

Simple Method of Changing the Frequency Range of a Power Amplifier Circuit

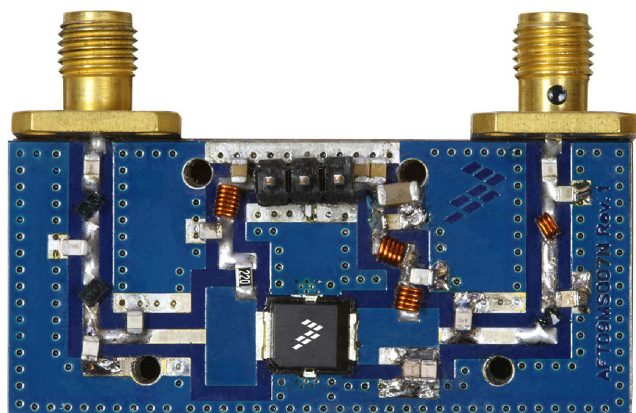
Amplifier designers often face the challenge of modifying an existing circuit optimized for one frequency range to operate over a different and perhaps wider frequency range, which may be higher or lower in frequency, using the same RF power transistor or transistors. This situation occurs when a manufacturer wants to reduce the number of designs required to cover its product portfolio or to create custom products to meet the needs of a specific application in a short time. When manufacturers meet market requirements with fewer designs, they can reduce cost, complexity, and time to market.

Given an unlimited amount of time and budget, the ideal approach would be to create an entirely new design, requiring extensive simulation and a new circuit board, assuming the new frequency range is within the capabilities of the transistor. However, this being a less-than-ideal world, there is often neither the time nor budget available to take this approach. Fortunately, as this application note will show, if the design is single-ended and has no complicated matching sections, it is reasonably easy to extend or shift the bandwidth of the existing circuit design without resorting to extensive resimulation, a new PCB, and many component changes. The approach reduces the time required for the transformation from weeks to as little as one day.

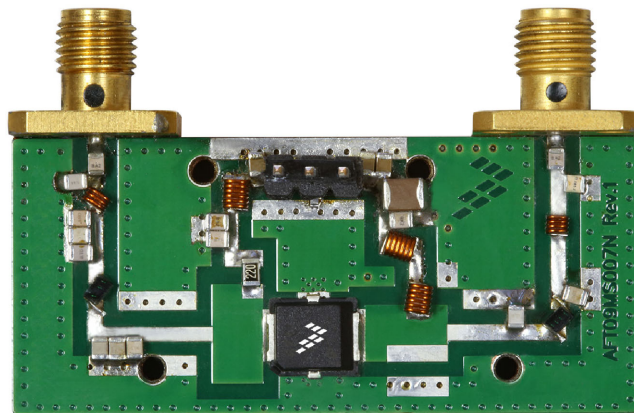
The Challenge

This discussion is based on an actual situation that occurred at Freescale when an evaluation board (Figure 1) that was created using Freescale's 7 W AFT09MS007N Airfast RF power LDMOS transistor to cover a 70 MHz frequency range of 450 to 520 MHz later had to be modified to cover a 120 MHz frequency range of 350 to 470 MHz. The gain, RF output power, and efficiency of the original design were to be maintained. The time available to complete the design did not allow for extensive resimulation or a PCB revision.

The AFT09MS007N is an unmatched RF power transistor designed for use in battery-operated, handheld radios that have a supply voltage of about 7.5 Vdc. This transistor can be matched to operate over various sub-bands within its frequency range of 136 to 941 MHz and can deliver more than 7 W RF output power from 200 mW of drive. Broadband circuit efficiency can exceed 70%. The extremely rugged device operates into a VSWR greater than 65:1 at all phase angles without degradation, even when driven at twice its rated drive power and 30% overvoltage. It includes an internal electrostatic discharge protection circuit that protects the MOSFET gate structure from short duration, high-voltage



450 to 520 MHz



350 to 470 MHz

Figure 1. 7 W AFT09MS007N RF Power LDMOS Transistor

Table 1. 450–520 MHz UHF Broadband Performance (In Freescale Reference Circuit, 50 ohm system)

$V_{DD} = 7.5$ Volts, $I_{DQ} = 150$ mA, $T_A = 25^\circ\text{C}$, CW

Frequency (MHz)	P_{in} (W)	G_{ps} (dB)	η_D (%)	P_{out} (W)
450	0.21	15.4	57.7	7.5
485	0.21	15.5	56.0	7.5
520	0.18	16.2	66.3	7.5

Table 2. 350–470 MHz UHF Broadband Performance (In Freescale Reference Circuit, 50 ohm system)

$V_{DD} = 7.5$ Vdc, $I_{DQ} = 200$ mA, $T_A = 25^\circ\text{C}$, CW

Frequency (MHz)	P_{in} (W)	G_{ps} (dB)	η_D (%)	P_{out} (W)
350	0.15	16.6	60.9	7.3
410	0.15	16.6	66.5	7.3
470	0.20	15.6	70.1	7.3

discharge that may be encountered during assembly. The transistor is housed in an over-molded plastic package. Its key specifications are shown in Table 1.

Getting Started

The original 450 to 520 MHz circuit delivered the gain, efficiency, and output power versus a fixed input power of 7.5 V shown in Figure 2. The Iowa Hills Smith Chart program from Iowa Hills Software¹ was used to determine if simple Smith chart software rather than comprehensive design software

could be used to facilitate the frequency shift. This software is one of many free Smith chart programs available on the web. The transmission line parameter calculator from Clemson University² was used to estimate the degrees of separation and impedance of the transmission line. Other calculators are also available, including the Freescale Engineering Tools³ app for Android and iPhone, Transmission Line Calc for iPhone from Black Cat Systems, and TX-LINE, a Windows[®]-based transmission line calculator from AWR⁴.

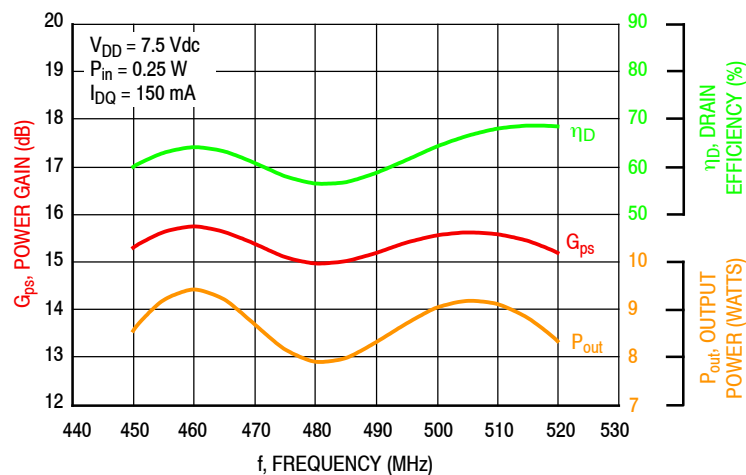
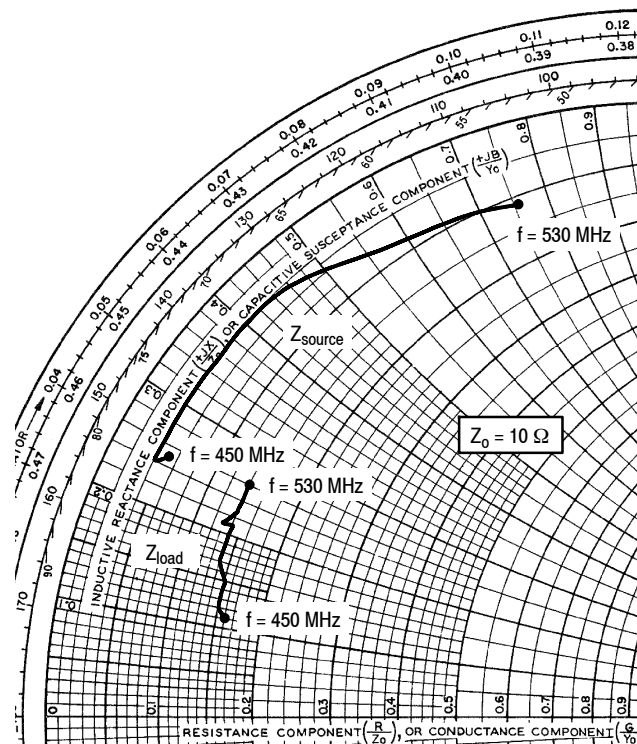


Figure 2. 450–520 MHz Power Gain, Output Power and Drain Efficiency versus Frequency at a Constant Input Power — 7.5 V



$V_{DD} = 7.5 \text{ Vdc}$, $I_{DQ} = 150 \text{ mA}$, $P_{out} = 7.5 \text{ W}$

f MHz	$Z_{source} \Omega$	$Z_{load} \Omega$
450	$0.45 + j2.46$	$1.56 + j1.05$
460	$0.40 + j2.37$	$1.52 + j1.24$
470	$0.40 + j2.97$	$1.46 + j1.51$
480	$0.38 + j3.56$	$1.39 + j1.71$
490	$0.41 + j4.16$	$1.35 + j2.06$
500	$0.51 + j4.79$	$1.34 + j2.06$
510	$0.70 + j5.54$	$1.37 + j2.30$
520	$0.93 + j6.44$	$1.40 + j2.50$
530	$1.14 + j7.56$	$1.42 + j2.62$

Z_{source} = Test circuit impedance as measured from gate to ground.

Z_{load} = Test circuit impedance as measured from drain to ground.

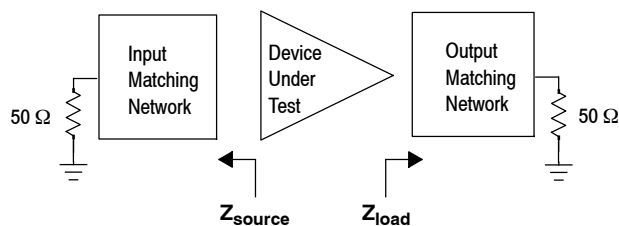


Figure 3. UHF Broadband Series Equivalent Source and Load Impedance — 450–520 MHz

First, experimental tuning was employed to shift the frequency directly from the test bench. The tuning was based on tuning tips written when the 450 to 520 MHz design was completed. This allowed the achievement of a 70 MHz bandwidth from 400 to 470 MHz. More tuning resulted in a bandwidth of 85 MHz from 380 to 465 MHz, but the desired 120 MHz bandwidth from 350 to 470 MHz remained elusive. At this point it appeared that only a redesign could solve the problem, but as this would have required significantly more time, including the time required to obtain materials, a different approach was selected.

The Solution

To meet the challenge, the current PCB, its microstrip transmission lines, and the position of the lumped element were retained to save time and cost. The transmission line impedances were calculated in the transmission line program based on the material properties of the board. Shunt capacitors and series inductors used in the original design were maintained and their values optimized. An adjustment of the transmission line characteristics between these lumped components would have required a PCB revision.

The Iowa Hills Smith Chart program uses a combination of fixed and optimized values to achieve the desired impedance

transformation. The starting position in a 50 ohm system at the RF input or output is assumed to be $50 + j0$ ohms, so the Z_0 of the Smith chart is then 50 ohms. For the AFT09MS007N, the gate and drain impedances were each expected to be around 2 to 3 ohms based on interpolation between known narrowband impedances at 136 MHz and broadband impedance from 450 to 520 MHz (the bandwidth of the original circuit). The impedance of LDMOS transistors typically increases as frequency decreases because the reactive part of the impedance is more capacitive, causing the impedance to be inversely proportional to frequency. The capacitive reactance $X_C = 1/(2\pi \times f_0 \times C)$.

As can be seen from the Smith chart (Figure 4), the transformation plot follows a tighter Q circle than the actual measurements portray, because here ideal components and approximations are used. In the future, the circuit could be designed for a tighter Q circle with the knowledge that bandwidth could be maintained in the physical circuit with limitations on accuracy.

The impedance was transformed with three matching sections of shunt capacitor plus series inductor following a reasonable Q circle across the Smith chart. The Q was determined via the classic method, $Q = \text{center frequency} / \text{bandwidth}$.

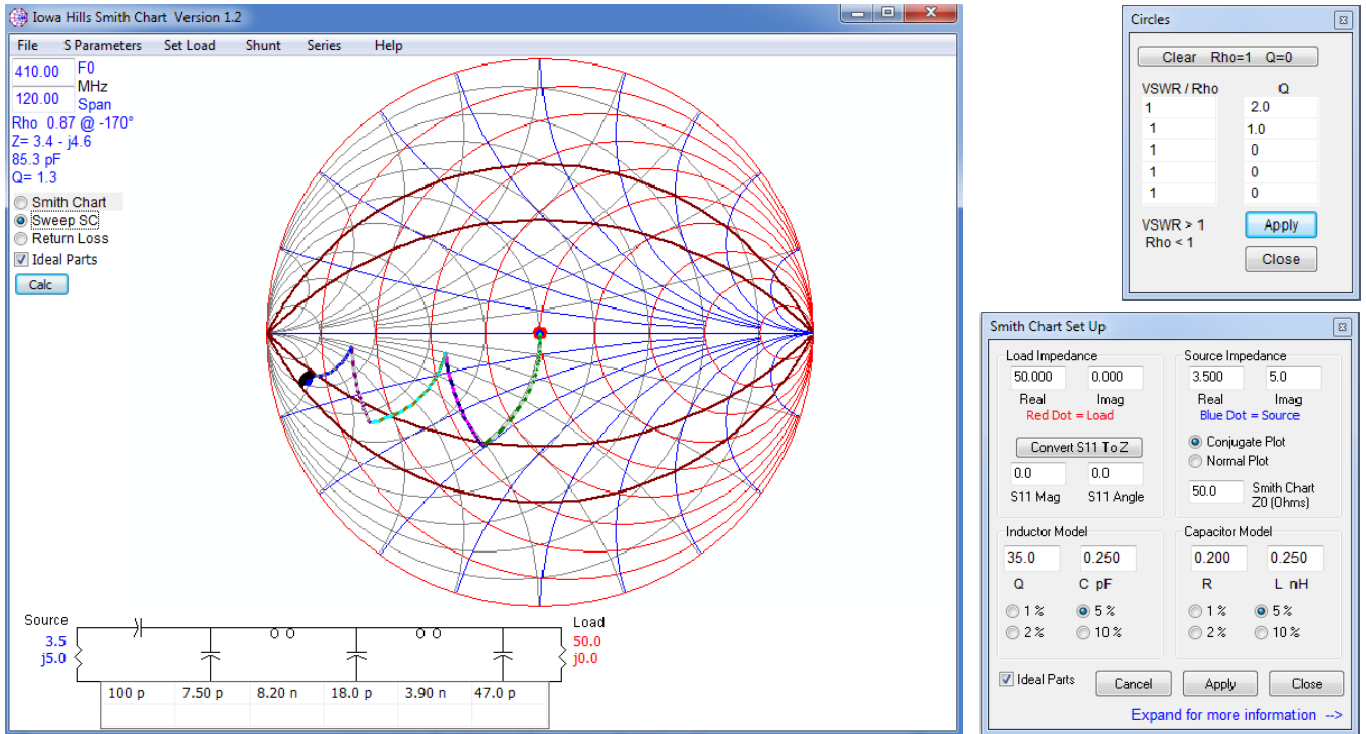


Figure 4. Smith Chart¹ — 350–470 MHz

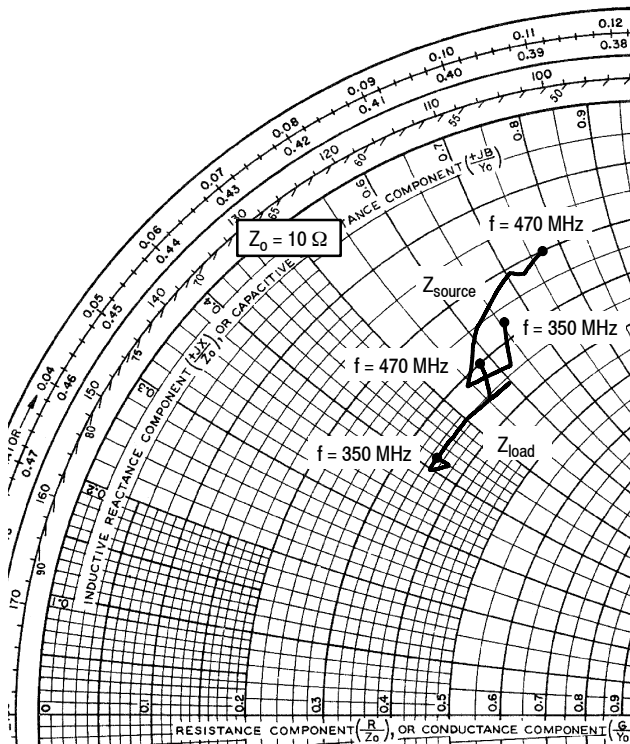


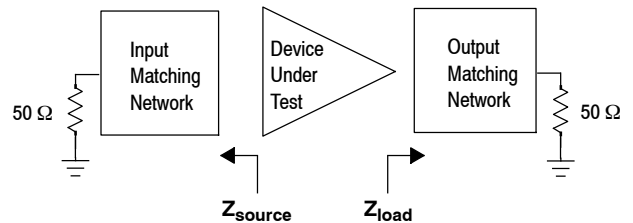
Figure 5. UHF Broadband Series Equivalent Source and Load Impedance — 350–470 MHz

$V_{DD} = 7.5 \text{ Vdc}$, $I_{DQ} = 200 \text{ mA}$, $P_{out} = 7.3 \text{ W}$

f MHz	$Z_{\text{source}} \Omega$	$Z_{\text{load}} \Omega$
350	2.7 + j6.6	3.5 + j4.2
370	3.3 + j6.2	3.7 + j4.2
390	3.1 + j5.4	3.5 + j4.0
410	2.6 + j6.1	3.5 + j5.0
430	2.1 + j7.1	3.6 + j5.9
450	2.2 + j7.3	3.6 + j5.6
470	2.0 + j7.7	3.0 + j5.8

Z_{source} = Test circuit impedance as measured from gate to ground.

Z_{load} = Test circuit impedance as measured from drain to ground.



Optimization

The process of optimization in the Smith Chart program consisted of checking multiple frequencies across the band of interest, making sure that the resulting impedances for 350 and 470 MHz were not too distant from each other. (Such impedances are a hallmark of broadband design.) Once the optimal output match was determined in the Smith Chart program, the components were changed, and focus moved to the input-side transformation. The same process was

followed: The components on the RF input were modified, and the new circuit design was taken to the test bench.

Using a vector network analyzer, $S(1,1)$ was checked, and a few components were adjusted on the input match to improve the input return loss to ensure optimal gain and to center the frequency response. It became obvious from this exercise that the new match was superior to the old one, which was saved for comparison. The new match improved the return loss by twice the value and did so across a wider frequency. It was then time for the large-signal test.

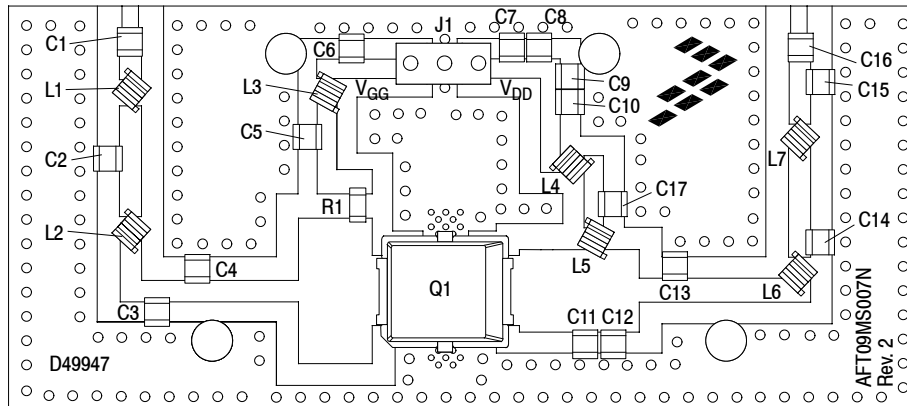


Figure 6. AFT09MS007NT1 UHF Broadband Reference Circuit Component Layout — 450–520 MHz

Table 3. AFT09MS007NT1 UHF Broadband Reference Circuit Component Designations and Values — 450–520 MHz

Part	Description	Part Number	Manufacturer
C1, C16	100 pF Chip Capacitors	ATC600F101JT250XT	ATC
C2	7.5 pF Chip Capacitor	GQM2195C2E7R5BB12D	Murata
C3	5.6 pF Chip Capacitor	ATC600F5R6BT250XT	ATC
C4	39 pF Chip Capacitor	ATC600F390JT250XT	ATC
C5, C9	240 pF Chip Capacitors	ATC600F241JT250XT	ATC
C6, C7	0.1 μ F Chip Capacitors	GRM21BR71H104KA01B	Murata
C8	0.01 μ F Chip Capacitor	GRM21BR72A103KA01B	Murata
C10	2.2 μ F Chip Capacitor	GRM31CR71H225KA88L	Murata
C11, 12	12 pF Chip Capacitors	ATC600F120JT250XT	ATC
C13	8.2 pF Chip Capacitor	ATC600F8R2BT250XT	ATC
C14	20 pF Chip Capacitor	ATC600F200JT250XT	ATC
C15	2 pF Chip Capacitor	ATC600F2R0BT250XT	ATC
C17	47 pF Chip Capacitor	ATC600F470JT250XT	ATC
J1	3-pin Header	22-28-8360	Molex
L1	2.55 nH Inductor	0906-3JLC	Coilcraft
L2	3.85 nH Inductor	0906-4JLC	Coilcraft
L3	22 nH Inductor	0908SQ22N	Coilcraft
L4, L5	17 nH Inductors	0908SQ17N	Coilcraft
L6	1.65 nH Inductor	0906-2JLC	Coilcraft
L7	8.1 nH Inductor	0908SQ8R1N	Coilcraft
R1	22 Ω , 1/10 W Chip Resistor	RR1220Q-220-D	Susumu
Q1	RF Power LDMOS Transistor	AFT09MS007NT1	Freescale
PCB	Shengyi S1000-2, 0.020", $\epsilon_r = 4.8$	D49947	MTL

Initial efficiency was low, but the desired output power was achieved across the entire 120 MHz bandwidth and actually extended to 300 MHz. After about a half hour of tuning, the bandwidth was tightened to the 350 to 470 MHz specification,

the efficiency met the required minimum of at least 60%, gain was reasonably flat, and output power with a fixed input power of 250 mW was at least 7 W. The desired performance was obtained in less than one day of redesign and testing.

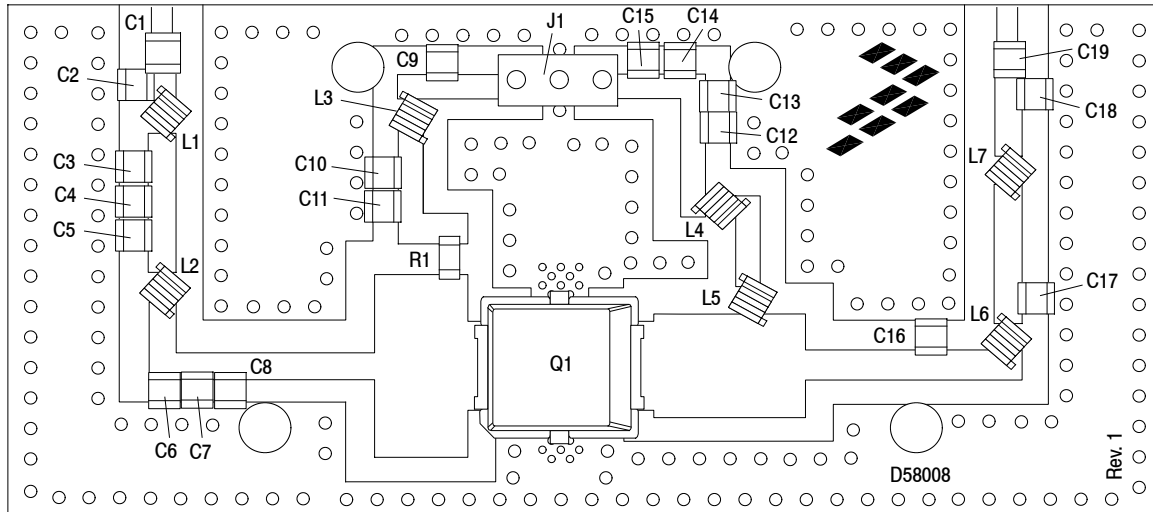


Figure 7. AFT09MS007NT1 UHF Broadband Reference Circuit Component Layout — 350–470 MHz

Table 4. AFT09MS007NT1 UHF Broadband Reference Circuit Component Designations and Values — 350–470 MHz

Part	Description	Part Number	Manufacturer
C1, C10, C19	100 pF Chip Capacitors	ATC600F101JT250XT	ATC
C2	10 pF Chip Capacitor	ATC600F100JT250XT	ATC
C3	3.0 pF Chip Capacitor	ATC600F3R0BT250XT	ATC
C4, C8	27 pF Chip Capacitors	ATC600F270JT250XT	ATC
C5	5.1 pF Chip Capacitor	ATC600F5R1BT250XT	ATC
C6, C7	30 pF Chip Capacitors	ATC600F300JT250XT	ATC
C9	10 nF Chip Capacitor	C1210C103J5GAC-TU	Kemet
C11	82 pF Chip Capacitor	ATC600F820JT250XT	ATC
C12	240 pF Chip Capacitor	ATC600F241JT250XT	ATC
C13	2.2 μ F Chip Capacitor	C3225X7R1H225K250AB	TDK
C14	0.1 μ F Chip Capacitor	GRM21BR71H104KA01B	Murata
C15	0.01 μ F Chip Capacitor	GRM21BR72A103KA01B	Murata
C16	47 pF Chip Capacitor	ATC600F470JT250XT	ATC
C17	18 pF Chip Capacitor	ATC600F180BT250XT	ATC
C18	7.5 pF Chip Capacitor	ATC100A7R5JT150XT	ATC
J1	3-pin Header	22-28-8360	Molex
L1	8.1 nH Inductor	0908SQ8N1	Coilcraft
L2	2.55 nH, 3 Turn Inductor	0906-3JLC	Coilcraft
L3, L4, L5	21.5 nH Inductors	0908SQ22N	Coilcraft
L6	3.85 nH, 4 Turn Inductor	0906-4JLC	Coilcraft
L7	8.9 nH Inductor	0806SQ8N9	Coilcraft
Q1	RF Power LDMOS Transistor	AFT09MS007NT1	Freescale
R1	62 Ω , 1/10 W Chip Resistor	RG2012N-620-B-T1	Susumu
PCB	Shengyi S1000-2, 0.020", $\epsilon_r = 4.8$	D58008	MTL

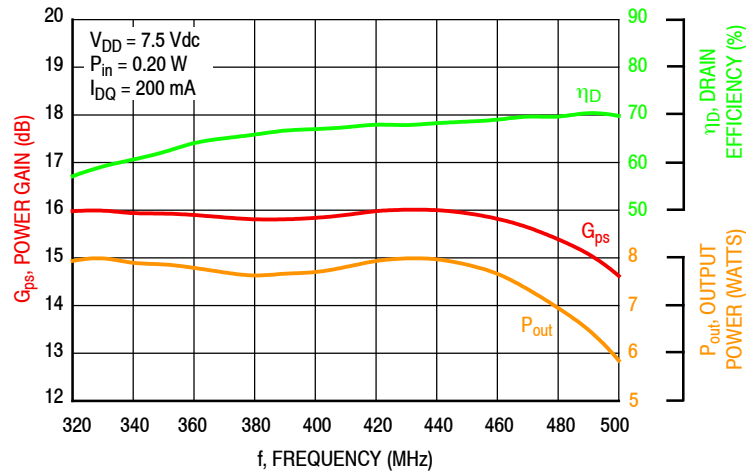


Figure 8. 350–470 Power Gain, Drain Efficiency and Output Power versus Frequency at a Constant Input Power

The previous board required 25 passive components (19 unique values), and the new board requires 27 (with 21 unique values). The total cost of increasing the bandwidth from 70 to 120 MHz was negligible. The component layout and values of the circuit are shown in Figure 7, and the gain, RF output and efficiency of the final circuit are shown in Figure 8.

Summary

When faced with extending the bandwidth and the possibility of shifting the operating frequency range of an existing circuit, logic dictates that significant additional simulation, a new PCB, and additional components all will be required. However, this is not always necessary or even possible within given time and cost constraints. The process described in this application note was achieved using only Smith chart and transmission line calculation software, demonstrating that experimental tuning and review with a Smith chart can avoid the possibility of creating an untenable design. The approach can be applied to other RF power outputs, frequency range conversions, and bandwidth extensions, but it is important to remember the following:

- When converting from a low-power design to a high-power design, any new components, the PCB, and the microstrip line must be able to handle the increased power.
- It is possible to change the frequency range when the original range is reasonably close to the one desired. However, if the original design was centered on 20 MHz (for example) and the new frequency range is centered on 500 MHz, the conversion probably would not be achievable.
- If the conversion is to a higher frequency, component values get smaller, but transmission lines may have to be widened to reach the desired impedance.

- If the conversion is to a lower frequency, transmission line widths can probably remain the same as in the original design, but component values get larger.

Additional Reading

Chris Bowick, *RF Design*, 2nd Edition, 2008, pp. 69–102 (for Q and Smith chart impedance matching).
 David M. Pozar, *Microwave Engineering*, 3rd Edition, 2005, p. 272, Table 6.1 (for common equations used in RF circuit design).

Sources of Smith Chart and Transmission Line Tools

1. Iowa Hills Software (Smith chart program), <http://www.iowahills.com/9SmithChartPage.html>
2. Clemson University transmission line parameter calculator, http://www.cvel.clemson.edu/Emc/calculators/TL_Calculator/
3. Freescale RF Engineering Tools App V1.0 (Transmission line calculator and other features), <http://www.freescale.com/RFENGTOOLS>
4. AWR Corp. TX-LINE (Transmission line calculator), <http://www.awrcorp.com/products/optional-products/tx-line-transmission-line-calculator>

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