PA.

II. PACKAGE TOPOLOGY

A complete package is realised based on a single PCB stack. For this purpose, the BFACP antenna is very well suited. In the prototypes of the BFACP antennas, the dielectric layers have been realised from teflon-based materials (NY9217 [2], $\varepsilon_r = 2.17$). The low dielectric constant of this material and the inherent surface-wave suppression of the antenna element provides a high radiation efficiency.

Although teflon-based materials have good RF performance, they cannot be employed to create a complete package. The disadvantages of teflon-based materials are that they are not very rigid and that they have a large thermal expansion coefficient. Therefore, this material cannot be used for the realisation of a rigid package and the implementation of vias can be difficult because of the relatively large thermal expansion. An improved PCB stack that can function as a package is shown in Fig. 1. The upper layer of this package is realised from teflon-based material to ensure good RF performance. The lower layers are realised from a glass-reinforced hydrocarbon/ceramic material (Ro4350B [3]). This material is much more rigid compared to teflon-based materials and has low dissipative losses as well. The dielectric constant of this material is specified to be 3.66 at 10 GHz. The lowest dielectric layer of the package is used to provide the package with its mechanical rigidity. The middle layer is a thin layer that is used to create a well-defined RF feed. This layer also allows the realisation of vias, such that the routing of control signals can be simplified. The dielectric layers are laminated together with adhesive layers in between that are tailored for adhesion with these materials.

III. MATERIAL CHARACTERISATION

The electrical properties of teflon-based materials are well-established owing to their stability over a wide frequency band (up to 100 GHz) [4]. The same needs to be investigated for the Rogers Ro4350B material that is used in the package since the available datasheet specifies its properties up to 10 GHz only. For this purpose, a two-port ring resonator has been designed.

Figure 1: Schematic layout of PCB package with integrated IC and antenna.
The resonance frequency of the ring resonator is directly related to the material properties of the dielectric [5], since the resonance frequency of the $n^{th}$ parallel resonance of the unloaded ring resonator is given by

$$f_{0,n} = \frac{cn}{L\sqrt{\varepsilon_{\text{eff}}}},$$  \hspace{1cm} (1)$$

where $c$ is the speed of light in vacuum, $L$ is the length of the ring resonator and $\varepsilon_{\text{eff}}$ is the effective dielectric constant of the transmission line. From the effective dielectric constant, the dielectric constant can be determined as well [6] through the relation

$$\varepsilon_{\text{eff}} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2\sqrt{1 + 12d/w}},$$  \hspace{1cm} (2)$$

where $d$ is the thickness of the dielectric and $w$ is the width of the microstrip line. The resonances of the ring can be recognised in the transmission measurement of the two-port structure that peaks near these frequencies. The attenuation constant $\alpha_n$ of the microstrip line can be determined from the quality factor of the transmission peak as well [5].

A circuit model of the ring resonator structure can be used to relate the dielectric constant of the dielectric and the transmission peaks of the ring resonator (see [5] and Fig. 3). The transmission peaks do not exactly correspond to the resonance frequency of the unloaded ring resonator since the ring is loaded by the microstrip transmission lines. In the circuit model, this effect is accounted for.

The ring resonator has been designed on a Ro4350B dielectric with a thickness of 101 $\mu$m (4 mil). The length of the ring has been chosen such that the 4th resonance of the ring lies close to 60 GHz ($L = 11.65$ mm). The width of the microstrip line is 203 $\mu$m, and the metal thickness is 25 $\mu$m. This results in a characteristic impedance of $Z_0 = 50$ $\Omega$. The width of the gap between the microstrip transmission line and the ring is 90 $\mu$m, which is the minimum spacing of the used PCB manufacturing process. The ring resonator is connected with ground-signal-ground (GSG) RF probes and is measured with a two-port measurement. The transition from GSG probe to microstrip is de-embedded from the measurements. For this purpose, through, reflect and line structures have been realised and measured as well.

From the circuit model, the dielectric constant can be obtained as a function of resonance frequency. This relation is shown in Fig 4 for the 4th resonance. To validate the circuit model, the obtained results are compared with full-wave simulations that have been performed with CST Microwave Studio. The discrepancy between the dielectric constants that are predicted by both models lies within 1%. The measured resonance frequency is 60.42 GHz, which implies a dielectric constant of 3.74. As mentioned before, the attenuation can be determined from the 3 dB bandwidth of the transmission peak. This bandwidth is 1.3 GHz, which implies an attenuation constant $\alpha = 23$ Np/m. The corresponding attenuation of the microstrip line is 1.0 dB/cm. A similar analysis has been performed for the other (lower) resonance frequencies as well. These results are listed in Table I.

<table>
<thead>
<tr>
<th>$n$</th>
<th>$f_{0,n}$ [GHz]</th>
<th>$\beta_{3dB,n}$ [GHz]</th>
<th>$\varepsilon_r$</th>
<th>attenuation [dB/cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15.24</td>
<td>0.49</td>
<td>3.67</td>
<td>0.38</td>
</tr>
<tr>
<td>2</td>
<td>30.46</td>
<td>0.69</td>
<td>3.66</td>
<td>0.53</td>
</tr>
<tr>
<td>3</td>
<td>45.55</td>
<td>1.0</td>
<td>3.69</td>
<td>0.77</td>
</tr>
<tr>
<td>4</td>
<td>60.42</td>
<td>1.3</td>
<td>3.74</td>
<td>1.0</td>
</tr>
</tbody>
</table>

IV. PACKAGE PROTOTYPE

To investigate the difficulties associated with the implementation of a transceiver package that embeds antennas and electronics, a prototype has been built. This prototype embeds a power amplifier (PA) integrated circuit (IC) and a BFACP antenna into one package. A schematic layout of the package is shown in Fig. 1. The antenna is optimised for this stack following the approach presented in [7]. The frequency band of the optimised antenna ranges from 56 to 65 GHz and the radiation efficiency in this band is larger than 75% (see Fig. 5). The PA is realised in 65 nm CMOS technology and is initially characterised with RF probes that connect directly to the chip.
Table II: Dimensions of the optimised antenna.

<table>
<thead>
<tr>
<th>Element</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>patch</td>
<td>length</td>
<td>1.37 mm</td>
</tr>
<tr>
<td></td>
<td>width</td>
<td>1.60 mm</td>
</tr>
<tr>
<td>slots</td>
<td>length</td>
<td>1.44 mm</td>
</tr>
<tr>
<td></td>
<td>width</td>
<td>0.20 mm</td>
</tr>
<tr>
<td>reflector</td>
<td>length</td>
<td>2.13 mm</td>
</tr>
<tr>
<td></td>
<td>width</td>
<td>1.00 mm</td>
</tr>
<tr>
<td>dipole</td>
<td>length</td>
<td>2.09 mm</td>
</tr>
<tr>
<td></td>
<td>width</td>
<td>0.15 mm</td>
</tr>
<tr>
<td>feed</td>
<td>width</td>
<td>0.10 mm</td>
</tr>
<tr>
<td></td>
<td>spacing</td>
<td>0.12 mm</td>
</tr>
</tbody>
</table>

Figure 5: Reflection coefficient (solid) and radiation efficiency (dashed) of the optimised antenna. Dimensions in Table II.

The maximum gain of the PA is about 5-8 dB and the 3 dB gain bandwidth ranges from 54 to 66 GHz.

A. Flip-chip interconnect

To integrate the IC with the antenna, a reliable interconnection needs to be realised. Traditionally, the interconnection between IC and PCB is realised through wire-bonding, but the performance of this type of interconnect decreases rapidly for higher frequencies, because of the large wire inductance that is associated with the wire-bond (see e.g. [8]). Alternatively, flip-chip technologies can be employed to provide a better interconnection, since flip-chip interconnections have lower and more predictable parasitic inductances [9], [10]. In flip-chip technology the metallic pads on the IC are connected to a corresponding set of pads on the PCB using an array of balls or bumps. These balls or bumps can be realised from solder or metal like gold and copper [10]. In this demonstrator, gold stud bumps have been used in combination with an anisotropic conductive adhesive [11]. First, the gold bumps are placed on the pads of the IC. Second, the IC is flipped and pushed onto the PCB. In between the IC and the PCB, an adhesive is placed that contains silver particles. Because of the applied pressure, these particles form a conducting path in between the stud bumps and the PCB pads. A microscopic photograph of the cross-section of such a flip-chip interconnection is shown in Fig. 6.

B. Chip mount

The layout of the chip mount is shown in Fig. 7. This chip mount has been designed such that the pads on the PCB correspond with the pads of the PA. The input signal of the PA can be provided through the ground-signal-ground (GSSG) connection on the PCB. Vias have been used to connect all the grounds to a large metal plane underneath the chip mount. The DC supply and bias voltages can be applied to the PA from the PCB as well. RF stubs have been employed to suppress the RF signals on the DC supplies. The output of the PA connects directly to the differential feed of the antenna.

C. Package

The complete package is depicted in Fig. 8. Here, the layout of each layer can be easily identified. The width and length of the package is 18 × 28 mm, whereas the total thickness is 0.82 mm. The used material layers and the corresponding thicknesses are shown in Table III. The coplanar microstrip feed connecting the PA and the antenna is constructed such that it has a ground plane underneath it near the PA and above it near the antenna. In this way, the characteristic impedance of the differential feed is close to 100 Ω everywhere.
Table III: Stack build-up of package prototype. The layers are numbered from top to bottom.

<table>
<thead>
<tr>
<th>layer</th>
<th>type</th>
<th>name</th>
<th>$\varepsilon_r$</th>
<th>thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>teflon-based</td>
<td>NY9217</td>
<td>2.17</td>
<td>254 $\mu$m</td>
</tr>
<tr>
<td>2</td>
<td>adhesive</td>
<td>SpeedBoard C</td>
<td>2.6</td>
<td>112 $\mu$m</td>
</tr>
<tr>
<td>3</td>
<td>ceramic-based</td>
<td>Ro4350B</td>
<td>3.74</td>
<td>102 $\mu$m</td>
</tr>
<tr>
<td>4</td>
<td>adhesive</td>
<td>Ro4403</td>
<td>3.17</td>
<td>102 $\mu$m</td>
</tr>
<tr>
<td>5</td>
<td>ceramic-based</td>
<td>Ro4350B</td>
<td>3.74</td>
<td>254 $\mu$m</td>
</tr>
</tbody>
</table>

Figure 8: Layout of package. (a) Top view. (b) Explored view.

**D. Measurements**

To characterise the performance of the packaged PA and antenna (Fig. 9), the performance of the antenna is evaluated first. Since the antenna has a differential feed, GSSG RF probes have been used in combination with an external balun to provide the balanced input signal. The RF probe has been calibrated with a one-port load-reflect-match (LRM) calibration. The measured and simulated reflection coefficients are shown in Fig. 10. It is observed that the matching of the antenna is below -10 dB in the frequency range from 57.7 to 65.0 GHz. This corresponds well with the gain bandwidth of the PA that ranges from 54 to 66 GHz.

The performance of the packaged PA and antenna has been investigated as well. The operation of this package has been tested on a probe station first (see Fig. 11). A GSSG RF probe has been used to connect the RF input signal to the PA. The DC supply and bias voltages have been applied with DC probes. We compared the gain of the combined PA and antenna with the gain of the antenna alone (i.e., without PA). To characterise the radiation pattern of the combined PA and antenna, wires have been soldered to the DC bias and supply connections of the package and the radiation patterns are measured on the far-field radiation pattern measurement setup [12].

The gain of the antenna alone and the PA-antenna combination is compared in Fig. 12. It is observed that the gain of
It is observed that both measured radiation patterns are very similar. This indicates that the power is radiated by the antenna alone and no significant amount of power is radiated by the RF probe, the PA or the flip-chip transitions. Moreover, it is observed from Fig. 13 that the radiated patterns are in good agreement with simulated results.

V. CONCLUSIONS

The integration of a differential CMOS PA and a BFACP antenna has been investigated. First, a topology has been proposed for the integration of the BFACP antenna and a PA. This topology has been designed in detail and the performance of the integrated module has been measured. It has been demonstrated that the embedded antenna shows good performance, viz a measured bandwidth that ranges from 57.7 to 65.0 GHz and a maximum gain of 7 dBi. Moreover, it has been shown that the BFACP antenna can be integrated with a PA although the gain of the PA-antenna combination is lower then expected. Possible causes for this reduction in gain have been discussed and will be a topic for future research.

ACKNOWLEDGMENT

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REFERENCES

[2] Nelco RF / Microwave circuitry materials, Park Electrochemical Corporation, Melville, USA.
[3] RO4000 Series high frequency circuit materials, Rogers Corporation, Chandler, USA.