# Switchless Matching Networks for Dual-Band Class-E Power Amplifiers

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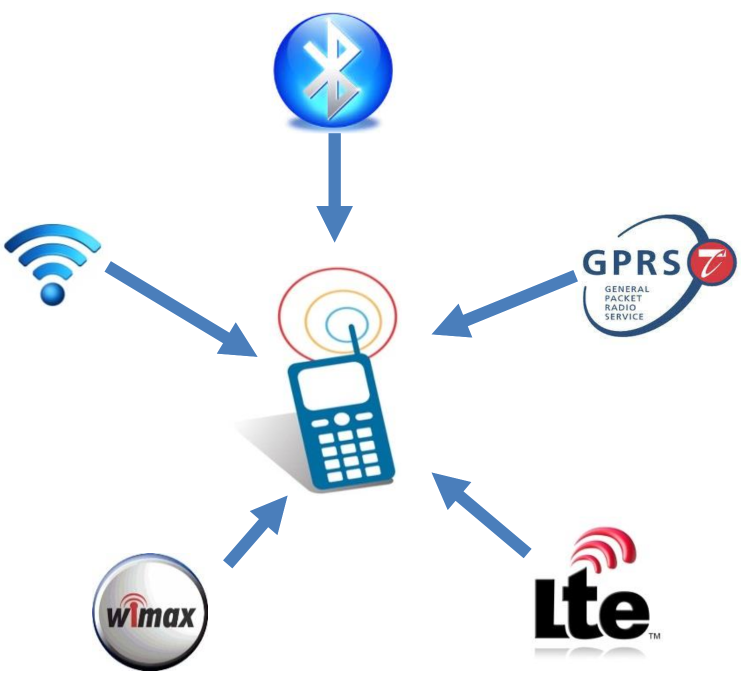
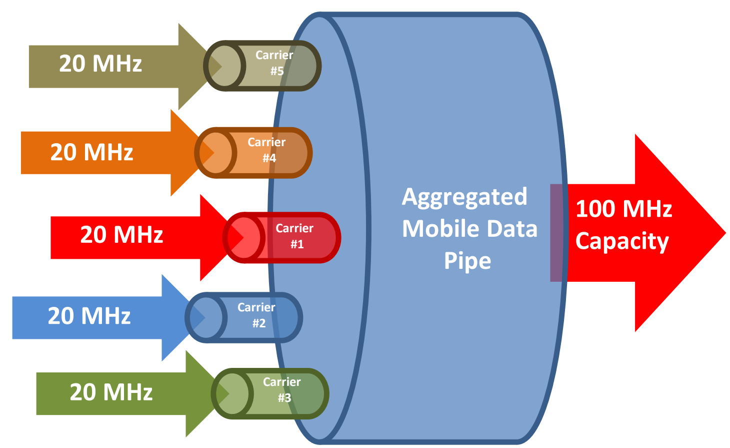
# Outline

- Motivations
- Dual-Band Matching Networks for Power Amplifiers
- Proposed Dual-Band Matching Networks for Class E PA
- Simulation Results
- Conclusion

# Motivations

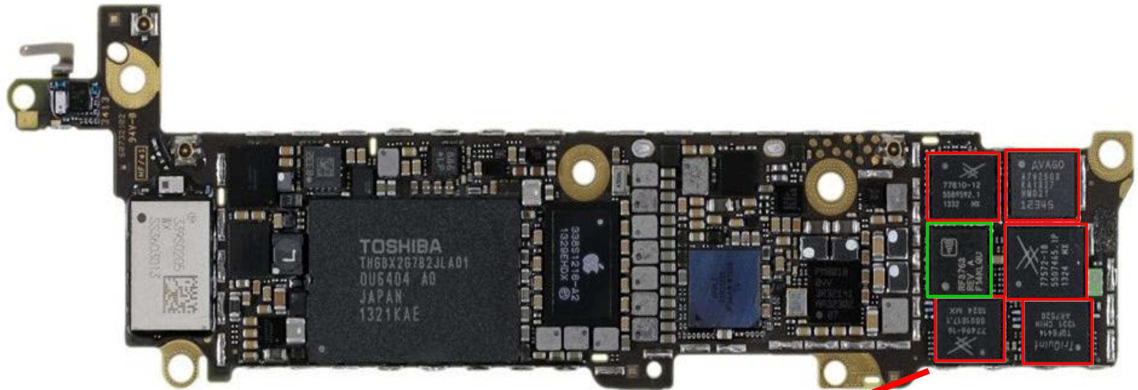
- Multi-band radio is a basic requirement for today's wireless devices
- Non-contiguous Carrier Aggregation requires concurrent operation
- Simultaneous tasks



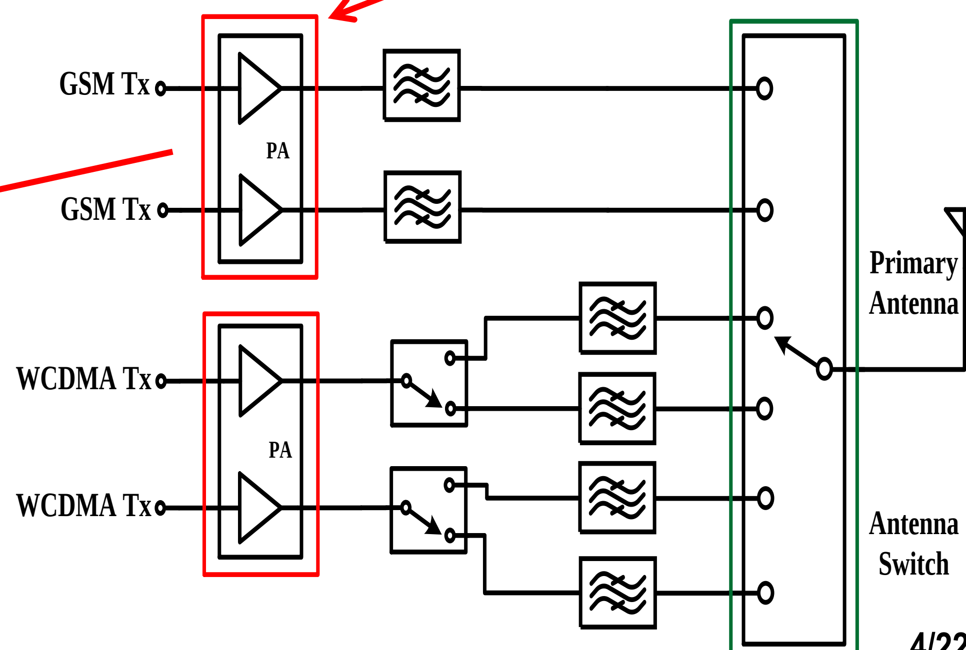



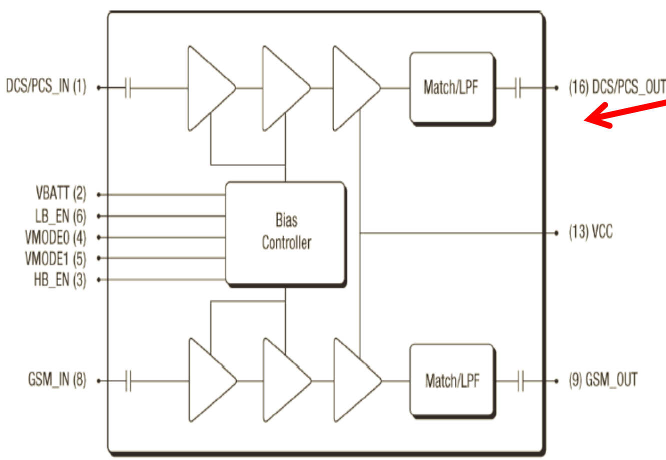
# Motivation for Dual-Band/Multi-Band Power Amplifier

- PA is a major part of RF front end
- Multi-band PA brings
  - Smaller area
  - Lower cost




IPhone 5 mother board




Typical PA module

# Outline

- Motivations
- Dual-Band Output Matching Networks for Power Amplifiers
  - Switch-Based
  - Transmission-Line Based
  - Lumped Element Based
- Proposed Dual-Band Matching Networks for Class E PA
- Simulation Results
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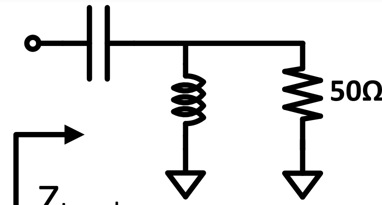
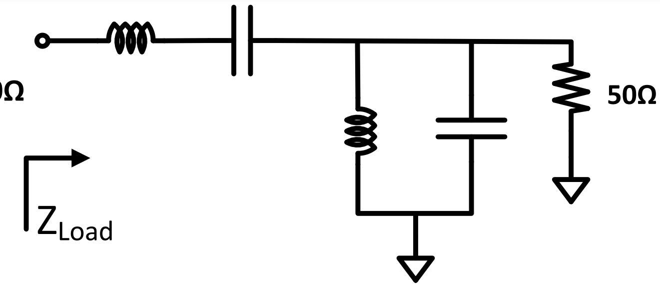
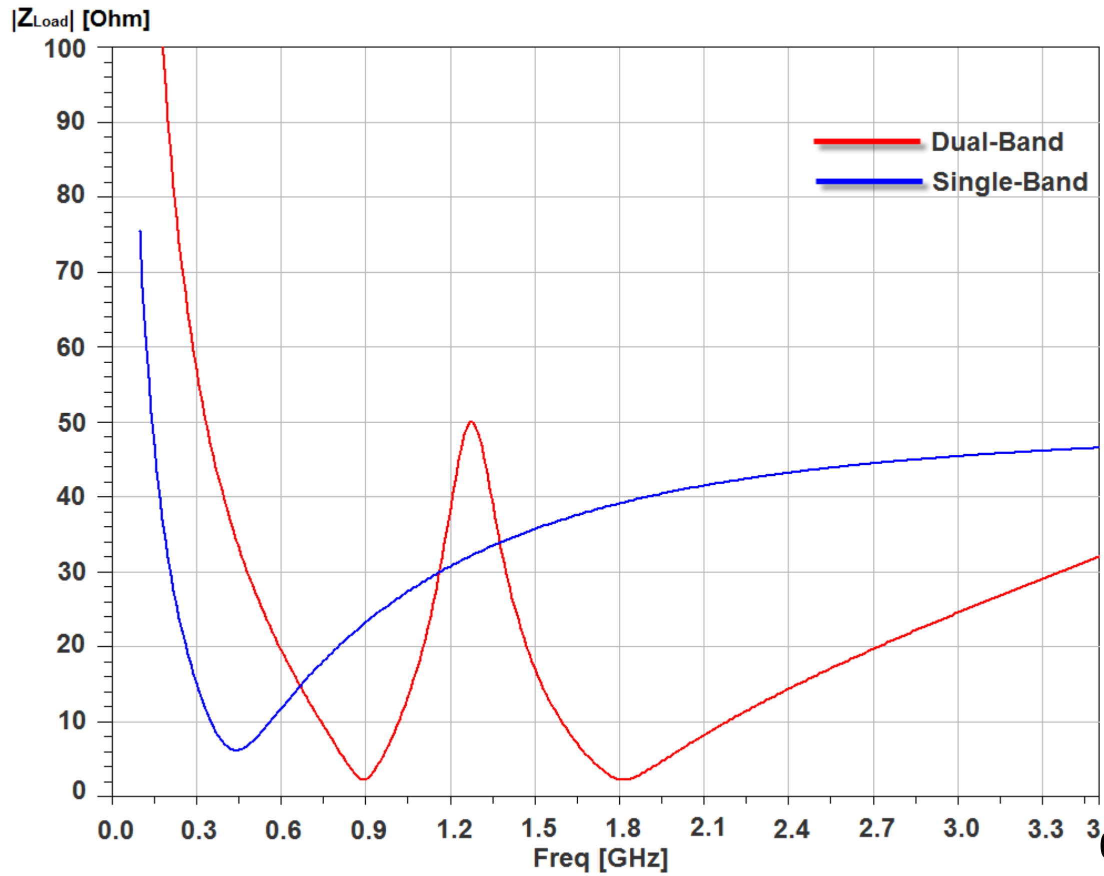
# Single and Dual-Band Output Matching Networks

- Output matching networks converts 50Ω antenna load to desired load impedance ($Z_{Load}$) seen by the transistor
- Usually low impedance
- Single-band OMN: conversion only achieved at one frequency
- Dual-band OMN: conversion can be achieved at two frequencies
- We care about:
  - desired impedance
  - loss

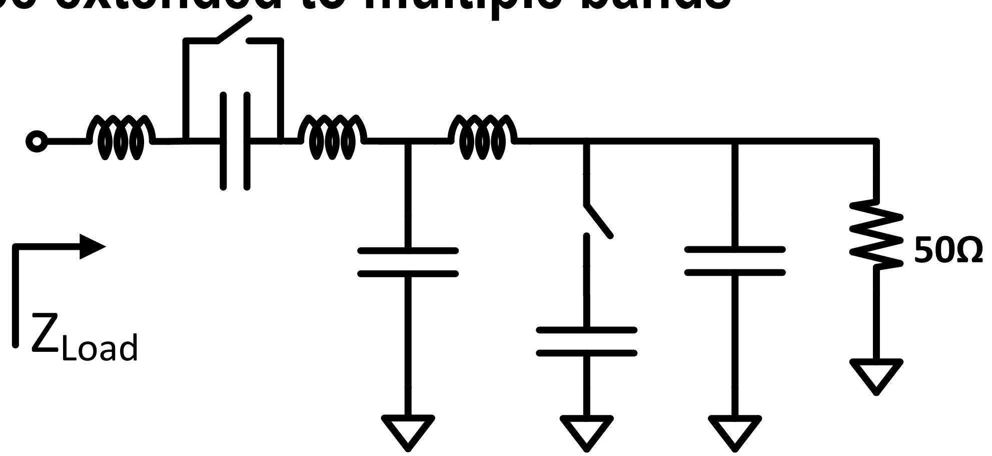


# Switch-Based Output Matching Networks

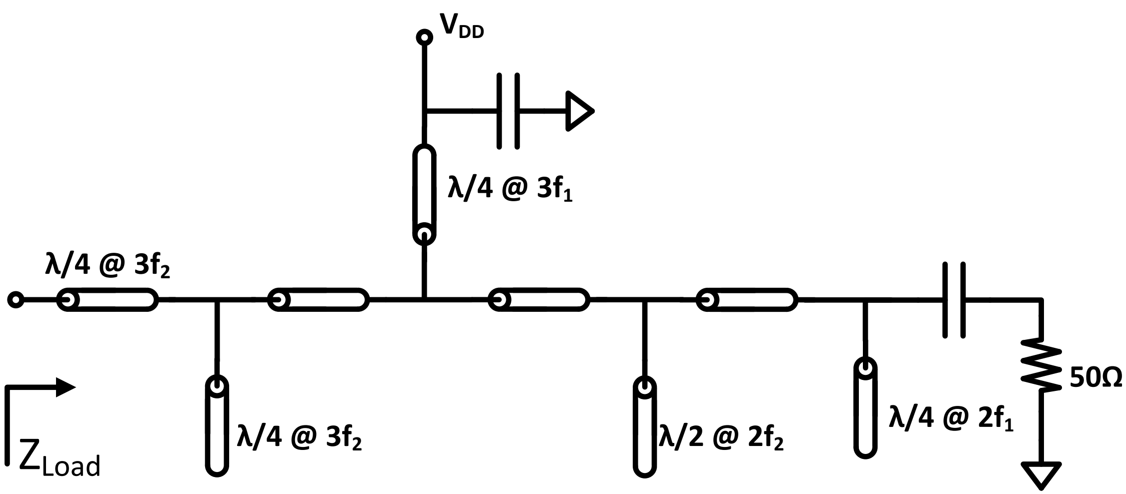
- Disadvantages
  - Extra cost of RF switches
  - Extra loss of RF switches
  - Does not support concurrent operation
- Advantages
  - Simple design
  - Can be extended to multiple bands

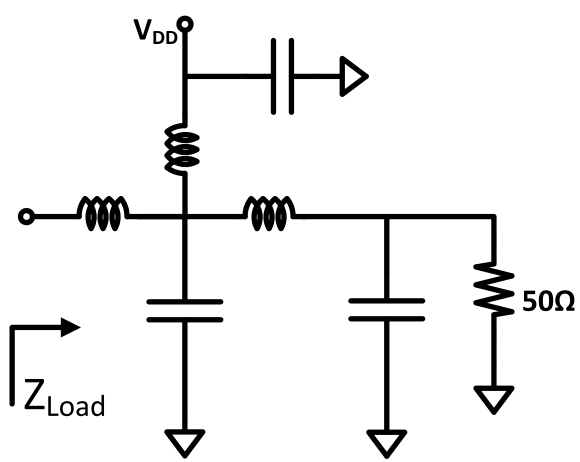



Luca Larcher et al, Design, Automation & Test in Europe Conference & Exhibition, Apr. 2009, pp.364-368.

# Transmission Line and Lumped Element Output Matching Networks

- **Transmission line OMN**
  - Disadvantages: Large area
  - Advantages: Low loss
- **Lump element OMN**
  - Advantages: Small area.
  - Disadvantages: Circuit complexity an loss increase with number of supported frequency bands (beyond 3 bands)
  - This particular lumped element OMN has no control on harmonics




Danish Kalim et al, IEEE International Microwave Symposium Digest(MTT), Jun. 2011, PP.1-4.
Koji Uchida et al, IEEE Asian-Pacific Microwave Conference Proceedings, Dec.2005.

# Outline

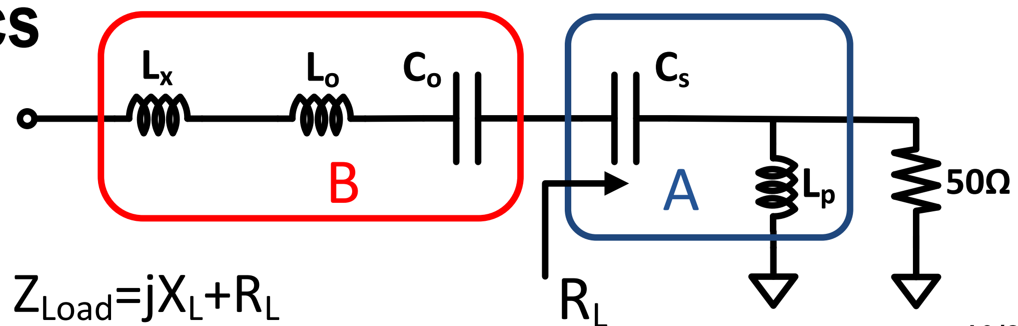
- Motivations
- Dual-Band Matching Networks for Power Amplifiers
- **Proposed Dual-Band Output Matching Networks for Class E PA**
  - **All Lumped Element Output Matching Network**
  - **Transformer-Based Output Matching Network**
- Simulation Results
- Conclusion

# Conventional Single-Band Output Matching Network for Class E PA

- Desired $Z_{Load}$=7+j8 Ω at the design frequency, and high absolute impedance at harmonics

- Part A realizes real-to-real impedance conversion, providing real part of desired impedance, $R_L$, at design frequency

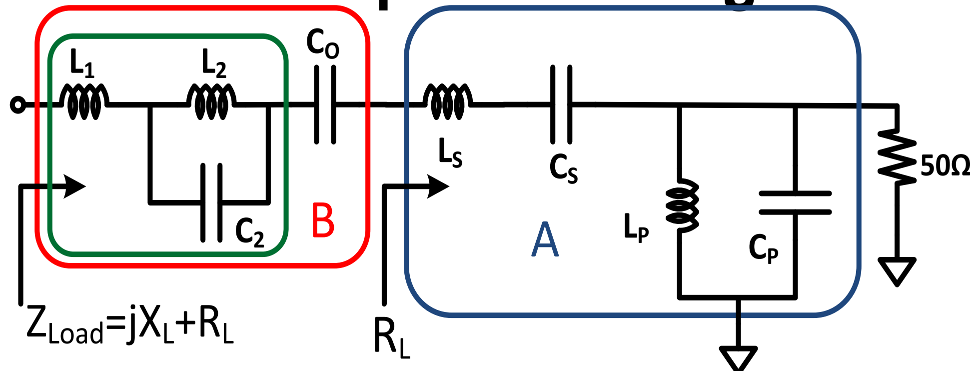
- Part B provides $X_L$ at the design frequency and high impedance at harmonics



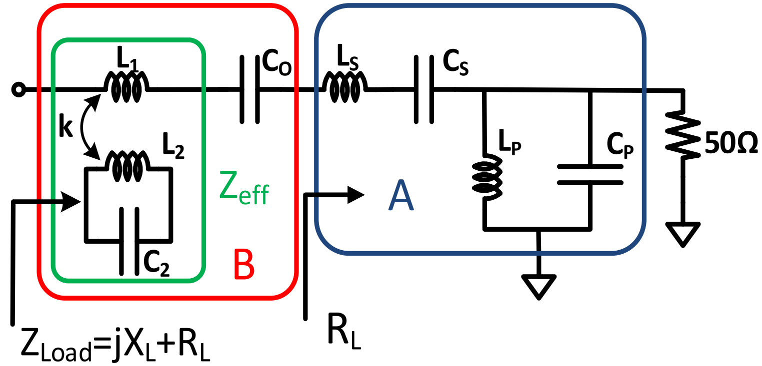
# Proposed Dual-Band Output Matching Networks for Class E PA

- Desired impedance: 7+j8 Ω @ 800MHz and 1900MHz

- Proposed all-lumped element output matching network

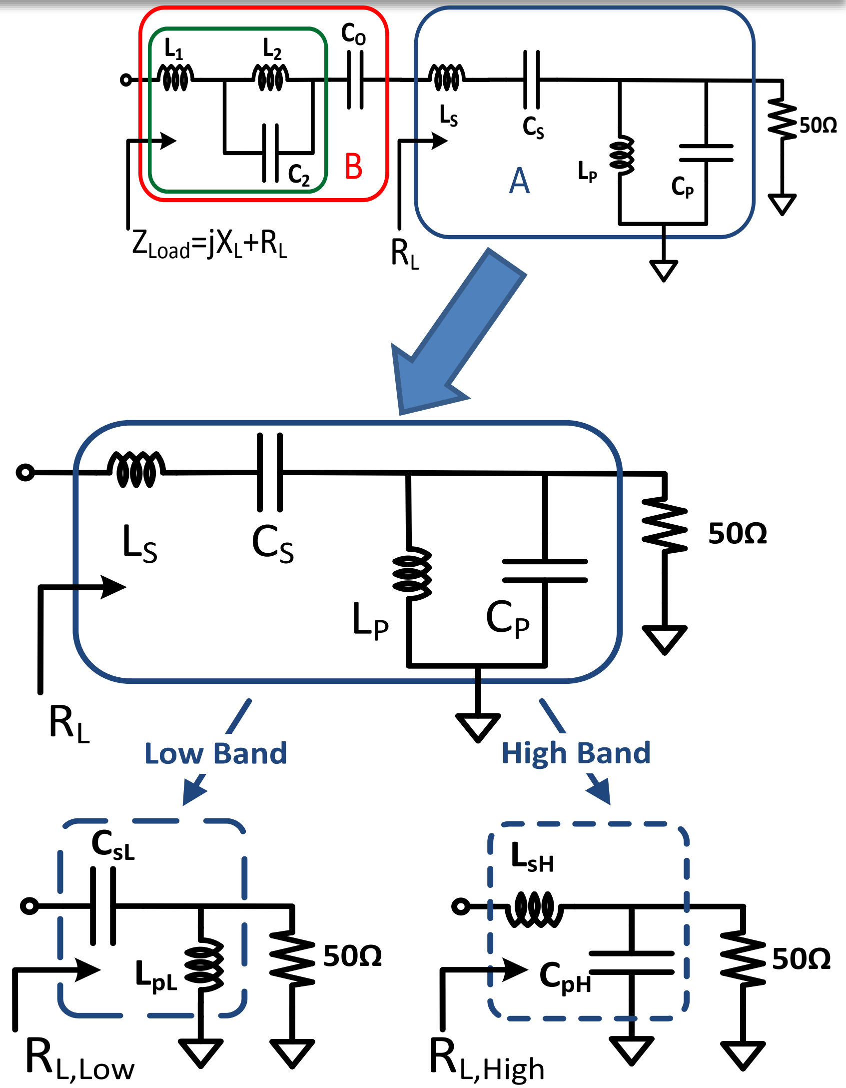



- Proposed transformer-based output matching network



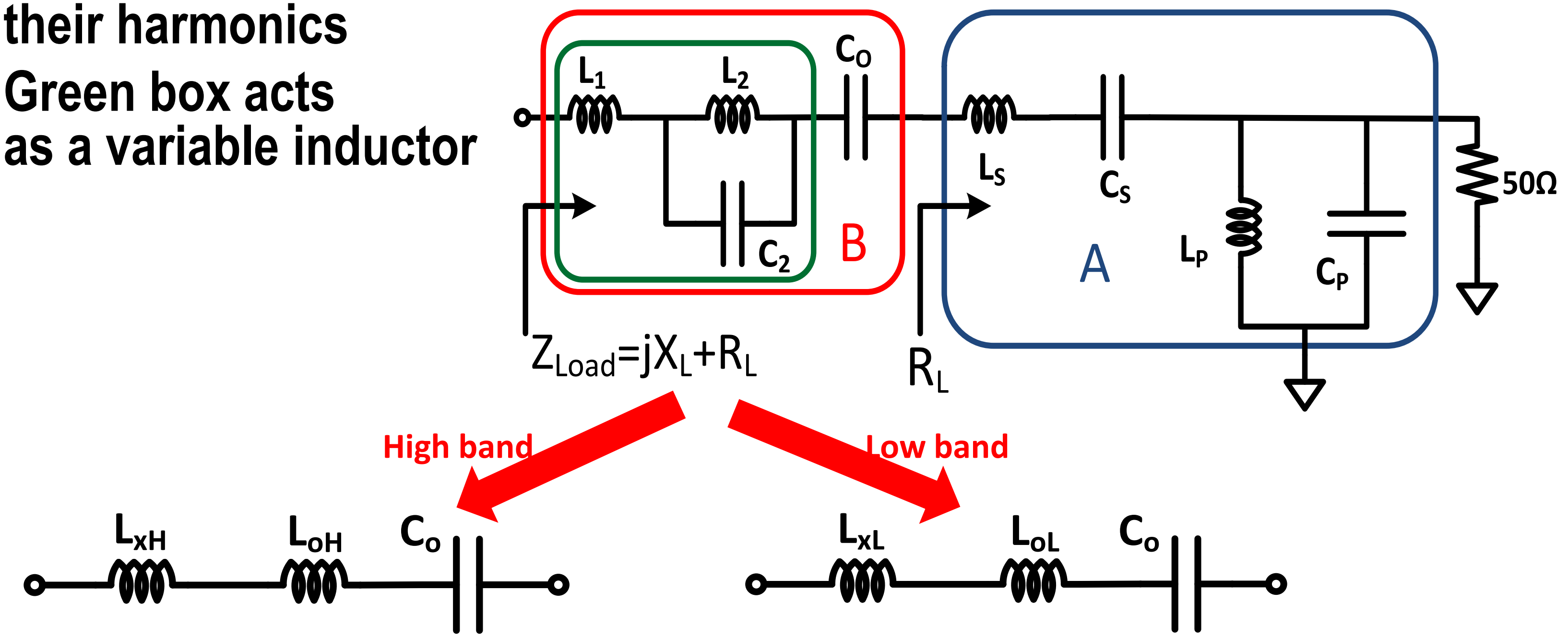
# All-Lumped Element Dual-Band OMN

- First consider the real-to-real impedance conversion
- Part A converts 50Ω to 7Ω at both frequencies
- $C_{sL}$, $L_{pL}$ form equivalent low-band L match
- $C_{sH}$, $L_{pH}$ form equivalent high-band L match
- Component values in equivalent single-band MNs can be calculated at each frequency



# All-Lumped Element Dual-Band OMN

- **Now consider the positive reactance**
  - Part B provides +j8 Ω at both frequencies and high impedance at their harmonics
  - Green box acts as a variable inductor




- **How to determine $C_O$**
  - Trade off between harmonic impedance (loss in power transistor) and loss in the matching network

# Transformer-Based Dual-Band OMN

- Part B provides +j8 Ω at both frequencies, and high impedance at their harmonics
- Green box acts as a variable inductor
  - Red part of the expression is what we used
  - The rest is parasitic resistance

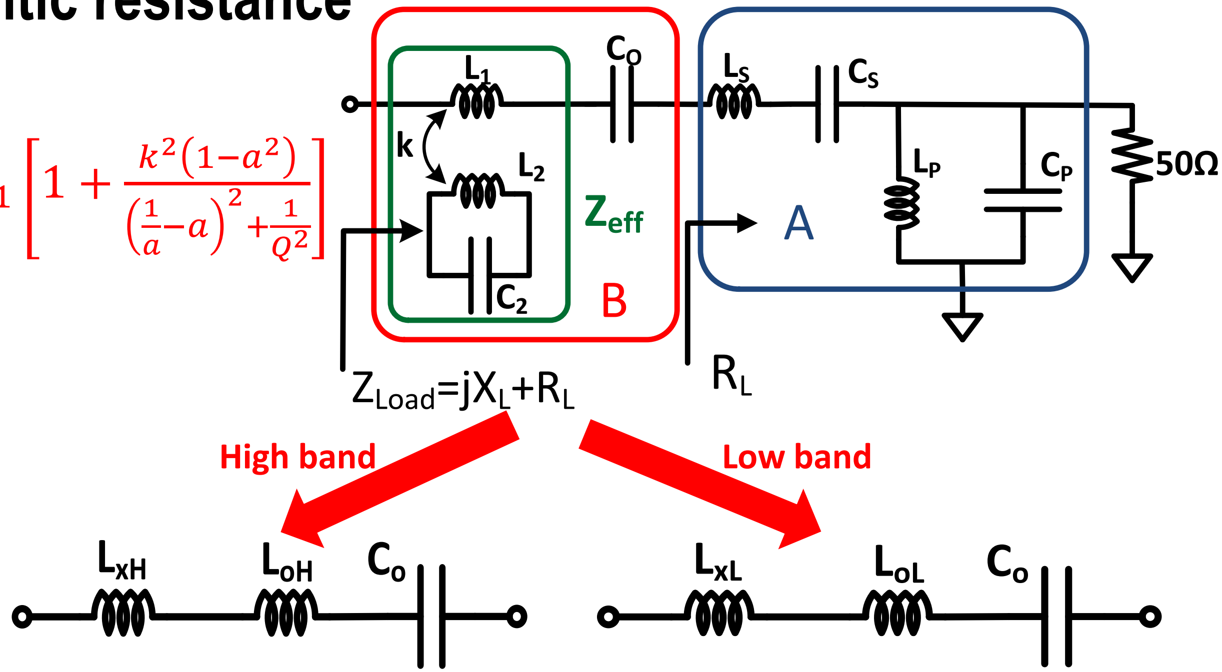
$$Z_{eff} = \omega L_1 \frac{\frac{k^2 a}{Q}}{\left(\frac{1}{a}-a\right)^2+\frac{1}{Q^2}} + j\omega L_1\left[1+\frac{k^2(1-a^2)}{\left(\frac{1}{a}-a\right)^2+\frac{1}{Q^2}}\right]$$

where

$$\omega_o = 1/\sqrt{L_2 C_2},$$

$$Q = \frac{\omega_o L_2}{R_2},$$

$$a_{(L,H)} = \omega_{(L,H)}/\omega_o$$

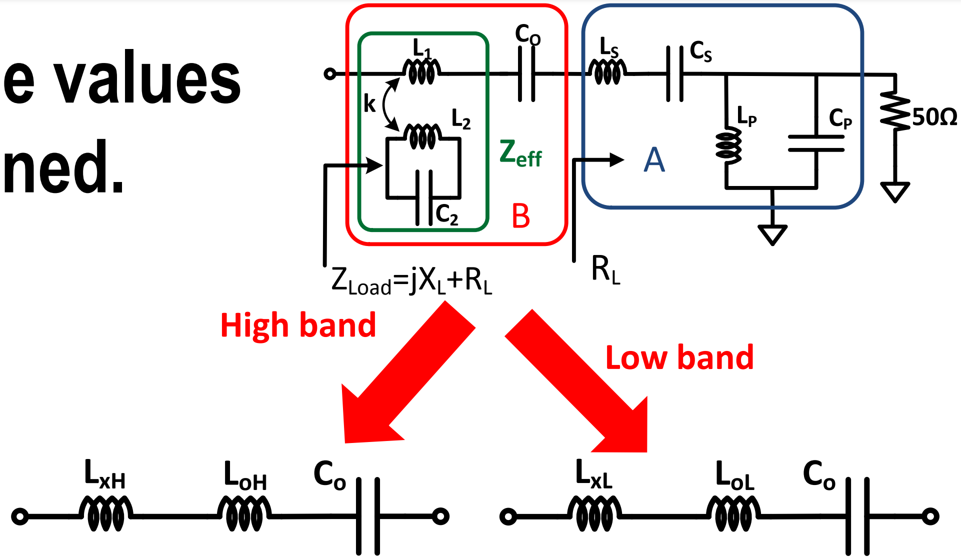


# Loss Optimization of Transformer-Based OMN

- Sweep $\omega_o$, for each $\omega_o$, the values of $L_1$ and $k$ can be determined.

$$L_1\left[1+\frac{k^2(1-a^2)}{\left(\frac{1}{a}-a\right)^2+\frac{1}{Q^2}}\right]=\omega_L(L_{XL}+L_{OL})$$

$$L_1\left[1+\frac{k^2(1-a^2)}{\left(\frac{1}{a}-a\right)^2+\frac{1}{Q^2}}\right]=\omega_H(L_{XH}+L_{OH})$$




- Loss model
  - Total loss in terms of parasitic resistance is expressed as

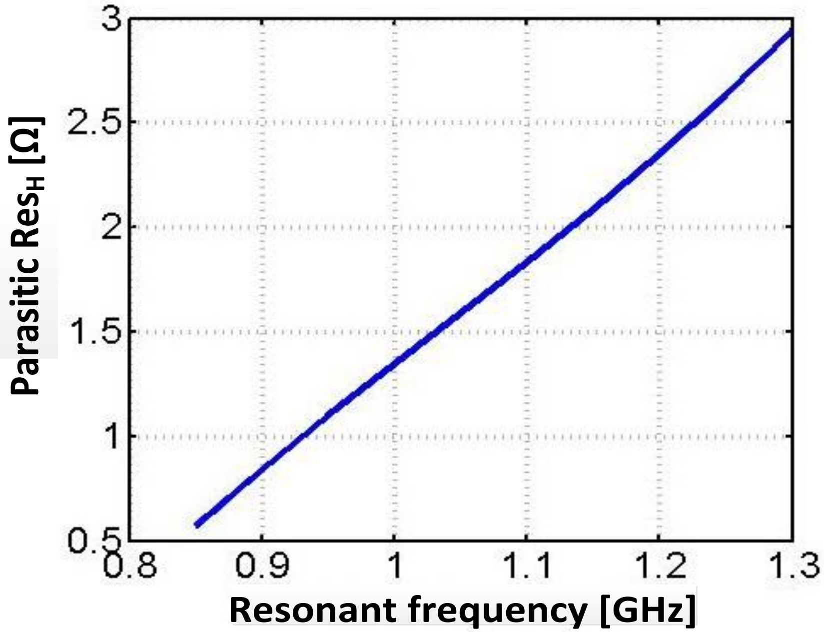
$$Parasitic\ Res(\Omega)=\omega L_1\frac{\frac{k^2a}{Q}}{\left(\frac{1}{a}-a\right)^2+\frac{1}{Q^2}}+\frac{\omega L_1}{Q_x}$$

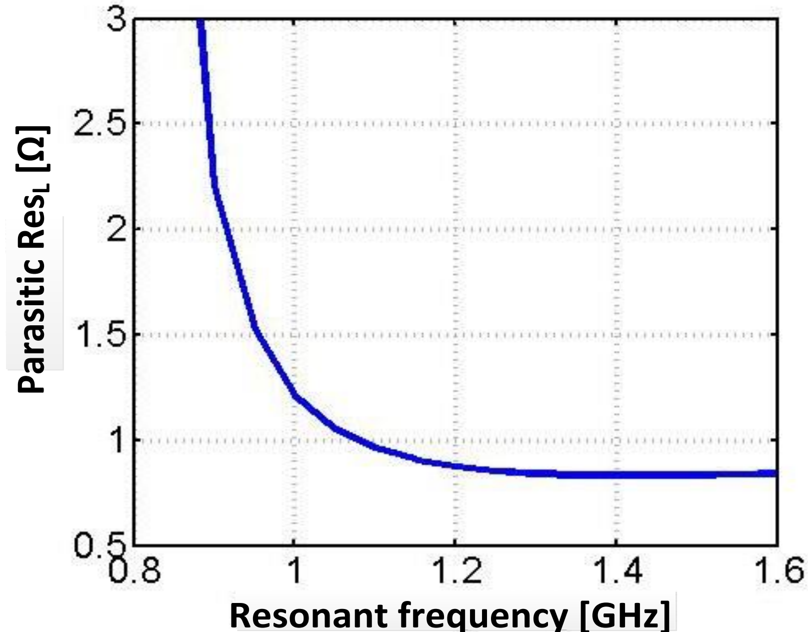
$Q_x$ is the quality factor of $L_1$ at each frequency

  - Parasitic resistance from the primary winding
  - Reflected parasitic resistance from the secondary winding

# Loss Optimization of Transformer-Based OMN

- Trade off between OMN loss and transistor loss
  - Higher harmonic impedance -> low loss in transistor
  - To increase the impedance at the 2nd harmonic of low band, $\boldsymbol{\omega_0}$ should be closer to $2f_L$.
- $\omega_o$ is set at 2π*1.25G rad/s
  - Higher loss in high band OMN
  - Higher loss in low band power transistor



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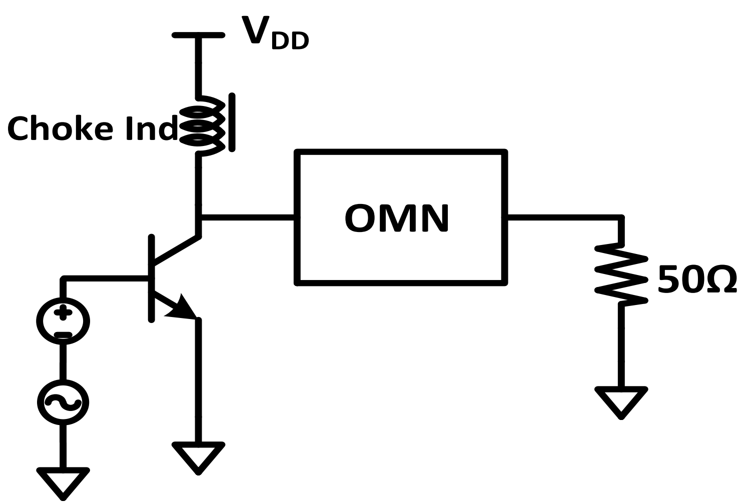
# Simulation Results

- Simulation environment
  - HBT power transistor with 3.5V power supply
  - TDK MHG0603 (mm) inductors
  - Murata GJM 0603 (mm) capacitor
  - Low DC resistance (mΩ) 1μH choke Inductor
  - Operation frequencies: 800MHz and 1900MHz
  - Substrate: 2-layer PCB with a thickness of 864μm, average dielectric constant of 3.57, metal thickness of 18μm, average loss tangent of 0.0036
- Component values

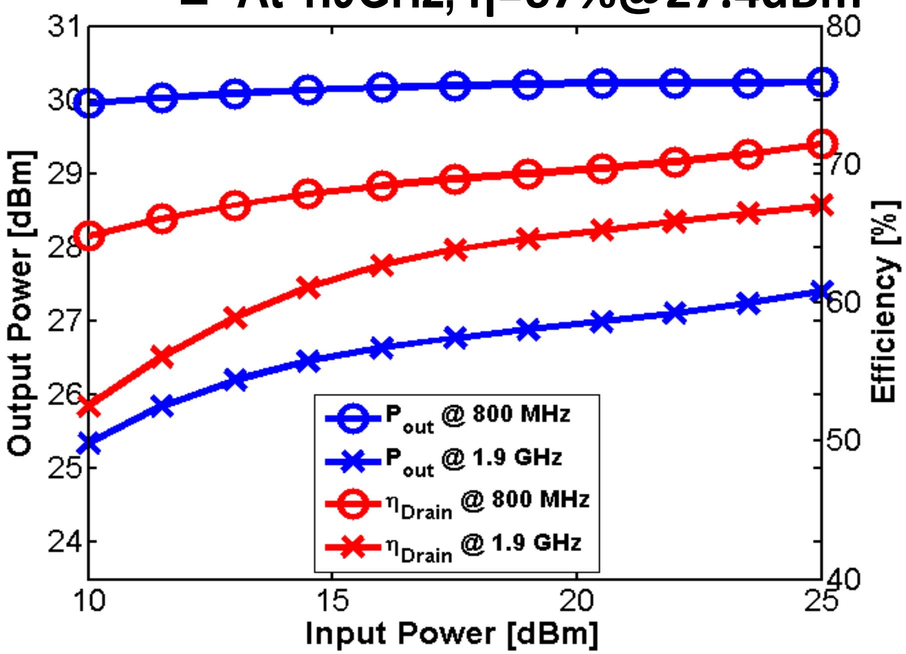
| $L_S$ (nH) | $C_S$ (pF) | $L_P$ (nH) | $C_P$ (pF) |
| --- | --- | --- | --- |
| 2.5 | 6.6 | 2.3 | 7.2 |

| | $L_1$ (nH) | $L_2$ (nH) | $C_2$ (pF) | $C_3$ (pF) | k |
| --- | --- | --- | --- | --- | --- |
| All-lumped | 7 | 3.7 | 3.5 | 3.6 | – |
| Transformer -based | 8.1 | 4 | 4.1 | 4.5 | 0.64 |

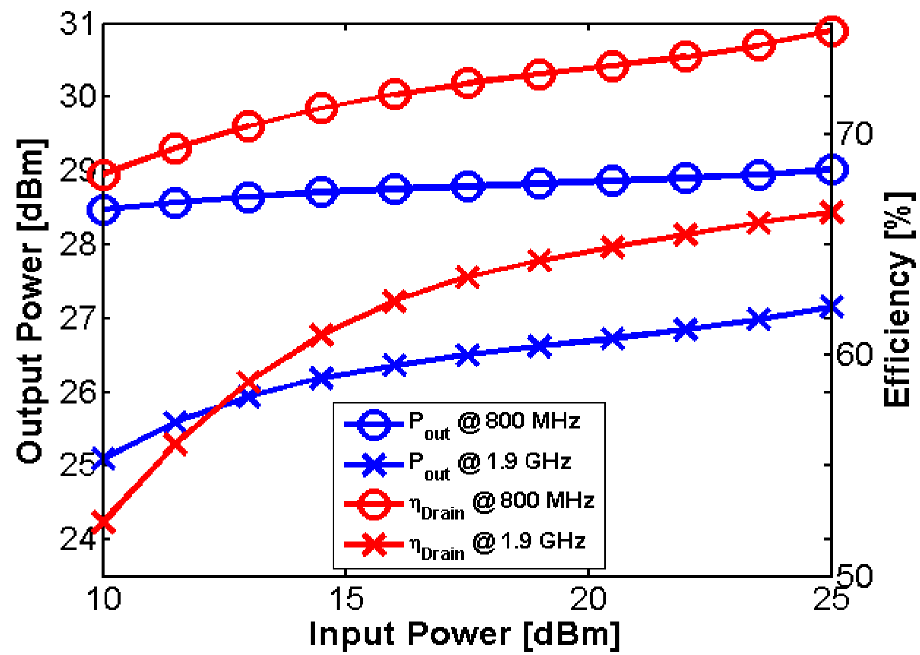


# Simulation Results

- All-lumped output matching network
  - At 800MHz, η=71%@30.2dBm
  - At 1.9GHz, η=68%@29dBm
- Transformer-based output matching network
  - At 800MHz, η=75%@30.1dBm
  - At 1.9GHz, η=67%@27.4dBm




All-lumped element




Transformer based

# Simulated Performance Comparison

| Ref | Frequency Band (GHz) | Simulated output Power* (watt/$V^2$) | Simulated Efficiency (%) | Load Type |
|---|---|---|---|---|
| [2] | 0.9/1.8 | 0.011 | η=44/40 | Switch-based/off chip |
| [3] | 1.9/2.3/ 2.6/3.5 | 0.02 | η=64/62 /59/58 | On-chip |
| [4] | 1.81/2.65 | 0.0075 | η=73.6/ 70.1 | TLs |
| [6]** | 0.8/1.5 | 0.05/0.026 | PAE=51.6/ 51.9 | Lumped/ Off chip |
| This work all-lump load network | 0.8/1.9 | 0.067/0.038 | η=75/67 | Lumped/ Off chip |
| This work transformer based | 0.8/1.9 | 0.038 | η=71/68 | Lumped/ Off chip |

* Output power normalized to $V^2_{DD}$

** Measured Result


Luca Larcher et al, Design, Automation & Test in Europe Conference & Exhibition, Apr. 2009, pp.364-368.
Ki Young Kim et al, IEEE Microwave and Wireless Components Letters, vol.21, no.7, July.2011.
Danish Kalim et al, IEEE International Microwave Symposium Digest (MTT), Jun. 2011, pp.1-4.
Koji Uchida et al, IEEE Asian-Pacific Microwave Conference Proceedings, Dec.2005.

# Conclusion

- Two compact switchless dual-band output matching networks are designed for class E power amplifier which achieve drain efficiency above 67%, with transformer-based one having a little higher efficiency.
- All-lumped element OMN is preferred when area is the main concern. Transformer could be several times larger than a lumped component.
- Transformer-based OMN is preferred when performance is the main concern. Especially with advanced substrate and thick metal. In such circumstances, transformer based PA will have higher efficiency than all-lumped element PA.

# Questions