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RF Power Amplifiers Operate Cooler with Improved Reliability Using ATC's EIA 600 Series Ultra-Low ESR Ceramic Capacitors

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Today's focus in wireless infrastructure development revolves around providing more efficient and affordable solutions for wireless RF Power Amplifiers (PAs). Wireless infrastructure designs have become a challenging task given the many modulation schemes along with more stringent performance requirements such as increased output power, higher efficiency, better linearity, lower inter-modulation distortion and improved receiver sensitivity as well as lower cost. PAs are further challenged by new modulation formats that facilitate high data rates while providing optimal spectral efficiency. With the demand on the designer to increase the number of users per sector, in some cases by two times, along with additional services such as high-speed data (GPRS) and video streaming, it is essential that base station (BTS) equipment be built to meet these ever increasing demands. Performance requirements combined with increased functional complexity of new BTS amplifier designs give rise to the need for superior components. Low loss capacitive devices are essential building blocks necessary for meeting the demands of leading edge infrastructure base station designs. The combination of low cost and exceptional performance is crucial for a design project to be successful in today's marketplace.

ATC's new EIA 600 Series family of high quality NPO ultra-low effective series resistance (ESR) ceramic RF chip capacitors improves circuit performance to meet these demands. They were specifically designed for use in the most critical RF and microwave applications. The product line encompasses both the lowest ESR with the highest voltage rating in its class, making it ideal for large signal applications. This combination of attributes allows the designer to achieve a new level of amplifier performance by enhancing power added efficiency (PAE), linearity, noise figure and phase distortion in BTS designs. The EIA 600 Series family of capacitors was designed for high-volume next generation infrastructure applications such as GSM/GPRS, PCS, 3G, UMTS, WCDMA, broadband wireless services, satcom, point-to-point (LMDS) and point-to-multipoint (MMDS) systems. The superior heat-conducting properties of the EIA 600 Series devices allow them to operate cooler in large signal applications. When used in small signal applications, these devices will improve thermal noise (KTB) performance allowing for improved signal to noise ratio as a direct result of the ultra-low ESR characteristic. These products are available in widely used EIA case sizes (0402, 0603, 0805, 1210) as well as the traditional ATC "A" case size (0.055" x 0.055") and "B" case size (0.110" x 0.110").

Device Reliability Overview

All ATC core products are qualified to MIL-PRF-55681 and are listed in the published military qualified products list (QPL) as qualified to the S-level failure rate. This is a failure rate of less than 0.001% per thousand hours or 10 FITs (failures in time). FITs are failures in a population during a period of 10^9 device-hours. One failure in 10^9 device-hours is defined as one FIT. The reciprocal of failure rate is mean time between failures (MTBF). The MTBF associated with S-level reliability is 10^8 hours or 11,415 years. All new products such as ATC's EIA 600 Series family not listed on the QPL also have a design failure rate goal of S-level and are supported by ATC's internal qualification requirements for meeting a 2,000-hour life test. ATC must verify the established reliability rating of its QPL products every six months in accordance with the requirements of the Defense Logistics Agency program, in order to maintain the QPL status.

Reliability Model

The Military Handbook (MIL-HDBK-217) model for accelerated life testing of insulation resistance failures in low and mid K ceramic multilayer capacitors is given below. This model combines the power law for voltage dependence with the Arrhenious equation for temperature dependence to describe reliability over a range of conditions with reference to rated voltage and temperature. It can be used to predict MTBF for temperatures other than 125º C at various use voltages.

V1 Rated Voltage	V2 Acceleration Voltage	T1 Standard Test Temp. 125º C	T2 Accelerated Temp. (º C)	Accelerated Factor	MTBF (Hours)
150	150	125	125	1	10^8
150	75	125	125	0.125	8×10^8
150	200	125	125	2.370	0.4210^8
150	150	125	85	0.0386	25.9×10^8
150	150	125	135	2.048	0.49×10^8

Table 1: Reliability at Various Voltages and Temperatures

$$\frac{t_1}{t_2} = \left(\frac{V_2}{V_1}\right)^n \times \exp\left[\left(\frac{E_a}{K}\right) \times \left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right]$$

Where:

t_1 = MTBF associated with the rated condition
t_2 = MTBF associated with the test condition
V_1 = rated voltage
V_2 = test voltage (2 x WVDC) or any accelerated or decelerated voltage or use voltage
T_1 = max. rated temperature in degrees Kelvin (125º C + 273.14) = 398.14º K for ceramic capacitors
T_2 = accelerated or decelerated temperature in degrees Kelvin (º C + 273.14) or use temperature
n = voltage stress exponent normally accepted to be 3 from the cube power rule referenced in MIL-HDBK-217
E_a = the temperature activation energy, established to be 1.0 eV for ceramic capacitors and is accepted as the predominant conduction mechanism below 300º C
K = Boltzmann's constant (8.617×10^{-5} eV / ºK)

The above model is associated with the mobility of oxygen vacancies in the lattice structure of low and mid K ceramics while under a voltage stress. The use of this model in relationship to analysis of insulation resistance degradation in a ceramic capacitor assumes that the failure mechanism results from the increased mobility of these oxygen vacancies.

Reliability is defined relative to the reference conditions– in this case rated voltage at maximum rated temperature for the device under test. Burn-in and life testing represent accelerated tests relative to the rated conditions. These tests typically take place at 125º C and twice-rated voltage as outlined in MIL-PRF-55681. Using n=3 in the power law portion of the equation will yield an acceleration factor of 8x rated ($2^n = 2^3 = 8$).

The same model can be used to extrapolate reliability to other voltage and temperature conditions that are both accelerated or decelerated. For a given capacitor with a voltage rating of 150 WVDC, the reliability at various voltages and temperatures could be established by applying the equation in the above model as outlined in **Table 1**. From this an acceleration factor can be calculated. This is the factor by which the MTBF will change from the reference. In the table the first row shows an acceleration factor of 1, which is associated with rated conditions. As the voltage or temperature is changed from the rated conditions, the MTBF will be altered by the acceleration factor. **Table 1** gives examples of acceleration factor as a function of various voltages and temperatures.

The MTBF of the accelerated or decelerated condition will be equal to the initial MTBF divided by the acceleration factor. For example, if the applied voltage is equal to the rated voltage and the temperature is increased from the maximum rated 125º C to 135º C, the MTBF is cut approximately in half.

Performance Advantages

The advantages of ATC's EIA 600 Series ultra-low ESR capacitors can be immediately seen in the performance of PA matching, coupling/DC blocking and bypass applications. Many benefits such as providing design margin, improving production yields, and cutting unwanted thermal rise while increasing reliability are achieved by using ultra-low ESR capacitors in various circuit applications. In addition the bill of material (BOM) costs are reduced.

Reduce BOM Costs and Circuit Complexity in Coupling Applications

Amplifier designers are always looking for cost effective approaches to reduce passive circuit losses. Today's multistage feed-forward and pre-distortion approaches are limited by the capacitors that are used. Interstage coupling losses can quickly add up. By using ATC's EIA 600 Series ultra-low ESR capacitors, several tenths of a dB of gain per stage in the signal path is readily recaptured. This allows the designer the latitude of using smaller RF semiconductor die sizes. The RF semiconductor devices are the single largest cost driver in an RF power amplifier design. This cost benefit can be realized with as little as three gain stages in a PA circuit path. **Figure 1,** illustrates a power amplifier lineup consisting of multiple cascaded gain stages with interstage coupling capacitors and their associated ESR losses. The cumulative insertion loss is equal to the summation of the individual insertion losses of each coupling capacitor ($IL_1 + IL_2 + IL_3 + \bullet\bullet\bullet\ IL_N$). The insertion loss is largely a function of the capacitor's ESR losses. Therefore, a lower ESR will yield lower end-to-end insertion loss and higher effective gain.

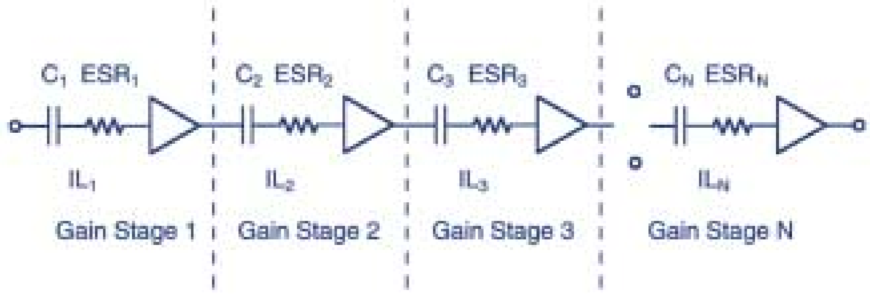

Figure 1: Typical Power Amplifier Lineup

Provide Necessary Design Margin and Improved Yields in Matching Networks

ATC's EIA 600 Series ultra-low ESR capacitors afford the designer better matching network performance. In addition, manufacturing operations will realize improved product yields, while reducing development design iterations. In matching applications the shunt capacitor closest to the active device plane is the most critical since it will sink the largest amount of current. An ultra low-ESR capacitor will increase both the efficiency and the effectiveness of the match, providing accurate and repeatable circulating current flow from module to module. The effects of mechanical component placement or *skewing* become less of a variant in this scenario, resulting in improved manufacturing yields. This is known as "lock-down effect" in matching network circuit design. These devices provide excellent performance repeatability and will therefore unburden the criticality of component placement alignment on the board during the manufacturing process. Allowing the capacitor to 'take up the slack' from board dielectric tolerances and skewing effects will minimize rework and the need for tuning, resulting in increased yield. This in turn will reduce the number of rejected amplifier modules in any given production lot. **Figure 2** illustrates a PA output matching circuit. Capacitor C_M is illustrated with its ESR loss. Parasitic inductances L_{P1} and L_{P2} are associated with the physical matching of the capacitor's termination profile and the microstrip line width. The mismatch between the capacitor's terminations and the microstrip line width will disturb the characteristic shunt impedance,

$$Z_O = \sqrt{\frac{L}{C}} \quad .$$

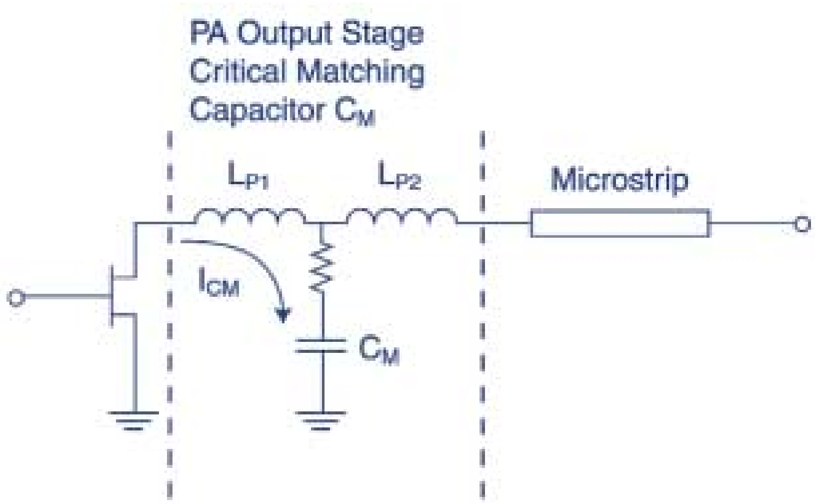

Figure 2: Critical Capacitor match in PA Output Module

Reduce Unwanted Thermal Rise While Increasing Product Reliability

ATC's EIA 600 Series will allow PAs to operate cooler while increasing reliability. For example, code division multiple access (CDMA) and wideband CDMA (WCDMA) systems require a multi-carrier PA that must exhibit extreme linearity. These base station PA modules are usually operated as class A or AB. In these configurations the amplifier typically operates with an 8 to 12 dB peak to average power ratio. For instance, a 25W WCDMA BTS PA is required to have a peak power of about 250W, while maintaining the required linearity levels of - 45 dBc per the 3GPP standard. Using 600 Series capacitors in the match will optimize linearity, and pro-

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vide increased headroom, while providing better thermal performance resulting in higher reliability. Thermal management and reliability become major factors as these designs typically generate a large amount of heat, which can easily affect module reliability. A case study follows.

Thermal Comparison between ATC 600S and Brand A

A comparison between ATC's 600S Series (EIA 0603 case size) RF chip capacitors and a competitor's High-Q EIA 0805 SMT, to be referred to as Brand A showed that the overall performance of 600S series capacitors is notably better. Both the 600S and Brand A capacitors were tested and compared in an actual 2 GHz power amplifier application by an impartial third party. The unit under test was a 2 GHz power amplifier module using a single Motorola MRF21125, LDMOS transistor. The outcome of this A/B comparison test illustrates that ATC's 600S (EIA 0603 size) capacitors operate cooler than the competitor's larger EIA0805 size High-Q capacitor in the same application. (See **Figures 3** and **4**)

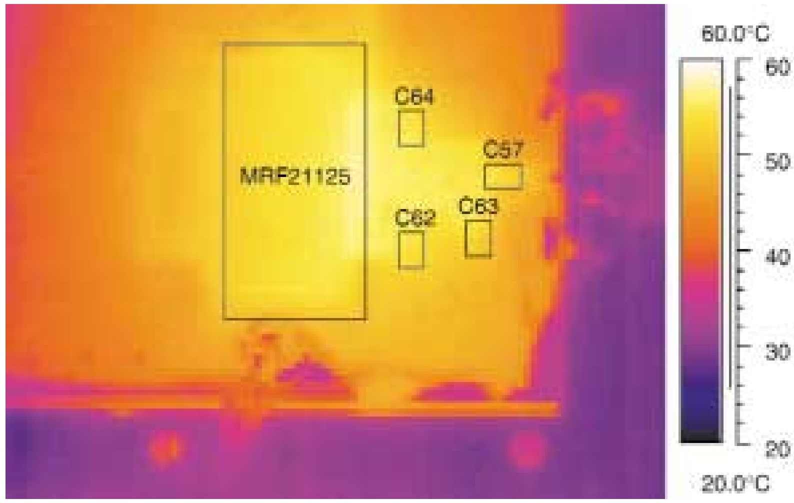

Figure 3: Thermal Scan of Test Board Using Brand A Capacitors

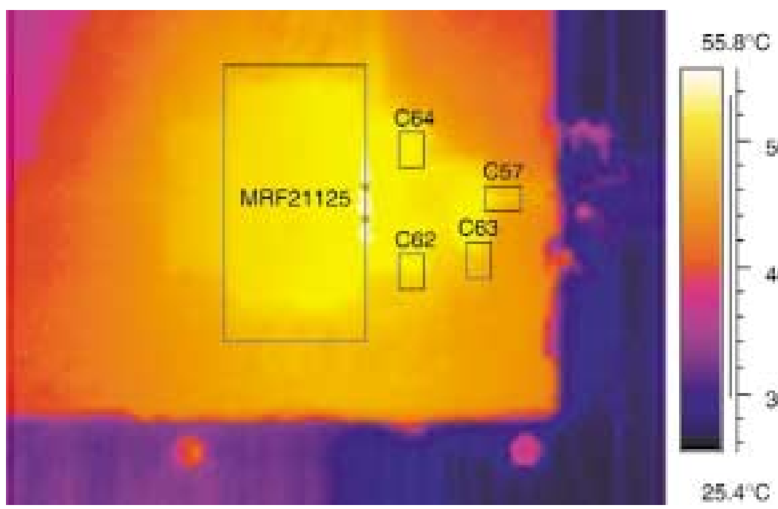

Figure 4: Thermal Scan of Test Board Using 600S ATC Capacitors

Infrared Scan of the MRF21125 RF Device

The following test details were provided by Motorola Development Engineering.

Motorola performed infrared (IR) scans on a UMTS Power Amplifier test module in order to characterize the thermal performance of its MRF21125 LDMOS device and associated matching and coupling circuitry. A worst-case operational test scenario was implemented for this study. ATC's 600S and Brand A capacitors were tested separately using the same test board and under the same test conditions. **Figure 6** is a photo of the actual test module.

Test 1 - PA test module with Brand A, EIA 0805 size capacitors, fan voltage at 8 V (minimum fan speed)

Test 2 - PA test module with ATC 600S EIA0603 size capacitors, fan voltage at 8 V (minimum fan speed)

Test Setup:

RF output power = 22 W,
Frequency = 2.14 GHz
Modulation = WCDMA
Drain voltage = 27 V
Active Device = MRF21125
Bias current = 1.3 A

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Note 1: Module was painted black using Plasti Dip spray paint, to provide a uniform emissivity

Note 2: Module was mounted on a finned heat sink

Test Results

Table 2 shows a summary of the operating temperatures of the 600S (EIA 0603 size) and the EIA 0805 Brand A devices under the same test conditions. From the data collected it can be seen that the low capacitance 600S samples in the matching network (C62, C63 and C64) appear to be thermally equivalent, if not slightly better, than the Brand A devices. Large thermal contributions from the transistor in proximity to C62, C63 and C64 may explain the relatively higher constant device temperatures measured in this region. However, it is interesting to note that the 18 pF DC blocking / coupling capacitor designated as C57 is about 6 degrees centigrade cooler than the Brand A device. Since the coupling capacitor experiences the full output power of the amplifier, it will dissipate power in direct proportion to its ESR (P_{CD} = I^2 ESR). The lower operating temperature of the 600S is attributed to the fact that the 600 series capacitors exhibit a lower ESR than that of Brand A. At 2 GHz the ESR of the ATC 600S180 (18pF) capacitor is typically 0.08 ohms, while the 18 pF Brand A capacitor exhibits about 0.18 ohms, more than 200 percent higher. The thermal scan data below illustrates a significant difference in temperature between both products. (See **Figures 3, 4** and **5**).

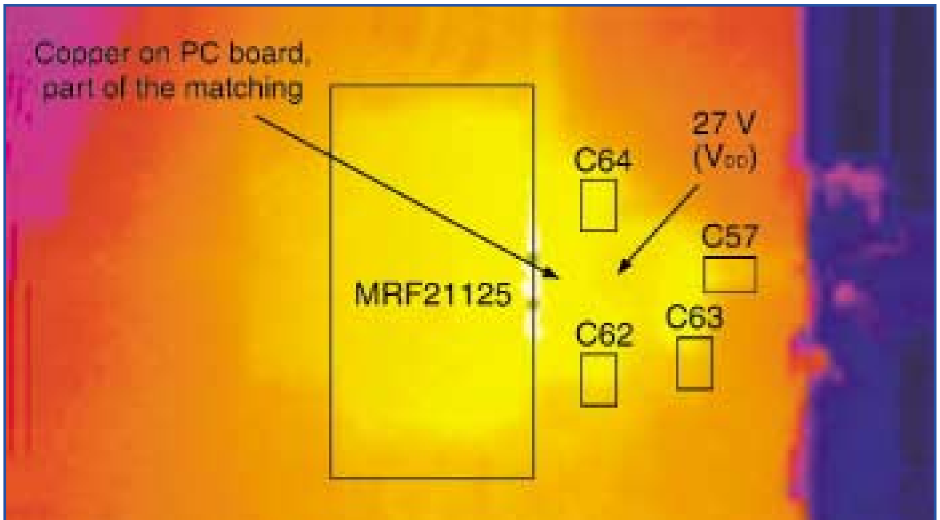

Figure 5: Thermal Map showing location of various parts and PC Board artwork.

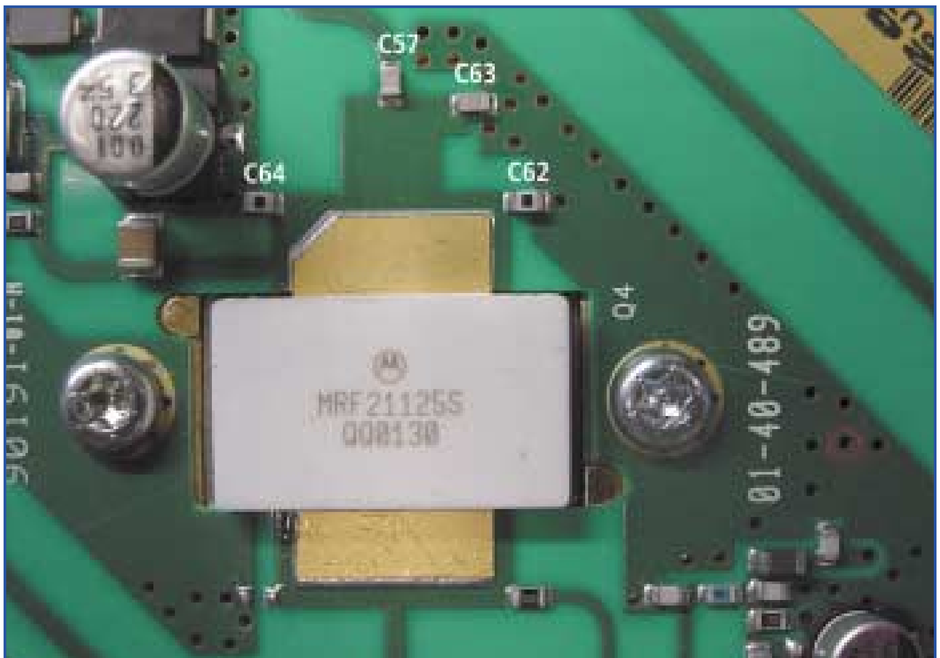

Figure 6: Actual PA Test Board

Test Conclusion

The thermal scans above clearly show that the 600S180 (18 pF) C57 output coupling capacitor did not significantly contribute to the thermal rise of this module. C57 was selected for this discussion because it couples the full output power of the amplifier to the load. In addition C57 is mounted far enough away from the transistor, which is the main heat contributor, such that the thermal effects of the transistor could be essentially isolated and not overshadow the heating effects of the subject capacitor. The measured temperature of the 600S C57 was 49.2º C. In comparison the temperature of the 18 pF Brand A device is 55º C which is approximately 6º C higher. From the thermal scans it can be seen that the EIA 0805 Brand A capacitor significantly contributes to the thermal rise of this module.

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- ATC 600S (C57) operates 6 degree cooler than Brand A in the same application.

- The ESR @ 2 GHz for ATC's 600S -18 pF is 0.08 ohm as compared to 0.185 ohm for the Brand A -18 pF capacitor. The ATC 600S exhibits less than half the ESR as compared to Brand A.

Part	Brand A (0805) Temp. (º C)	ATC 600S (0603) Temp. (º C)
C62, 1 pF	55.6	54.5
C64, 1 pF	55.7	54.2
C63, 1.2 pF	55	54.3
C57, 18 pF	55	49.2

Table 2: Summary of Capacitor vs. Temperature Under Operating Condition

- The ESR @ 2 GHz for ATC's 600S -1 pF is 0.11 ohm compared to 0.3 ohm for Brand A 1 pF capacitor @ 1 GHz. The ATC 600S -1 pF exhibits approximately one third the ESR @ 2 GHz as compared to Brand A @ 1 GHz.

The 600 Series Advantage

- Lower Operating temperature in power amplifier applications
- Higher power handling due to ultra-low ESR
- Better volumetric efficiency; affords real estate savings
- Highest voltage rating in class for greater design margin
- Improves PA reliability by operating cooler
- Ideal for critical matching lock down
- Reduces insertion loss in coupling applications
- Reduces thermal noise (KTB) and improves signal to noise ratio (SNR) in receiver applications
- Improves rejection floor and selectivity characteristics in filters

Conclusion

This article discussed clear performance advantages associated with using ATC's ultra-low ESR EIA 600 Series capacitor products. The main performance attributes of capacitive components used in design projects are frequently a trade-off to cost. The 600 Series family has been designed to provide excellent RF performance along with cost and reliability advantages, giving the designer a competitive edge in today's marketplace. ATC offers technical applications support for their entire range of products.

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