Design of mm-wave Injection Locking Power Amplifier

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## Design Review

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Process</th>
<th>Topology</th>
<th>VDD (V)</th>
<th>Gain (dB)</th>
<th>P1dB (dBm)</th>
<th>Psat (dBm)</th>
<th>PAE (%)</th>
<th>Pin@Psat (dBm)</th>
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<td>18.6</td>
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Data with underline is estimated by difference between Psat and Gain
ILPA Design

• PA is the circuit increases power of a signal by taking energy from a DC supply
• The efficiency is most important, PA is the most power hungry block in a system
ILPA Design

• 1914 Armstrong demonstrated regenerative receiver to overcome low gain of vacuum tube

• Oscillator can achieve maximum 78.5% efficiency theoretically with infinite gain. Even, at mm-wave frequency, the efficiency is around 20%.
ILPA Design

Different Modulation Types

- OOK is simplest modulation scheme
  - Power oscillator requires a long start-up time
  - Output spectrum is poor & poor spectrum efficiency
- Phase modulation is preferred
ILPA Design

- A synchronization process between input signal and output signal of oscillator, in terms of frequency, phase.
- FM modulation using injection locking is widely employed in Frequency Hoping (FH) system, ex. Bluetooth.
- The problem is the achievable modulation frequency
ILPA Design

\[ \frac{d \varphi}{dt} = -\omega_B \sin \varphi + \Delta \omega_0 \]

\[ \omega_B = \frac{P_{\text{in}}}{P_{\text{out}}} \frac{\omega_0}{2Q} \]

Edler’s Equation

\varphi \quad \Delta \omega_0 \quad \omega_B \quad \text{Phase difference between input and output, frequency difference and the half injection lock bandwidth}

\begin{align*}
p_{\text{in}} & \quad p_{\text{out}} \quad \omega_0 \quad Q \quad \text{Input and output power into tank, free-running frequency and tank’s quality factor}
\end{align*}
ILPA Design

\[ \varphi = \varphi_{ss} + \{ \varphi_0 - \varphi_{ss} \} e^{-\omega_B t} \]

\[ \varphi_{ss} = \arcsin(\frac{\Delta \omega_0}{\omega_B}) \]

- The time constant is determined by half injection locking bandwidth
- Locking time is determined by phase difference and half injection locking bandwidth
ILPA Design

\[ \tau = \left( \frac{\omega_o}{2Q} \frac{P_{inj}(P_{inj} + P_{out} \cos \phi_{ss})}{(P_{out} + P_{inj} \cos \phi_{ss})^2} \right)^{-1} \]

Time constant versus injection frequency difference

- Time constant approaches minimum value when injection frequency equals to free-running frequency
- Time constant reaches infinite when injection frequency close to the limit of injection locking range
ILPA Design

- Gain versus frequency, maximum is shown in free running frequency
- Bandwidth is determined by injection-locking bandwidth

**Gain**

\[ Gain = \frac{P_{out}}{P_{in}} \]

\[ \omega_{inj} - \omega_o \]

ILPA gain versus injection frequency difference
PA Ex 1 : A Compact V-band Injection-Locked PA

- A single-Stage V-band has been ILPA implemented on STM 65nm CMOS technology
- A 2:1 transformer employed to transform a 50 ohm load to a relatively high impedance load
- Size: 250um x 400 um
Simulation shows $L_p$ of 180pH and $L_s$ 66pH

The simulated quality factor is 11 and 14.3 respectively for $L_p$ and $L_s$
PA Ex 1 : A Compact V-band Injection-Locked PA

Meas. PAE & Output Power VS VGG of ILPA

- Output power of 9.6 dBm has been achieved at 1 V gate bias, a slightly less than simulated 10.1 dBm
- Best efficiency 17.3 % is shown at gate bias of 0.7 V, 19.6 % is shown on simulation.
The injection locking range covers from 52.5 GHz to 54.5 GHz
The maximum gain is 29 dB at 53.5 GHz
## PA Ex 1: A Compact V-band Injection-Locked PA

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PA Ex 1 : A V-band Injection-Locked PA

The proposed ILPA can achieve 17.3% PAE and 9.6dBm output power with only one stage design in a compact layout using STM 65nm CMOS technology.

The proposed method can reduced the required input power to -20 dBm, Hence improves the PAE.

• Drawbacks
  – Direct transformer coupled output is sensitive to pulling and load.
  – Injection locking range is very small, just 2 GHz
  – Unable to support amplitude modulation
PA Ex 2 : A Dual-Mode Wideband ILPA

- To support amplitude modulation required in 60GHz standard, linear mode is necessary, for linear amplifier, a back-off is usually needed.
- The single carrier modulation using QPSK/BPSK does not require such high-back-off.
- Dual Mode PA is proposed, linear mode, non-linear mode.
PA Ex 2 : A Dual-Mode Wideband ILPA

- When V_M is low
  - Cross coupled pair is turned off, presents a high impedance to the load of 1st stage.
  - Cascode as 1st Stage, common source as output stage
PA Ex 2 : A Dual-Mode Wideband ILPA

- Size estimation based on gain budget for the optimization of efficiency.
- Proposed MAG based transformer impedance matching method for multi-stage impedance matching.

Conceptual Diagram of impedance matching

MAG over transformer size changing
PA Ex 2 : A Dual-Mode Wideband ILPA

- The parasitic capacitance and transformer inductance determines free-running frequency.
- Cascode input stage and output common source can reduce ratio of injection power and tank’s output power, Hence improve the locking bandwidth.
- Oscillation tank has been isolated from antenna.
- Output power level are variable according to gate bias of CS.
PA Ex 2 : A Dual-Mode Wideband ILPA

- Output spectrum with 2Gbps QPSK (left) and PI/4 DQPSK (right) shows an excellent Adjacent Channel Power Ratio (ACPR.)
- Better performance is shown in PI/4 DQPSK.
PA Ex 2 : A Dual-Mode Wideband ILPA

• EVM performance is shown in figure.
• EVM increases as data rate increases.
• PI/4 DQPSK shows better EVM performance
PA Ex 2 : A Dual-Mode Wideband ILPA

Design parameters relationship

Injection
Locking
bandwidth

Modulation
Type

EVM

Time
constant

Phase error
PA Ex 2 : A Dual-Mode Wideband ILPA

Meas. Small signal results

- Meas. Small signal gain 15.4dB and 3-dB bandwidth from 54.5-59 GHz
- About 5 GHz frequency discrepancy between simulation and measurement
PA Ex 2: A Dual-Mode Wideband ILPA

- P1dB is 10.1 dBm with an input of -2.9 dBm, while simulation results show a peak gain of 16 dB and P1dB of 7.0 dBm.
- The measured results show 21.7% PAE with 2dBm input
PA Ex 2 : A Dual-Mode Wideband ILPA

- 10.2dBm maximum output power at 55GHz from injection locking mode
- Locking range is from 50GHz to 59GHz, PAE is 15.4 %
A first wideband dual-mode PA has been demonstrated at V-band with a size of 260um x 400um.

The linear mode shows 10.1dBm P1dB and 21.7% PAE, with a small signal gain of 15.4dB.

The injection lock range can cover from 50GHz to 59GHz and the output is 10.2dBm with efficiency larger than 15%.
PA Ex 2 : A Dual-Mode Wideband ILPA

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<th>VDD (V)</th>
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2a, 2b are two different modes with the same circuit
2a is injection locking mode
2b is linear mode
Reference