An Integrated Transformer with Reconfigurable S/X-Band Operation in a Single CMOS Power Amplifier

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Abstract – An integrated reconfigurable transformer for a dual-band power amplifier (PA). The PA operating in the S/X-band is fully integrated using a 0.18-μm RF CMOS process. The switchable transformer is designed by tuning its primary winding and a shunt capacitor at 50 ohm load with passive efficiency of more than 62/67% for S/X-band. The measurement results show saturated output power ($P_{SAT}$) of 24.3/21.2 dBm with peak drain efficiency (DE) of 34.8%/12.2% at 3.1/8.0 GHz, respectively. The 1-dB bandwidth is 0.7/1.25 GHz (2.8–3.5/7.5–8.75 GHz) for the S/X-band.

Index Terms – CMOS, dual-band, power amplifier, radar transceiver, reconfigurable, switch, transformer.

I. INTRODUCTION

Modern radar systems often require multi-band operations due to the different characteristics of the environment and targets. For examples, S-band signals are resistant to severe weather and atmosphere attenuation. On the other hand, frequencies in X-band are often used for highly resolved target imaging [1], [2]. Achieving dual-band functionality has been challenging, especially when using fully integrated CMOS PAs, owing to their low breakdown voltage and low quality-factor. Most current CMOS PAs are not satisfied by radar systems using the aforementioned frequency bands and several single-band PAs directly assembled into a single chip have been presented [3].

There have been several approaches to implement broadband or multi-band characteristics in a single PA. One approach is to employ a transformer-based high-order output matching network (OMN) or a stacked stepped-impedance transformer to realize wideband operation [4], [5]. However, when using this approach, passive efficiency decreased rapidly, and load matching could not be maintained in lower bands. Another approach is to use parallel/series resonant LC structures or an off-chip combiner [6]; however, these are not suitable for single-chip integration and low-cost implementation.

This study proposes a single dual-band PA with a reconfigurable OMN, which is realized through the use of a switchable transformer. The design details and measurement results of the proposed dual-band PA are presented in the following sections.

II. OPERATION OF THE RECONFIGURABLE S/X-BAND PA

A. Reconfigurable Dual-Band Transformer

Given that optimum load resistance ($R_{opt}$) and device nonlinear output capacitance ($C_{device}$) in a power device are independent of the operating frequency, the optimum load impedance ($Z_{opt}$) moves on a conductance circle with $1/R_{opt}$, and smaller shunt inductance is required to resonate with the $C_{device}$ as the frequency increases [7]. As illustrated in Fig. 1, an equivalent circuit of a high-Q transformer and additional capacitors ($C_1$, $C_2$) are employed for the OMN. Assuming that the coupling factor ($k$) is 0.7 and the quality factor (Q) is 10, the transformed impedance was simulated for two cases. First, load impedance ($Z_{Load}$) was calculated by varying $C_1$ (0.1–2.0 pF) and $C_2$ (0.8–2.0 pF), maintaining $L_1$ (0.36 nH), and optimizing $L_2$ (0.73 nH) in the X-band. To achieve $Z_{opt}$ for the S-band, the trajectories of
Load were drawn by varying $L_1$ (0.2~0.75 nH) and $C_2$ (0.8~2.0 pF), and keeping $C_1$ (1.43 pF) fixed in the S-band. As $L_1$ increases the real/imaginary parts of $Z_{\text{Load}}$ and $C_2$ precisely controls $Z_{\text{Load}}$ to the $Z_{\text{opt}}$, higher $L_1$ (0.58 nH)/$C_2$ (1.56 pF) and lower $L_1$ (0.36 nH)/$C_2$ (1.24 pF) are required for the S- and X-bands, respectively, with fixed $C_1$ (1.43 pF) and $L_2$ (0.73 nH).

The proposed reconfigurable OMN is shown in Figs. 2 and 3 (a); $L_1$ increases for the S-band due to the inner turn winding and $C_2$ decreases for the X-band due to the OFF-capacitance ($C_{\text{OFF}}$) of S2. To ensure the operations, S1/S2 is turned OFF/ON for the S-band, while S1/S2 is turned ON/OFF for the X-band. To maintain the high passive efficiency in the X-band, a gap of 40 um exists between the conventional and inner primaries. When considering the gate width of S1 for low on-resistance ($R_{\text{on}}$), as shown in Fig. 3 (b), the $C_{\text{OFF}}$ must be taken into consideration in order to achieve optimum matching. The trade-off between $R_{\text{on}}$ and $C_{\text{OFF}}$ results in optimum device widths that balance the effect, as illustrated in Figs. 3 (b) and 4. With a $C_{\text{OFF}}$ of 1.69 pF and a $R_{\text{on}}$ of 0.9 Ω for the S1, the peak passive efficiencies of the proposed transformer show 64.5%/68.5% in the S/X-band. Including a $C_{\text{OFF}}$ of 0.35 pF for the S2, the load impedances at 3.0/8.5 GHz are well located at the targeted impedances (15.5+j15.8 Ω/11.02+j9.54 Ω), as shown in Fig. 4.

B. Circuit schematic of the Dual-Band PA

The S1 (4.608 mm/0.35-μm) and S2 (1.152 mm/0.18-μm) are implemented by a thick gate-oxide transistor and two stacked thin-gate transistors, respectively, which are sufficiently reliable for the OFF-state, as illustrated in Fig. 5. Fig. 6 shows a detailed circuit schematic of the dual-band CMOS PA with the reconfigurable OMN. The designed PA uses two series-resonance circuits for the X-band to alleviate the load asymmetric effects of the OMN, which mainly arise in the practical layout. Furthermore, to the extent that the PA operates stably, Miller capacitors ($C_{\text{mr}}$: 0.25 pF) are utilized to compensate for the gate capacitances of common-source amplifiers. The total gate widths of the common source/gate are
Table 1: Comparison with state of the art CMOS multi-band PAs

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Freq. [GHz]</th>
<th>Output Network Configuration</th>
<th>OMN Efficiency [%]</th>
<th>PSAT [dBm]</th>
<th>Peak Efficiency [%]</th>
<th>Tech [µm]</th>
<th>VDD [V]</th>
<th>Chip Size/PA Core Size [mm²]</th>
<th>PA Type</th>
</tr>
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<tr>
<td>[4]</td>
<td>5.0/14.0</td>
<td>1 TF + 1 inductor (Single IN - Single OUT)</td>
<td>30/38</td>
<td>18.5/21.5</td>
<td>69.5 (PAE)</td>
<td>90</td>
<td>2.8</td>
<td>0.697/1.4A</td>
<td>Linear (Class-AB)</td>
</tr>
<tr>
<td>[5]</td>
<td>3.5/9.5</td>
<td>1 TF (Single IN - Single OUT)</td>
<td>35/70</td>
<td>19.5/19.0</td>
<td>*20/19 (PAE) 24/20 (DE)</td>
<td>40</td>
<td>1.2</td>
<td>1.4/1.4A</td>
<td>Digital (Class-E)</td>
</tr>
<tr>
<td>[8]</td>
<td>1.95/2.4</td>
<td>4 TFs (Single IN - Single OUT)</td>
<td>N.A.</td>
<td>31.8/32.0</td>
<td>28.8/32.4 (PAE)</td>
<td>65</td>
<td>3.6</td>
<td>5.4/2.71</td>
<td>Linear</td>
</tr>
<tr>
<td>[9]</td>
<td>2.0/6.0</td>
<td>1 TF + 3 inductors (Single IN - Single OUT)</td>
<td>N.A.</td>
<td>22.4/20.1</td>
<td>28.4/19 (PAE)</td>
<td>65</td>
<td>3.3</td>
<td>0.89/0.68</td>
<td>Linear (Class-AB)</td>
</tr>
<tr>
<td>[10]</td>
<td>2.6/4.5</td>
<td>1 TF (D Kent IN - Single OUT)</td>
<td>78.5/62</td>
<td>28.1/26.0</td>
<td>35/21.2 (PAE) 40/27 (DE)</td>
<td>65</td>
<td>3.0</td>
<td>2.25/0.96</td>
<td>Digital (Class-D+)</td>
</tr>
<tr>
<td>This work</td>
<td>3.18/8.0</td>
<td>1 TF + 2 SWs (Single IN - Single OUT)</td>
<td>64.5/68.2</td>
<td>24.3/21.2</td>
<td>33.4/7.7 (PAE) 34.8/12.2 (DE)</td>
<td>180</td>
<td>3.6</td>
<td>0.825/0.55</td>
<td>Linear (Class-AB)</td>
</tr>
</tbody>
</table>

1Values taken from Fig. 10 of [2]. 2Values taken from Fig. 14 of [2]. 3Values taken from Fig. 3 of [3]. 4Values taken from Fig. 5 of [3].

III. MEASUREMENT RESULTS

The single S/X-band PA with a reconfigurable transformer is fully implemented in a 0.18-µm 1P6M RF CMOS process that provides a 4.6-µm-thick aluminum layer as the top metal. Occupying a small core area of 0.636×1.297 mm² (Fig. 7), the PA is conducive to further integration with additional transceiver circuits to form a dual-band high resolution radar system on-chip. The IC was mounted on a Duroid 5880 PCB and bond-wire effects are included in the measurement results.

For the S/X-band, the amplifier consumes 222/250 mA of DC current. Figs. 8 and 9 show that PSAT is 24.3/21.2 dBm with peak DE of 34.8%/12.2% at 3.1/8.0 GHz, correspondingly. Note that the discrepancy for center frequencies between the simulation and the measurement is mainly due to large signal modeling of the CMOS and EM modeling. The 1-dB bandwidth is 0.7/1.25 GHz (2.8–3.5 GHz/7.5–8.75 GHz) with PSAT > 23.0/20.0 dBm for the S/X-band, respectively.

IV. CONCLUSION

In this study, a single reconfigurable dual-band PA is fully integrated in 0.18-µm 1P6M RF CMOS technology. This PA consists of a differential power stage with an input/output matching network and operates in the S/X-band. An integrated switchable transformer, a key element of the PA, was studied in terms of the equivalent circuit, the optimum-load matching, and passive efficiencies with transistors as high-power switches. With the OMN passive efficiency being 64.5%/68.2%, the measurement results show that PSAT is 24.3/21.2 dBm and peak DE is 34.8%/12.2% at 3.1/8.0 GHz, respectively. The measured 1-dB bandwidth is 0.7/1.25 GHz (2.8–3.5 GHz/7.5–8.75 GHz) for the S/X-band. Considering the specifications, this PA is likely suitable for use in a dual-band high-resolution radar system.

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