A 3.9-GHz-Band Outphasing Power Amplifier with Compact Combiner Based on Dual-Power-Level Design for Wide-Dynamic-Range Operation

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Outline

• Introduction
• Novel Miniature Outphasing Combiner Circuit
• Matching Circuit Design
  Based on Dual Power Level Optimization
• Evaluation of Outphasing GaN HEMT Amplifier at 3.9 GHz
• Conclusion
Introduction

High-data rate wireless communication

Wide-band & Wide-dynamic-range

High-efficiency amplifiers for digitally modulated signals with large *PAPR are required.

- Outphasing
- Doherty
- Envelope etc...

\[ P_{pk} - P_{ave} = \text{PAPR(dB)} \]

*Peak-to-Average Power Ratio

An input signal is separated into two outphased equi-amplitude signals. Thus, saturation amplifiers can be used.

\[ v_{in}(t) \rightarrow v_{a}(t), v_{b}(t) \]

\[ v_{a}(t), v_{b}(t) \rightarrow \text{Amplifier} \]

\[ \text{Combiner} \]
Novel Miniature Outphasing Combiner Circuit

**Typical**

Parallel-load-compensation

Load compensation elements are connected in parallel.

$\lambda/4$ line makes the circuit larger

**Proposed**

Series-load-compensation

$X_c$ : Compensation Component

$\lambda/4$ line is not required and the circuit size becomes small.

Dual-power-level design for PAs
Difference of Input Signal Separation

**Typical**

**Parallel-load-compensation**

\[
\begin{align*}
\nu_{in}(t) &= \nu(t) \cos[\omega t + \varphi(t)] \\
&= \nu_m \cos[\theta(t)] \cos[\omega t + \varphi(t)] \\
&= \frac{\nu_m}{2} \cos[\omega t + \varphi(t) + \theta(t)] \\
&\quad + \frac{\nu_m}{2} \cos[\omega t + \varphi(t) - \theta(t)] \\
&= \nu_{ia}(t) + \nu_{ib}(t)
\end{align*}
\]

\(\nu(t)\): Amplitude modulation \hspace{1cm} \varphi(t)\): Phase modulation

**Proposed**

**Series-load-compensation**

\[
\begin{align*}
\nu_{in}(t) &= \nu(t) \cos[\omega t + \varphi(t)] \\
&= \nu_m \sin[\theta(t)] \cos[\omega t + \varphi(t)] \\
&= \frac{\nu_m}{2} \sin[\omega t + \varphi(t) + \theta(t)] \\
&\quad - \frac{\nu_m}{2} \sin[\omega t + \varphi(t) - \theta(t)] \\
&= \nu_{ia}(t) - \nu_{ib}(t)
\end{align*}
\]

\(\nu(t)\): Amplitude modulation \hspace{1cm} \varphi(t)\): Phase modulation \hspace{1cm} \theta\): Outphasing angle
Operation of Proposed Outphasing PA

\[ v_\text{ia}(t) \rightarrow \text{PA}_a \rightarrow I_a \rightarrow Y_a \rightarrow jX_c \rightarrow Y_c \rightarrow jX_c \rightarrow V_L \]

\[ v_\text{ib}(t) \rightarrow \text{PA}_b \rightarrow I_b \rightarrow Y_b \rightarrow V_L \]

Signal processing

Input signal \( v_{in}(t) \) is processed and split into two paths, \( v_\text{ia}(t) \) and \( v_\text{ib}(t) \), which are amplified by power amplifiers \( \text{PA}_a \) and \( \text{PA}_b \), respectively. The amplified signals are combined and loaded into a reactive load \( R_L \). The design ensures efficient power transfer and minimized distortion.
The output signal is represented by a difference of two voltage signals.

\[ V_a = |V_0|(\cos\theta + j\sin\theta), \quad V_b = |V_0|(\cos\theta - j\sin\theta) \]

\[ jX_c I_a = V_a - V_L \quad -jX_c I_b = V_b - V_L \]

\[ V_L = R_L (I_a + I_b) = R_L \frac{(V_a - V_b)}{jX_c} = \frac{2R_L|V_0|}{X_c}\sin\theta \]
Load Modulation with Outphasing Angle

Load modulation is performed by outphasing angle, $\theta$.

The output signal is represented by a difference of two voltage signals.

**Equations:**

\[ V_a = |V_0|(\cos\theta + j\sin\theta), \quad V_b = |V_0|(\cos\theta - j\sin\theta) \]

\[ jX_c I_a = V_a - V_L \quad -jX_c I_b = V_b - V_L \]

\[ V_L = R_L(I_a + I_b) = R_L \left( \frac{V_a - V_b}{jX_c} \right) = \frac{2R_L|V_0|}{X_c} \sin\theta \]

\[ Y_a = \frac{R_L}{X_c^2} \left[ 2\sin^2\theta + j(\sin2\theta - \sin2\theta_c) \right] \equiv G_0 + jB_0 \]

\[ Y_b = \frac{R_L}{X_c^2} \left[ 2\sin^2\theta - j(\sin2\theta - \sin2\theta_c) \right] \equiv G_0 - jB_0 \]

$\theta_c$ : Compensation angle \hspace{1cm} (\(X_c = R_L\sin2\theta_c\))
Calculated Load Admittance for $\theta_c = 20\text{deg.}$

Pure conductance values are obtained at $\theta = 20\text{deg.}$ and $\theta = 90 - 20 = 70\text{deg.}$

A matching circuit has to be adjusted to obtain high-efficiency characteristics to both load conductances.
Matching Circuit Design
Based on Dual Power Level Optimization

\[ R_L = 50\Omega, \theta_c = 20\text{deg.} \text{ (9.3dB Back-off)} \]

\[ X_c = R_L \sin 2\theta_c = 32.1 \]

\[ G_0 = \frac{2R_L \sin^2 \theta}{X_c^2} = \begin{cases} \frac{R_L}{X_c^2} (0.23 + j0) = 11.1\text{mS} & (\theta = 20\text{deg.}) \\ \frac{R_L}{X_c^2} (1.77 + j0) = 85.7\text{mS} & (\theta = 70\text{deg.}) \end{cases} \]

Load modulation

Load-pull

GaN HEMT : CGHV1J006D ; Cree

\[ f_0: 3.95\text{GHz}, V_G: -2.8\text{V}, V_D: 30\text{V} \]

<table>
<thead>
<tr>
<th></th>
<th>Pin</th>
<th>Pout</th>
<th>( \eta_D )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low power level</td>
<td>23.0dBm</td>
<td>26.0dBm</td>
<td>55.0%</td>
</tr>
<tr>
<td>High power level</td>
<td>23.0dBm</td>
<td>34.6dBm</td>
<td>78.5%</td>
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</table>
Evaluation of Fabricated Amplifier for Low Power Level

Fabricated amplifier with an impedance transformer for the low power level

- Fabricated amplifier diagram
- Diagram showing GaN HEMT and impedance transformer
- Measurement results:
  - EM simulation: 26dBm, 28dBm, 57%
  - Measurement: 26dBm, 29dBm, 64%

Table:

<table>
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<tr>
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<th>Pin</th>
<th>Pout</th>
<th>$\eta_D$</th>
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<tbody>
<tr>
<td>EM simulation</td>
<td>26dBm</td>
<td>28dBm</td>
<td>57%</td>
</tr>
<tr>
<td>Measurement</td>
<td>26dBm</td>
<td>29dBm</td>
<td>64%</td>
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Evaluation of Fabricated Amplifier for High Power Level

Fabricated amplifier with an impedance transformer for the high power level

85.7mS ↔ 20mS (50Ω)

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<th>Pout</th>
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<tbody>
<tr>
<td>EM simulation</td>
<td>26dBm</td>
<td>34dBm</td>
<td>71%</td>
</tr>
<tr>
<td>Measurement</td>
<td>26dBm</td>
<td>34dBm</td>
<td>79%</td>
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</table>
Simulated Outphasing PA Operation

**EM simulation**

- **GaN HEMT**: CGHV1J006D; Cree
- **Inductor**: LQP03, 1.5nH; Murata
- **Capacitor**: GRM03, 1.1pF; Murata
- **Substrate**: 0.4-mm-thin Megtron7, $\varepsilon_r = 3.4$, $\tan\delta = 0.0015$; Panasonic

**Graphs**:

- **Efficiency**
  - $52\%$ @ 20deg.
  - $67\%$ @ 70deg.

- **Output Power**
  - $30\text{dBm}$ @ 20deg.
  - $37\text{dBm}$ @ 70deg.

- **Dissipation**
  - $13\text{mS}$ @ 20deg. (PAa)
  - $91\text{mS}$ @ 70deg. (PAa)

- **Output Impedance**
  - $1\text{mS}$ @ 20deg. (PAa)
  - $9\text{mS}$ @ 70deg. (PAa)

Each $P_{in}=25\text{dBm}$, $V_G=30\text{V}$, $V_D=-3.3\text{V}$, $f_0=3.85\text{GHz}$
Evaluation of Outphasing PA

Fabricated outphasing PA

The fabricated outphasing PA maintained high efficiency over the wide dynamic range.

<table>
<thead>
<tr>
<th></th>
<th>Psat</th>
<th>$\eta_{D_{\text{max}}}$</th>
<th>$\eta_D$(OBO)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EM simulation</td>
<td>37dBm</td>
<td>68%</td>
<td>&gt; 50%(7dB)</td>
</tr>
<tr>
<td>Measurement</td>
<td>37dBm</td>
<td>77%</td>
<td>&gt; 50%(7dB)</td>
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Frequency Characteristic of Amplifiers

### Outphasing PA

- **$f = 3.87 \sim 3.94 \text{ GHz}$**

### Single PA

- **For low power level**
- **For high power level**

#### Drain efficiency, ηD (%)
- **Outphasing Amplifier**
  - $\eta_D \text{ Potmax}$ > 55%
  - $\eta_D \text{ 6dB OBO}$ > 40%

- **PA Only**
  - $\eta_D \text{ High}$ > 60%
  - $\eta_D \text{ Low}$ > 40%

Frequency characteristics of the outphasing PA are narrowed by those of single PAs.
Conclusion

• An outphasing power amplifier with a novel compact combiner was developed.

• Dual-power-level optimization at two load conductance values was applied for the power amplifier design.

• A peak drain efficiency of 77% (37dBm) at 3.92 GHz was obtained, and a drain efficiency of more than 50% was maintained within an output back-off of 7dB.
Typical Outphasing Configuration

\[ V_a = |V_0|(\cos\theta + jsin\theta), \quad V_b = |V_0|(\cos\theta - jsin\theta) \]

\[ V_a = jZ_0I_{La} \quad \quad V_b = jZ_0I_{Lb} \]

\[ I_L = I_{La} + I_{Lb} = \frac{V_a + V_b}{jZ_0} = \frac{2|V_0|\cos\theta}{jZ_0} \]

\[ V_L = R_L(I_{La} + I_{Lb}) = \frac{2R_L|V_0|}{jZ_0} \cos\theta \]

\[ Y_a = \frac{R_L}{Z_0^2} \left[ 2\cos^2\theta - j(\sin2\theta - \sin2\theta_c) \right] \equiv G_0 - jB_0 \]

\[ Y_b = \frac{R_L}{Z_0^2} \left[ 2\cos^2\theta + j(\sin2\theta - \sin2\theta_c) \right] \equiv G_0 + jB_0 \]

\( \theta \): Outphasing angle

\( \theta_c \): Compensation angle
Equivalent Load Locus

EM simulation

\[ [Z_{aTr}, Z_{bTr}] \]
\[ [Z_a, Z_b] \]

Outphasing angle, \( \theta \): 0~90 deg.