

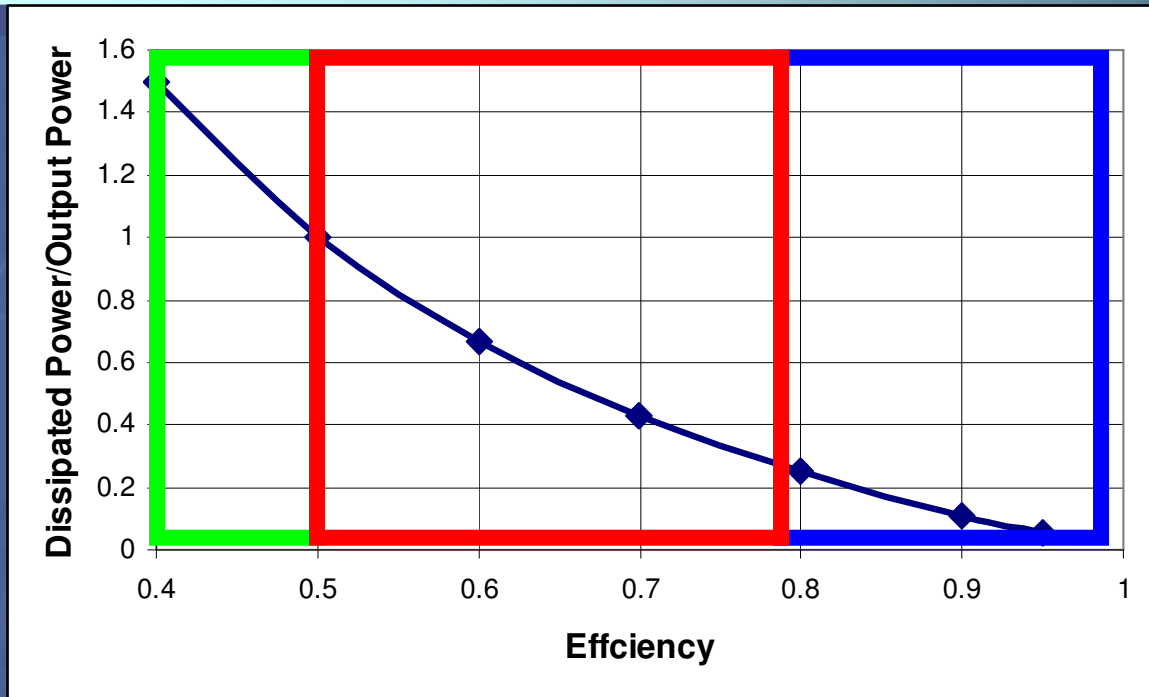
High Efficiency Class-E Amplifier Utilizing GaN HEMT Technology

William L. Pribble, Jim M Milligan, and
Raymond S. Pengelly

Cree Inc
4600 Silicon Drive,
Durham, NC 27703



Does Efficiency Matter?



- Class A
- Class B
- Switchmode
Class D,E
Class C,F?

- Increasing efficiency from 50% to 80% reduces dissipated power by 80% for a fixed output power
- Switchmode amplifier configurations can operate above 80% efficiency

Problem: Extend switchmode operating frequency beyond VHF

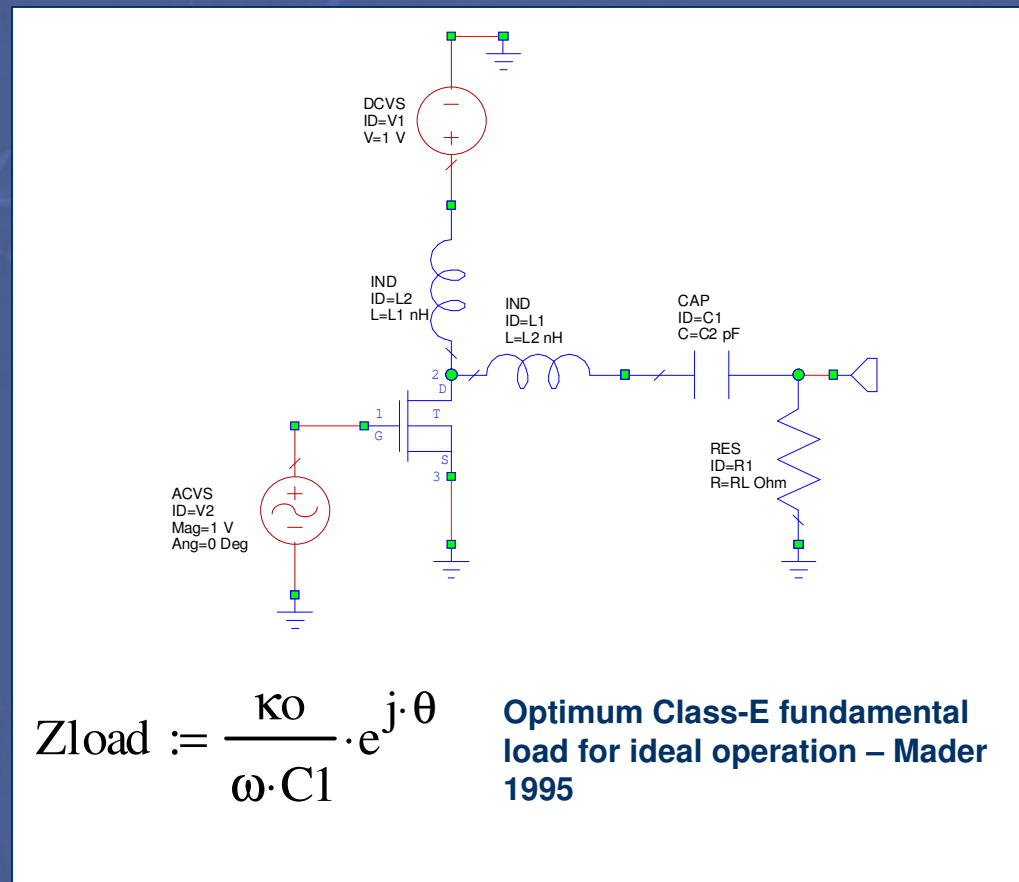


Why Switch Mode Amplifiers?

- With a suitable high frequency transistor technology they offer very high efficiencies compared with Class A/B amplifiers
- GaN HEMT technology is ideal
 - High f_T
 - Low input capacitance
 - Manageable output capacitance
 - Low $R_{DS(on)}$
- GaN HEMT is the first technology to offer the ability of realizing switch mode amplifiers to well over 3.5 GHz!

Class E Amplifier Basics

- FET used as switch is assumed to have high off-resistance
- Switch on-resistance assumed to be constant and must be minimized to achieve high PAE
- Output capacitance assumed to be independent of switch voltage
- Q factor of output circuit assumed large enough to suppress harmonics – “flywheel” effect insures sinusoidal output



Class E Power Calculations

$$V_{CC} := \sqrt{\frac{P_{out} \cdot r_l}{0.577}}$$

Relates peak output power for ideal class-E waveforms to supply voltage – This value is ~78% of peak Class-B output power

- To achieve peak Class-E output power as shown, peak voltage is calculated to be $3.56V_{CC}$, peak drain current $2.86I_{DC}$ (Solid State Radio Engineering – Krauss, Bostian, Raab)
- Typical class-B voltage waveforms peak at ~2X the supply voltage
- Ideal class-E operation produces lower power for higher peak voltage – *but with 100% efficiency*

The optimum class-E device must exhibit both low R_{on} and high breakdown voltage to function as a switch

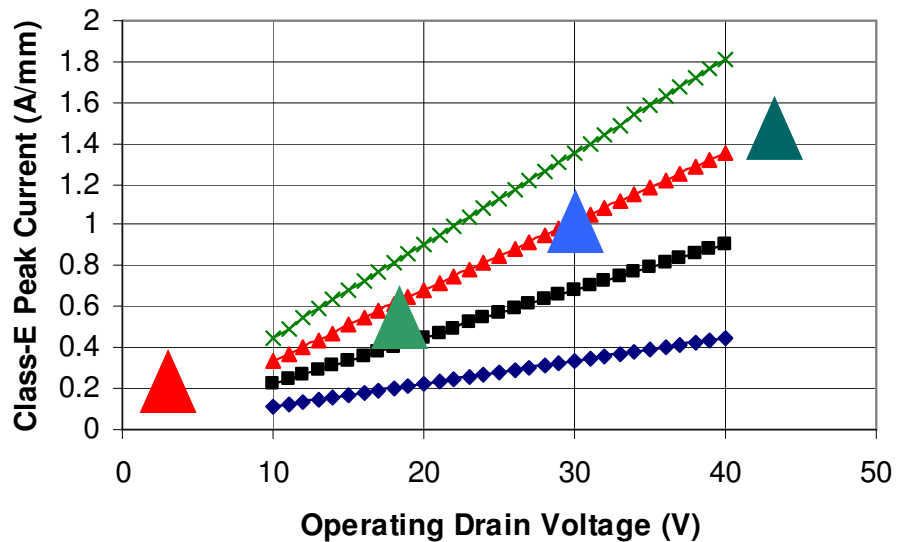


Basic Class E Equations/Limitations

$$f_{\max} := \frac{I_{\max}}{56.5 \cdot 10^{-12} \cdot C_1 \cdot V_{CC}}$$

$C_1 = C$

Fundamental frequency limit for ideal class-e operation related to output capacitance



GaAs PHEMT

High-Voltage GaAs

Cree GaN – qualified process available 1st quarter 2006

Cree GaN Process Goal

Plot shows required peak current vs supply voltage for operation at 4GHz for given output capacitance

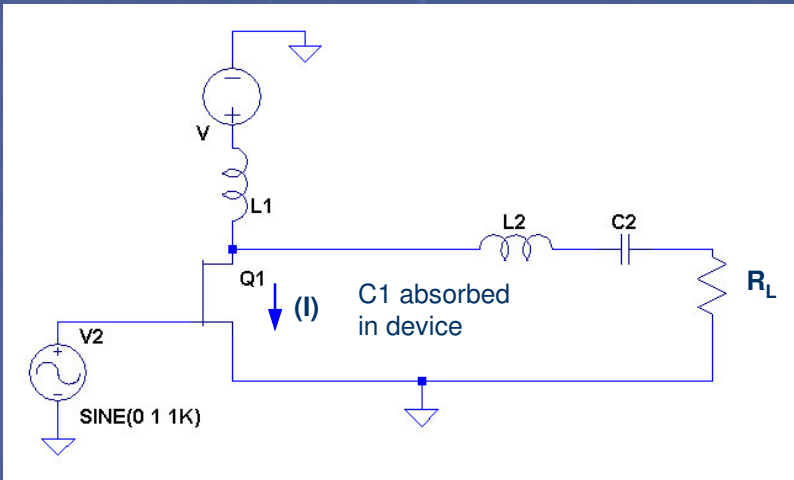


Summary of Class-E Device Requirements

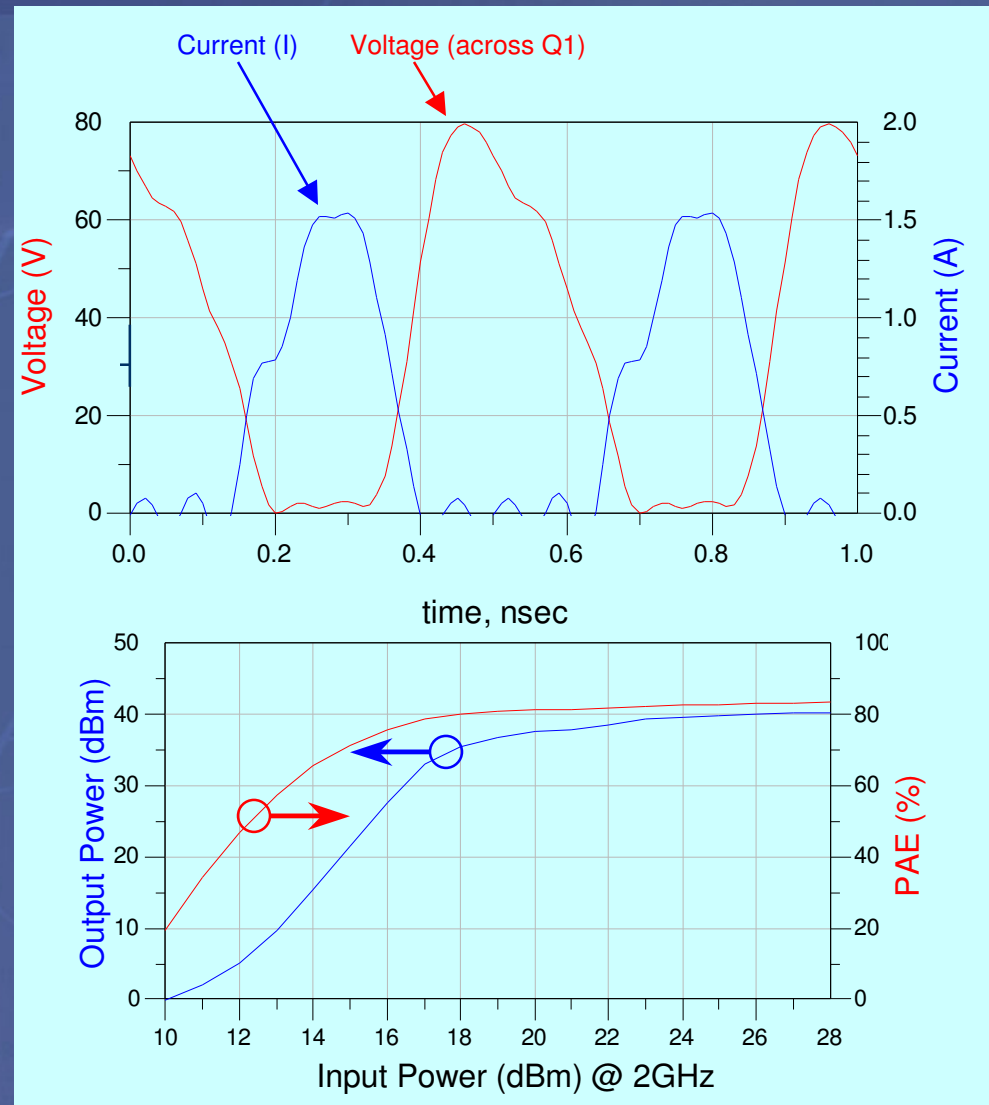
- High switching speed (related to input capacitance) required for switchmode operation – F_t as much as 10X operating frequency to minimize transition-time loss
- Low on-resistance/high peak current to approximate ideal switch and increase peak operating frequency
- High breakdown voltage to accommodate class-E peak voltage for > 50 watt output power

Gallium Nitride HEMT is the only presently available technology which provides these attributes

Class-E Switch Mode Amplifier Simulation using Cree GaN HEMT Large-Signal Model

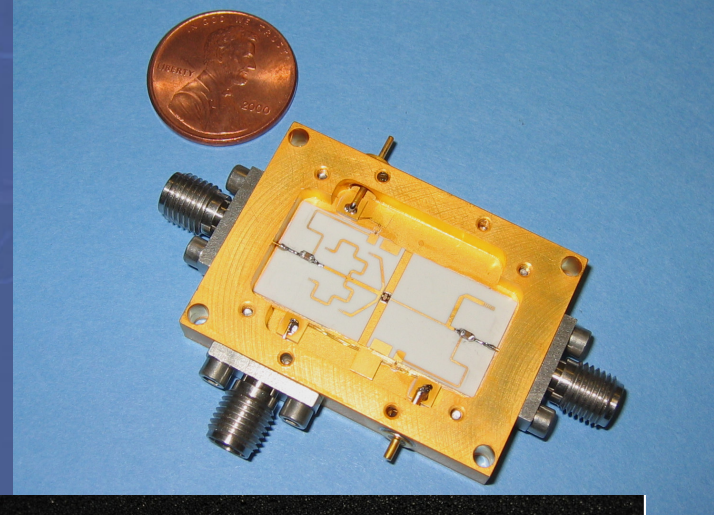
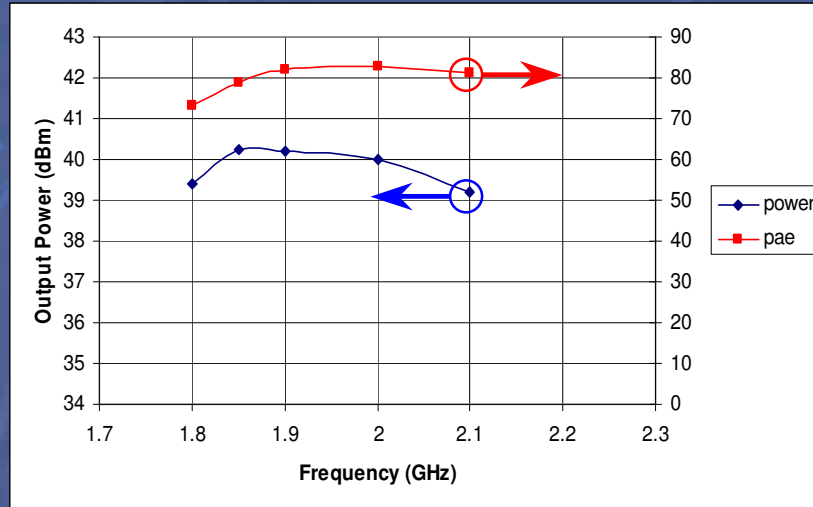


- Freq = 2.0 GHz
- Q1 = Cree 15 watt GaN HEMT
- $R_{ON} = 1.7\Omega$
- $V_D = V = 35V$
- $R_L = 26\Omega$, $C1 = 0.64pF$, $L1 = 50\mu H$
- $L2 = 13nH$, $C2 = 0.612pF$
- $P_{OUT} = 10$ Watts, $\eta = 82\%$



World Record 2.0 GHz High Efficiency GaN Amplifier

Measured Performance @ 30 V



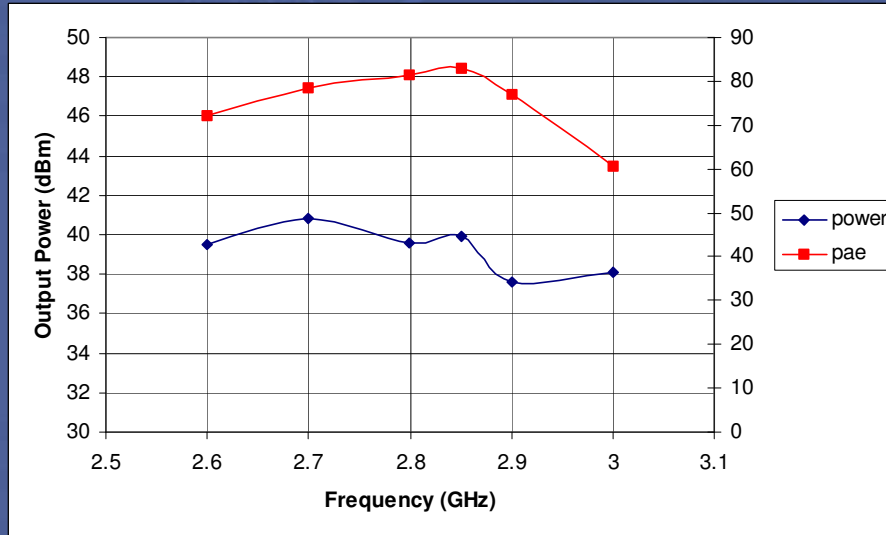
- Class E Hybrid amplifier
- $V_d = 30$ volts
- 50Ω input/output
- $10\text{ W } P_{\text{OUT}}$, **88% Drain Efficiency!**
 - 1.9 – 2.1 GHz!



CREE 

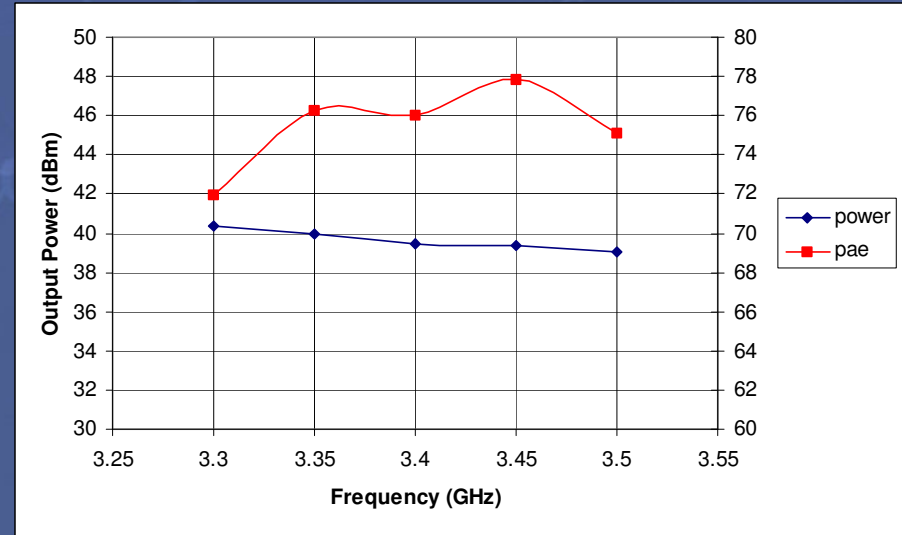
Approach Validated at Higher Frequencies and Moderate Bandwidths

Measured Data



- ~10 Watts RF Out
- 12 dB Power Gain
- 76-82% PAE
- 2.7 – 2.9 GHz

Measured Data

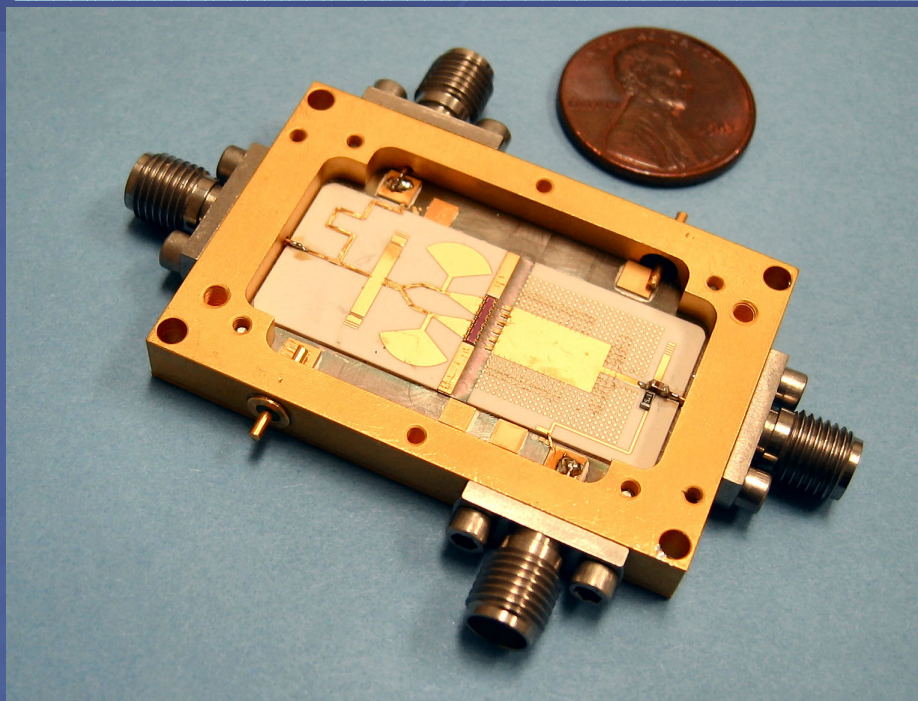


- ~10 Watts RF Out
- 11 dB Power Gain
- 72-78% PAE
- 3.3 – 3.5 GHz

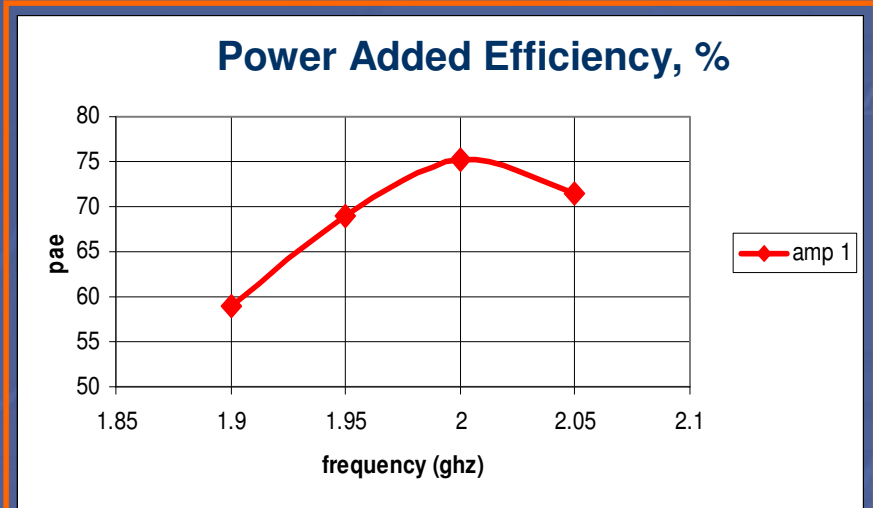
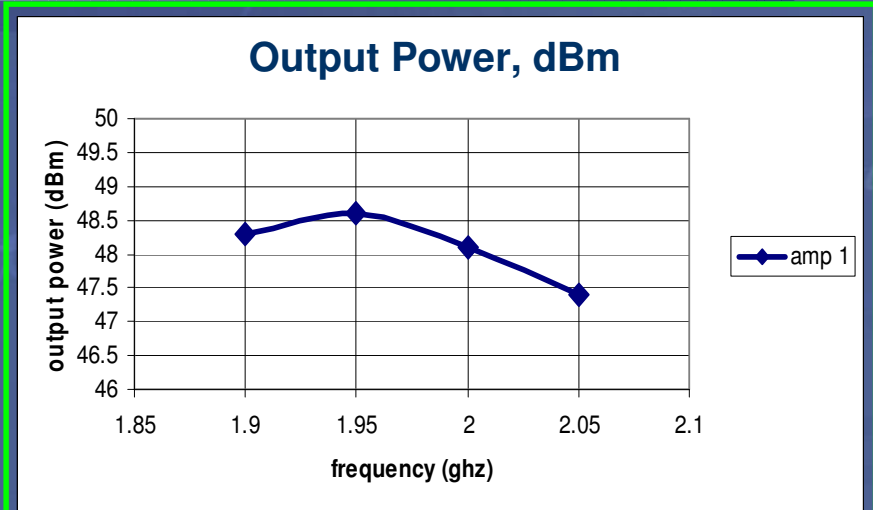
Cree's GaN Technology Enables High-Power High Frequency Class-E Operation



Approach Validated at Higher Power Levels



- 63 Watts Peak RF Output Power
- 18 dB Power Gain
- 75% PAE
- 2 GHz Operation



Summary

- **GaN HEMT-Class E amplifier / ET demonstrated linear PAE of 54%**
 - Much Superior to GaAs MESFET and LDMOSFET
 - Demonstrates “leapfrog” in efficiency when compared to conventional Class A/B biased amplifiers deployed today
 - High Power GaN HEMT-Class E modules built & measured
 - Overall efficiency in ET system at 56% with 20 Watts average power under CDMA 2000
 - Approach suitable for telecom. bands including 3.5GHz WiMax