Application Note

TVS Protection and Bias Sequencing for HBT Amplifiers

INTRODUCTION

RF medium and high power amplifiers realized with HBT technology are increasingly popular in telecommunications systems due to the inherently superior linearity and efficiency performance compared to competing technologies. The reliability of HBT RF devices is well known to be excellent from Highly Accelerated Stress Testing (HAST) and High Temperature Operating Lifetime (HTOL) testing. The ruggedness of RF power amplifiers is another issue altogether. RF power devices, regardless of the technology, tend to be quite sensitive to transient events such as Electrostatic Discharge (ESD), voltage transients, and power supply sequencing events. For example an RF power amplifier device typically has an ESD rating of Class 1 or Class 1A (250 V minimum) for the Human Body Model (HBM), and are operated at voltages that are greater than 50% of the specified Absolute Maximum Ratings (AMR).

This application note discusses the proper circuit design techniques for protecting sensitive RF power amplifiers from destructive voltage transients. TVS devices suitable for suppression of transients found in a telecommunications system are described in detail. In addition power supply sequences, which are a form of transient voltages, can destroy the device are described and proper supply sequencing is presented.

HBT RF POWER AMPLIFIER TOPOLOGY

The classic HBT power amplifier consists of a large periphery RF device, with a current mirror topology supplying bias to the base of the RF device. **Fig. 1** is a functional pin equivalent of a typical HBT RF amplifier. An external current source, realized with resistor R2 from a voltage source Vpd, supplies reference current Iref into series diodes. Vbias is a collector of a supply transistor. Usually for 5 V devices, ESD protection diodes are stacked up in the forward voltage direction to hold off the bias voltage and a single diode in reverse direction provides protection for negative voltages.

The internal ESD diode structures in 5V devices are sufficient to protect against the short duration voltage transients from a high impedance source characteristic of ESD strikes during handling and assembly. However these diodes are quite small periphery devices that cannot survive voltage transients from low impedance sources. The classic failure analysis signature from low impedance voltage transients is destruction or degradation of the ESD diode structures on the Vpd and Vbias lines.

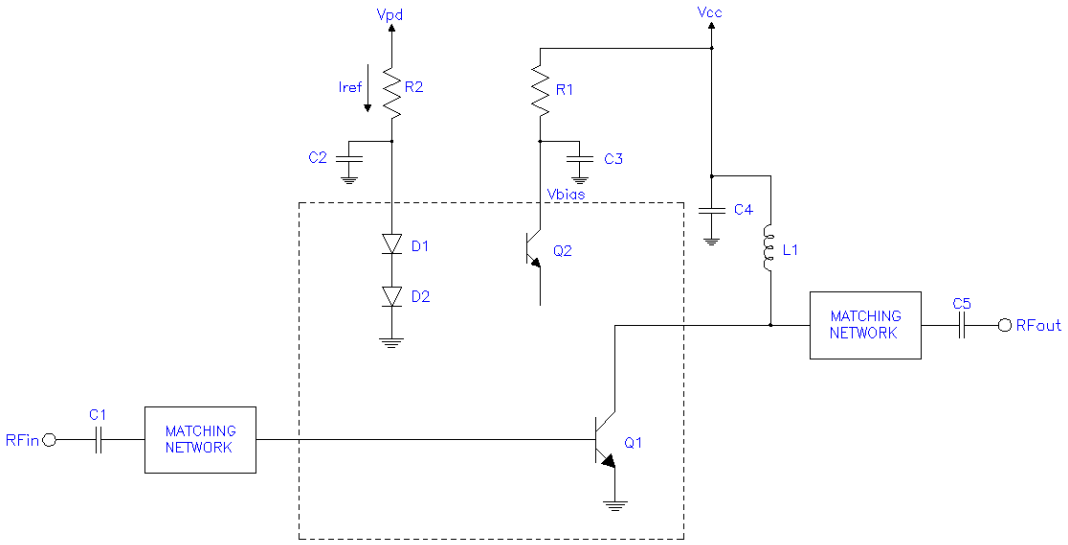

Figure 1. Functional pin equivalent of a typical HBT RF power amplifier. A current mirror circuit supplies bias to the base of the RF transistor. Vpd is often referred to as Vref, they are one in the same.

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TVS DEVICES

The wide variety of TVS devices on the market can be confusing at first glance. Luckily for the specific application of protecting HBT amplifiers from transients the TVS selection process can be reduced to one type of Uni-Directional device in two different flavors. The avalanche TVS is little more than a glorified Zener diode, beefed up to handle large surge currents and tailored for high speed response (**Fig. 2**).

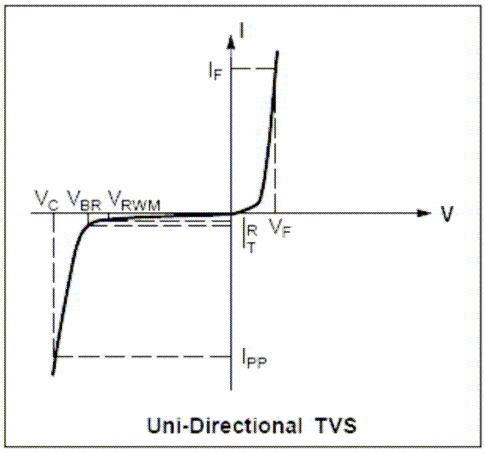

Figure 2. The Uni-Directional TVS is a Zener diode designed to operate at fast speeds and high pulse power levels.

This makes the avalanche diode the preferred method to protect HBT amplifiers from being damaged by voltage transients. The V_{BR} stands off the positive bias supply voltage, avalanche breakdown clamps at a voltage above the standoff rating, and in the negative voltage direction the device acts like a high speed rectifier, clamping at one diode drop below ground. **Table 1** lists characteristics for two different types of TVS diodes. The SOT-23 part is designed for transient protection of high speed data lines. It has low capacitance and the level of transient protection capability is specified by ESD test standard IEC 61000-4-2, level 4, 30KV for air discharge. The clamp voltage is less than the beefier SMA part, and total power dissipation for a single event is much less than the SMA part. The SMA TVS is designed for low impedance power supply lines. It has a higher clamp voltage and can dissipate far more power, 400 W for the much longer 10 x 100 uS waveform commonly specified by RTCA/DO-160E (or D) for lightening strikes in airborne applications.

Table 1. Comparison of Data Line (SP0502B) and Power Supply Line (SMA) TVS Devices

DEVICE	Standoff Voltage (V_{RWM})	Breakdown Voltage V_{BR} @ 10mA (V)			Capacitance (pF)	Max Peak Power Dissipation P_{PPM} (W)	P_{PPM} Waveform Rise/Fall time (uS)	Package
	Nom.	Min.	Nom.	Max.				
SP0502BAHTG	5	5.6	6.2	7.2	30	300	8 x 20	SOT-23 (dual)
SMAJ5.0A	5	6.4	7.0	7.8	1000	400	10 x 100	SMA

Both of these device types are available from a number of commodity semiconductor suppliers. **Table 2** lists manufactures and part numbers that are readily available on the market. The SMA part is ideal for Vcc bias lines, while the Vpd and Vbias lines are protected using the SOT-23 part.

The location of the TVS on a board depends on several factors. The standard philosophy of locating TVS devices is to place them at the noise source. This works well provided the noise source is identified. Placing the TVS right at the output of a noisy 5V supply puts the TVS at the noise source, but may not provide adequate protection against transients that couple onto the 5V line well after the 5V supply. For example if a 28 V power supply line is near the 5 V line in a 28 V PA design, voltage transients from the 28V being switched on/off can couple into the 5V line near the device. A TVS way back at the power supply may not help much in this case. Locating TVS devices right at the amplifier to be protected will be more effective when the noise source is difficult to identify or there are multiple noise sources due to other factors such as on/off switching, hot swapping or coupling. Placement at the RF circuit to be protected is less cost effective when a number of amplifiers must be protected, compared to a single TVS device back at a common supply point. Often some experimentation is needed to find the optimum number and location of TVS devices for the best performance versus cost trade off.

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Table 2. TVS Diodes for RF Power Amplifiers

Bias Line	Voltage	TQS P/N	Manufacturer	Manufacturer P/N	Description
Vpd	+5V	1069006	Littelfuse, Inc.	SP0502BAHTG	TVS DIODE ARRAY 2 CH, 5V SOT23, LEAD-FREE/GREEN
			On Semiconductor	SM05T1G	
			ST Microelectronics	ESDA6V1L	
			Microsemi	SM05E3	
Vcc / Vbias	+28V	1069003	Littelfuse, Inc.	SMAJ33A	DIODE TVS 33V 400W UNI 5% SMA
			Diodes Inc.	SMAJ33A-13-F	
			On Semiconductor	1SMA33AT3G	
			ST Microelectronics	SMAJ33A	
			Vishay/General Semiconductor	SMAJ33A	
Vcc / Vbias	+12V	1069002	Littelfuse, Inc.	SMAJ13A	DIODE TVS 13V 400W UNI 5% SMA
			On Semiconductor	1SMA13AT3G	
			ST Microelectronics	SMAJ13A	
			Diodes Inc.	SMAJ13A-13-F	
			Micro Commercial Co	SMAJ13A-TP	
Vcc / Vbias	+5V	864000-231	Littelfuse, Inc.	SMAJ5.0A	DIODE TVS 5V 400W UNI 5% SMA
			Diodes Inc.	SMAJ5.0A-13-F	
			On Semiconductor	1SMA5.0AT3G	
			ST Microelectronics	SMAJ5.0A	
			Vishay/General Semiconductor	SMAJ5.0A	

In 5V applications the question arises as to which TVS to employ. The SMA part is designed for low impedance power supply applications, and thus is a much larger device with higher power rating than the SOT-23 part. Yet the reality of the matter is that any telecommunications power supply that has transients capable of destroying the lower power SOT-23 data line device really needs to be redesigned anyway. Therefore while either device is acceptable, the SOT-23 device is a dual device that is about half the cost and one fourth the real estate per device, making it the part of choice in +5V supply applications.

28V HBT AMPLIFIER TVS PROTECTION

Fig. 3 provide details for the protection of a 28V HBT amplifier, for the case of Vcc=Vbias=28V and Vpd=5V. The 33 V SMA device is located on the VCC line just before the bypass capacitors. The SOT-23 device is used to protect the Vpd lines.

For the Vpd line the TVS must be placed as shown on the high side of the current source resistor R1. As can be seen from the schematic the voltage at the pin of the device should not exceed the 2 diode drops internal to the device, which is about 2.8 V in HBT technology (1.4 V per diode circuit). However the TVS doesn't start to clamp until at least 6.2 V, far above the forward voltage drop of those two series diodes realized by D1 and D2 (**Fig. 1**). The location of the TVS devices is shown in **Fig. 4** for the evaluation board. Since by definition the location of the noise sources for the evaluation board must be at the connector J1, the TVS devices are placed right at that connector.

Fig. 5 is a photograph of a AP60X evaluation board with TVS protection added to the bias lines.

The recommended configuration connects the Vbias line to the 28 V supply with a series dropping resistor. This topology avoids the cost of sequencing three supplies properly, at a small expense of efficiency. In this configuration the 33 V TVS protects both the Vcc and the Vbias lines. When connecting Vbias to the 28 V Vcc, use the dropping resistor values from **Table 3**. The resistor size is set by it's power dissipation. For normal operation in the backoff region the power dissipation of the bias resistor is much less than when the device is operated near P1dB. Therefore two resistor sizes are specified for the two different modes of operation. Resistors may be larger than the size specified, but parts smaller than the specified size will have their maximum power dissipation exceeded. The exact value of the resistor is not critical, existing part values on a BOM that are close to the values specified in the table are acceptable.

The Vbias line bypass capacitor can be selected to resonate in the band of operation. It should not exceed the 1000 pF shown in **Fig. 3** in order to minimize the RC time constant.

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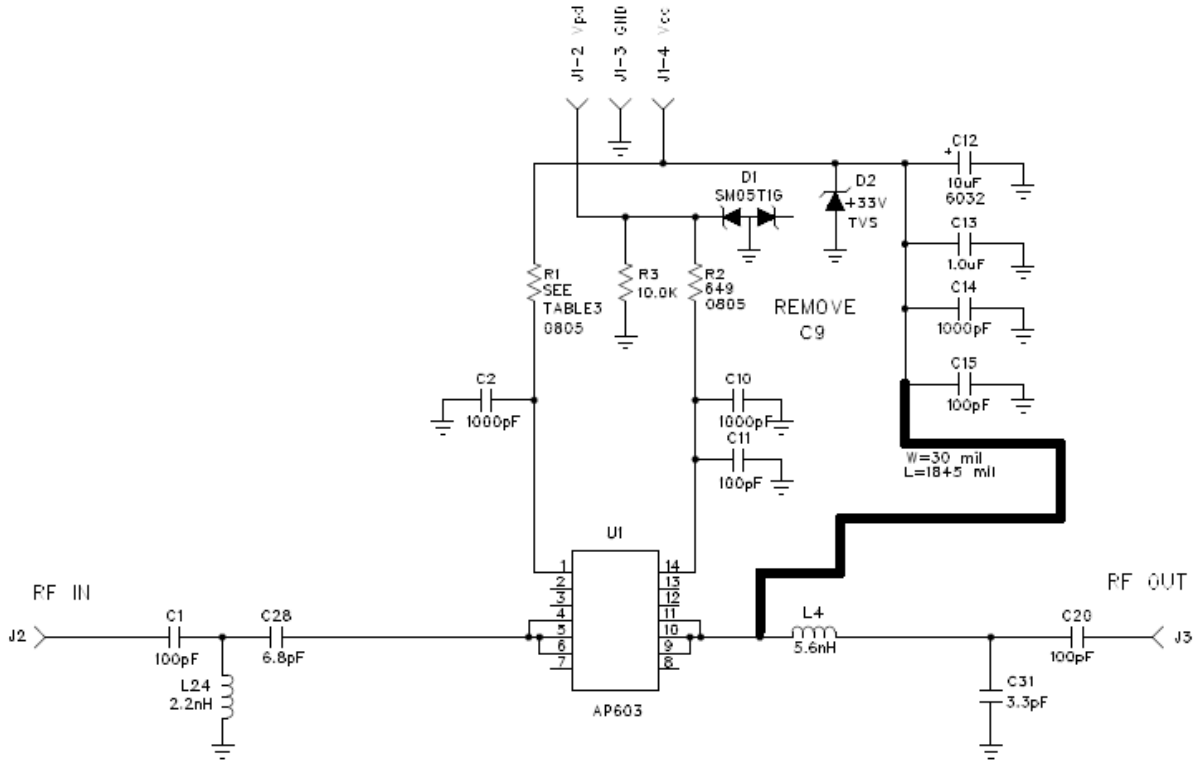

Figure 3. Schematic modifications for adding TVS protection to AP60X Evaluation Boards. Vbias is connected to Vcc with a dropping resistor as specified in **Table 3**. D1 is a +5V TVS diode added at Vpd line. R3 is a 10 KΩ added from Vpd to ground. D2 is a +33V TVS added from Vcc to ground, in addition to protecting the device from voltage transients, it also functions to protect against accidental shorts of the RF output trace.

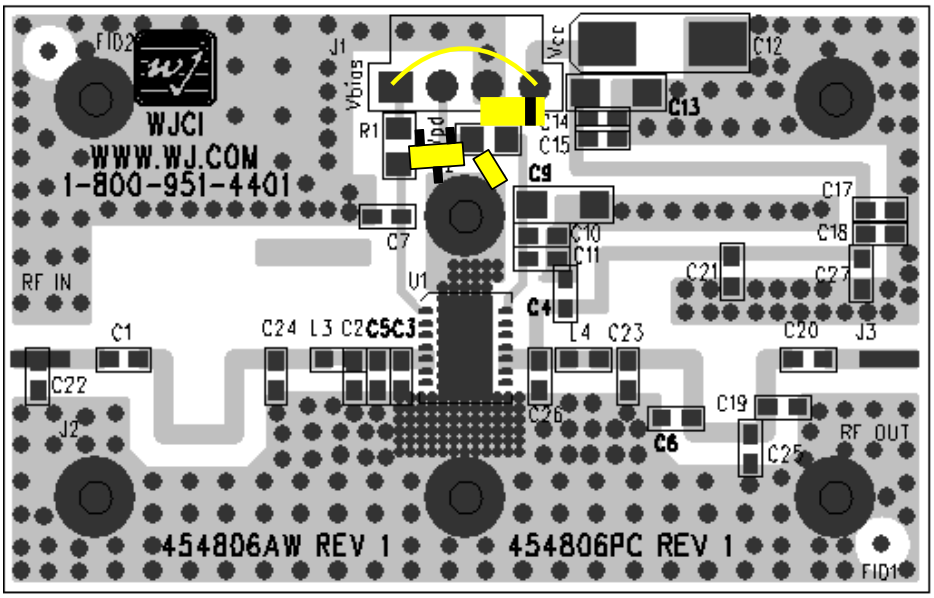

Figure 4. Assembly modifications for TVS protection. Remove C9 and place jumper wire from Vbias to Vcc. Add 10K to ground at R2. Place SOT-23 5V TVS diode from R2 to ground. Place SMAJ33V TVS diode at J1 pins 1 to 2.

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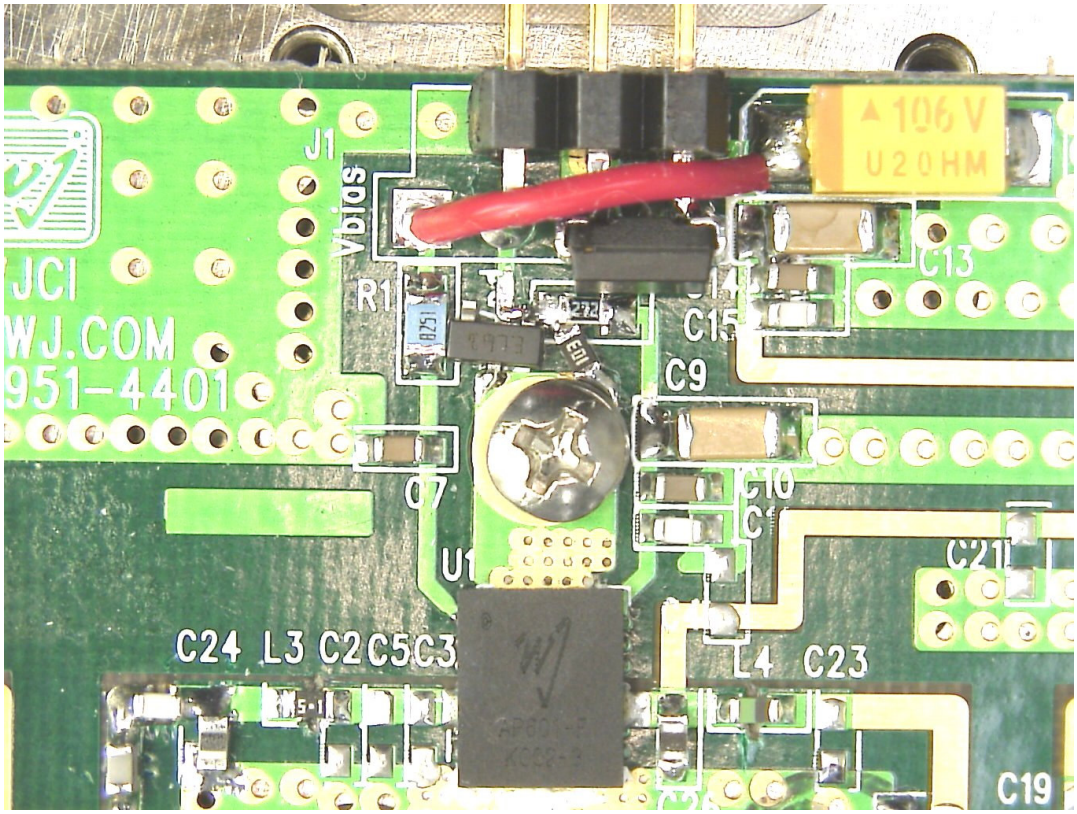

Figure 5. Picture for AP60X evaluation board modified for TVS protection.

Table 3. Bias Line Resistors for AP60X 28V HBT power amplifier

Device	Value (Ω)	Size for Normal Backoff Operation	Size for P1dB Operation
AP601	8.25K	0402	0805
AP602	4.22K	0603	1210
AP603	2.00K	0805	2010

12V HBT AMPLIFIER TVS PROTECTION

Fig. 6 provides details for the protection of a 12V HBT amplifier for the case of Vcc=Vbias=12 V and Vpd =5 V. The 13 V SMA TVS device is located on the VCC line just before the bypass capacitors. One half of the dual SOT-23 device is used to protect the Vpd line.

A TVS device is not provided on the Vbias line. For this application it is assumed that the Vbias line is connected to the Vcc line by the series dropping resistor specified in **Table 4**. Therefore the Vbias line is protected by the SMA TVS on the Vcc line. For applications where the bias line is connected to a 5 V supply, the other half of the SOT-23 TVS should be connected to the Vbias line as shown in the **Alternate Configuration** section of this document.

The assembly drawing showing the location of the TVS devices on the AP561 evaluation board is given in **Fig. 7** and a photograph showing the placement is given in **Fig. 8**.

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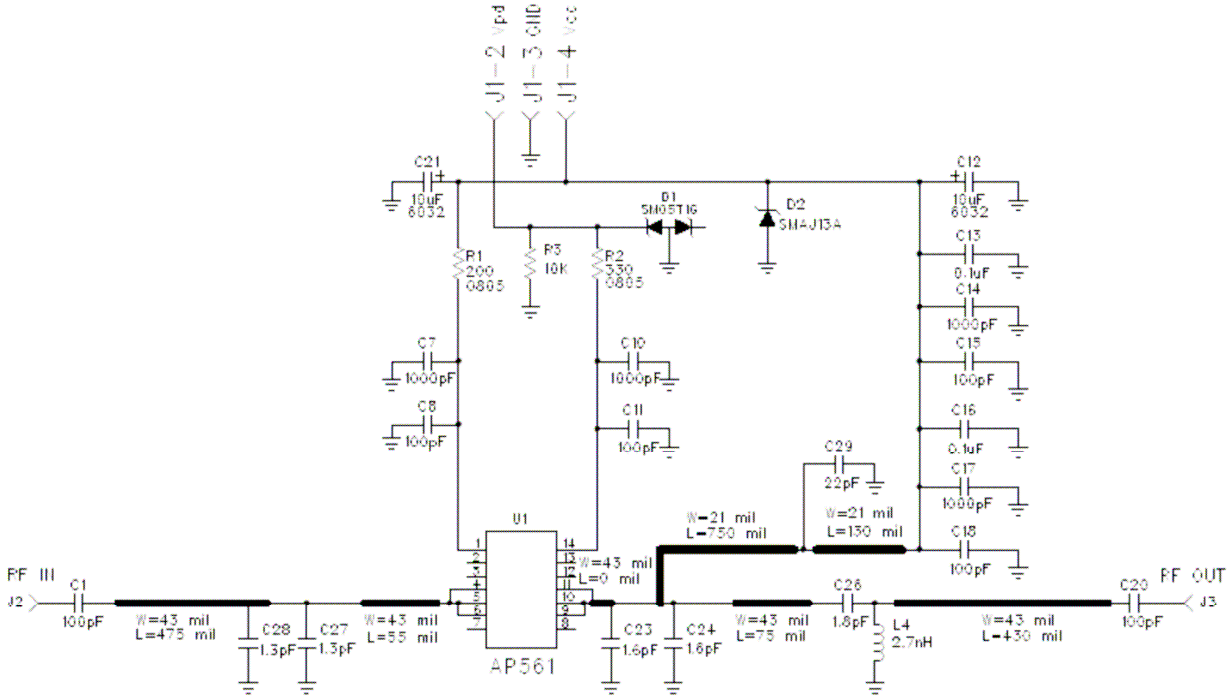

Figure 6. Schematic modifications for adding TVS protection to AP56X evaluation boards. Vbias is connected to Vcc with the 200Ω/0805 dropping resistor. D1 is a +5V TVS Diode added to the Vpd line. R3 is a 10KΩ added from Vpd to ground. D2 is a SMA packaged 13V TVS connected from Vcc to ground, in addition to protecting the device from voltage transients, it also functions to protect against accidental shorts of the RF output trace.

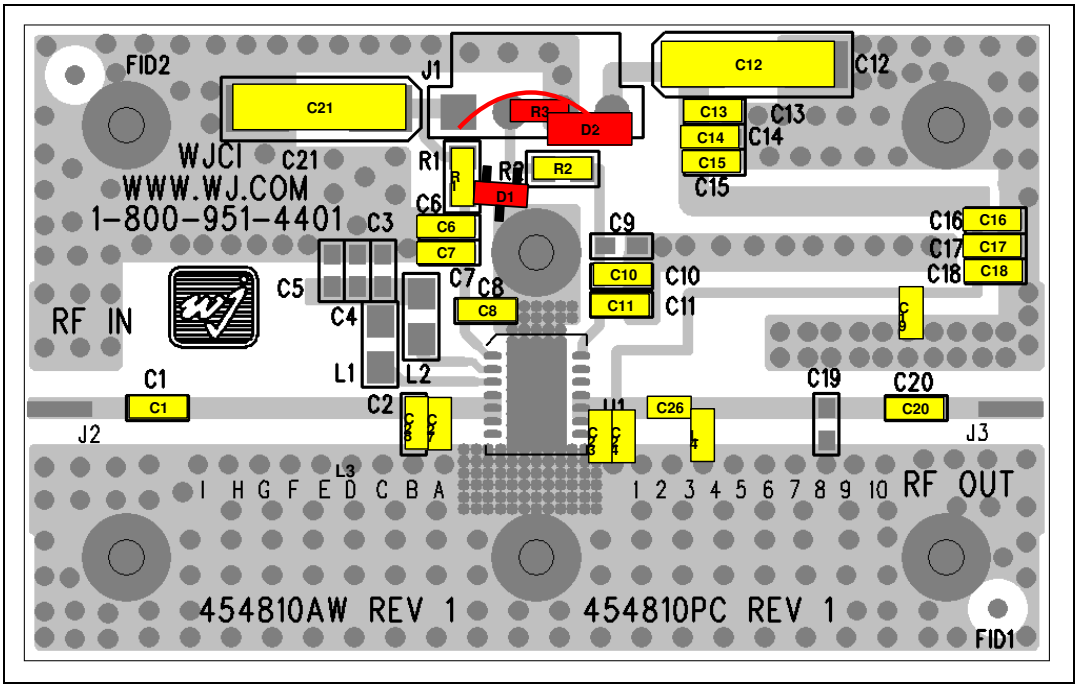

Figure. 7. Location of TVS devices on the 12V AP56X evaluation board.

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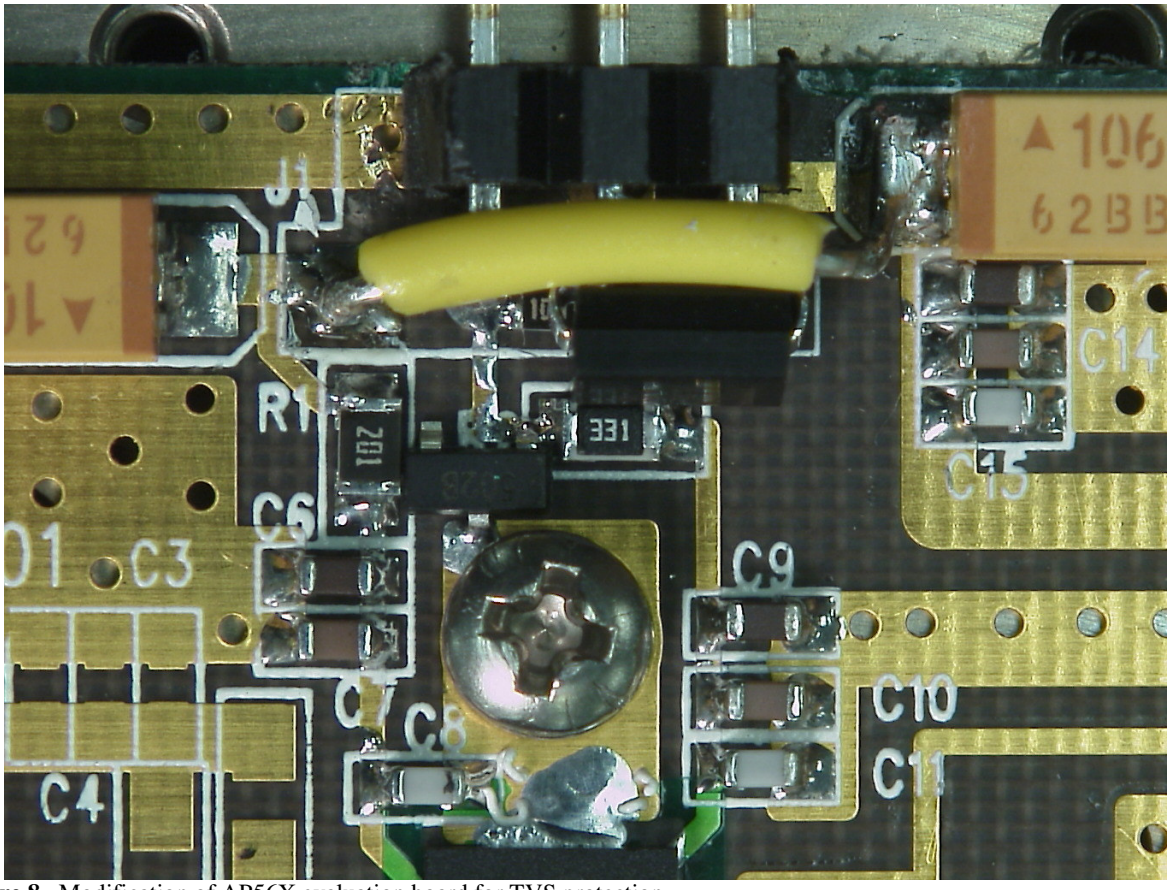

Figure 8. Modification of AP56X evaluation board for TVS protection.

Table 4. Bias Line Resistors for AP56X 12V HBT power amplifier

Device	Value (Ω)	Size, Backoff Operation	Size, P1dB Operation
AP561	200	0805	1210
AP562	200	0805	1210

5V HBT AMPLIFIER TVS PROTECTION

Fig. 9 provides details for the protection of a 5V HBT amplifier. TVS devices are placed at the Vcc line that also supplies Vref and Vbias. A second TVS device is placed at the Vbc line, which supplies bias to the first stage. While a second SOT-23 device is needed for the single layer evaluation board, on a multilayer board this second device can be eliminated. For the multi-layer board Vbc can be connected via an short length of inner layer trace to Vcc, requiring only one SOT-23 TVS at Vcc. Although the device shown is the SOT-23 device, the SMA part may also be specified in this application.

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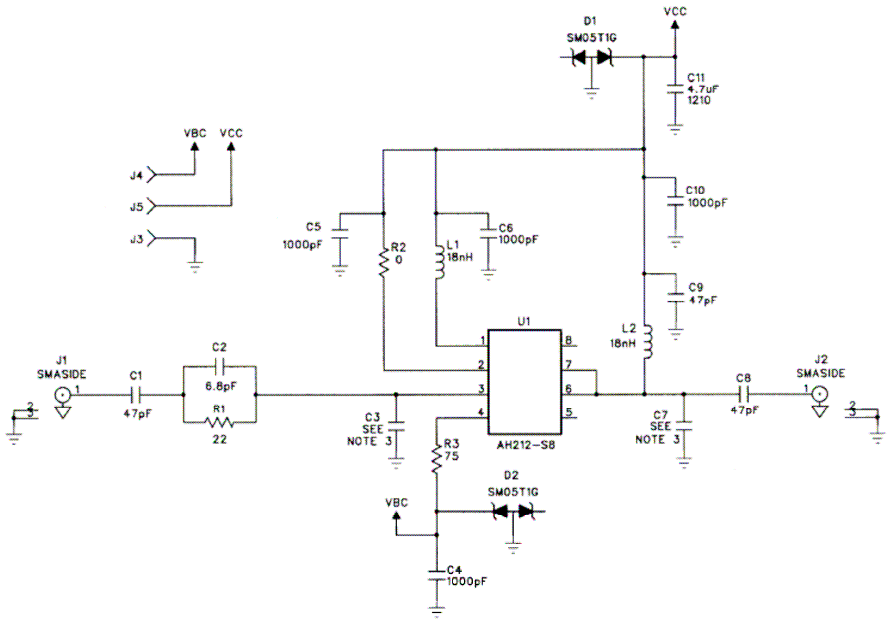

Figure 9. TVS protection for 5V HBT amplifiers. 5V TVS diodes are added to the Vcc and Vbc lines.

BIAS LINE SEQUENCING

The operating instructions for 12 V and 28 V evaluation boards calls out a specific sequence for applying and removing voltages from the bias lines. The intention of these instructions is not to convince the designer that sequencing is needed in a production environment. The reason is that these sequence procedures for the evaluation boards provide a systematic approach to applying power to the device such that damaging intermediate states are avoided.

The most damaging intermediate state is for the case of 5 V applied to Vpd and Vbias lines, while a low voltage, say 1 to 5 V is applied to the Vcc line. Most types of active biased HBT amplifiers are unstable point for this bias condition. LDMOS devices are also well known to be unstable for the case of low drain voltages with full gate bias. The device will break into oscillation and destruct. Therefore regardless if the device is a 5,12, or 28 V part, the condition of bias applied to the active bias ports Vpd and Vbias, while Vcc is at a low voltage needs to be avoided. The primary way to avoid this bias condition is to connect Vbias to Vcc via a dropping resistor described in **Table 3**. By first turning on the 28V to Vcc and Vbias before applying 5 V to Vpd, and removing 5V from Vpd before removing the 28 V, the conditions for oscillation are eliminated. For 5V HBT applications, powering all bias and Vcc with a common supply is acceptable.

A second intermediate state to be avoided occurs if RF is applied to the input while an under-voltage biases the device. For this case the destruct mechanism is RF overdrive due to a lowered compression point of the amplifier. The AP60X device, for example, has an absolute maximum input power rating of P6dB, that is, input power 5 dB beyond the 1dB compression point. Lower that compression point by lowering the bias voltages, and a fixed input power that was safe at full bias condition will soon exceed the reduced compression point by more than 5 dB. Failure from RF overdrive is the likely result. Again the use of a power up/down sequence that avoids applying RF input unless the device is biased properly will avoid this destructive intermediate state.

FLOATING GROUND TRANSIENTS

Floating grounds commonly occur during hot swapping and power supply turn on/off events. Even if a board is mounted on an inch thick metal plate, if any part of the power supply is located elsewhere and is cabled over to the board, a floating ground condition may occur. Lightening strikes, brown-outs, ground loops, or the inductive kick-back from a motor start-up are also known to be responsible for large transients on ground planes that are not completely tied to earth ground.

A floating ground condition applied to an HBT amplifier with active bias will not destroy the device…that is until the device is grounded. Then there will be instant catastrophic failure. With 5 V on the active bias circuit and 28 V on Vcc, the unconnected

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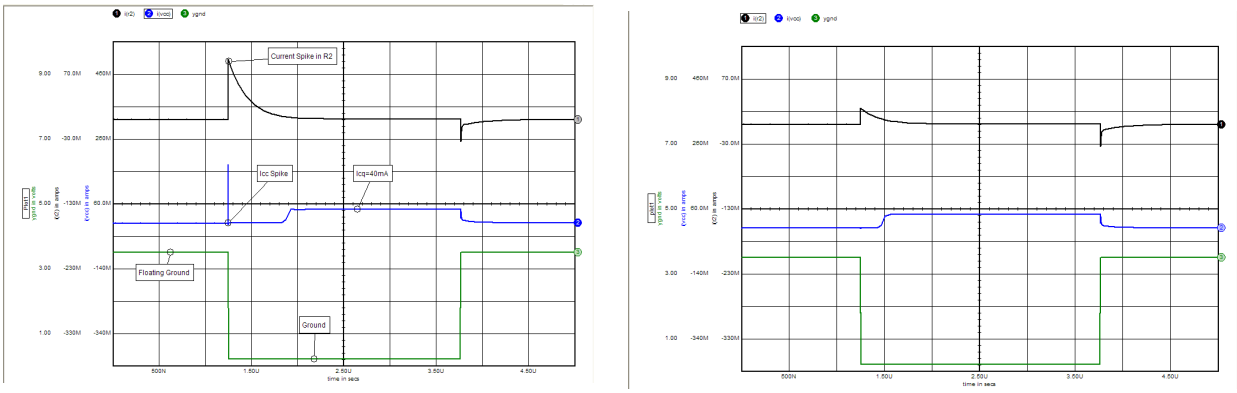
ground will float up to a voltage value somewhere between 5V and 28V. As can been seen in **Fig. 10 (a)**, at the instant the device is grounded, a large spike of current flow will destroy the active bias buffer transistor Q2.



(a) **(b)**

Figure 10. Time domain simulation of floating ground in a AP601. (a) At T=1.25 uS the floating ground is shorted to ground, resulting in large current flow in the bias transistor Q2 and the collector of the RF transistor. Although the simulation shows normal operation resuming by 1.75 uS, in reality the device is destroyed by the current spikes. (b) Simulation with Vbias connected to Vcc and a 10 K to ground added to the Vpd line. At T=1.25 uS the floating ground is shorted to ground. The current spikes are eliminated and normal operation starts shortly thereafter.

Certainly the best approach to the ground transients problem is to prevent them from happening in the first place with proper power supply and hot swap connector design. There are cases where this is not practical from a logistical or economical standpoint. Evaluation boards that are tested manually are a case where applying proper power supply design techniques are not practical. Even if the manufacturer is not concerned with the expense of the sequencing circuitry on a evaluation board, the first questions received from the customer will be regarding the need and expense of said components. It is also difficult to verify that ground transients will never occur in complex telecommunication systems that are manually repaired or are subject to brown-outs and lightening events in the field.

The TVS protection described here is essential for preventing floating ground failures. The ground cannot be raised more than one diode drop above the 5 V Vpd lines by virtue of the TVS uni-directional characteristic. A 10 Kohm resistor placed at Vbias or Vpd does the same thing, holding the ground at 5V when the ground is left floating. **Fig. 10(b)** is the time domain simulation with Vbias connected to Vcc and a 10K added from Vbias to ground. The current spikes are eliminated, making the design robust to floating ground faults. Connecting Vbias to Vcc will also eliminate the current spike on the bias line, since now the ground cannot be floated above a 5 V Vbias by the much larger 28 V Vcc.

ALTERNATE CONFIGURATION

While the connection of Vbias to Vcc using a dropping resistor protects against bias sequence faults and switching transients, collector efficiency is degraded by the increased power dissipation associated with using 28 V instead of 5 V for the bias line supply. For example, efficiency at 30 dBm is reduced by about 0.65 % as shown in **Fig. 11**. Since efficiency is about 10 % for this power level the drop in efficiency is on the order of 6.5 %.

For designs where efficiency is critical the design shown in **Fig. 12** will protect against transient events and bias line sequencing faults. TVS diodes D1 and D2 provide transient protection and the two 10 K resistors to ground, R4 and R19, are effective protection against floating grounds. Q2-B is act like a switch that triggers at approximately 14 volts by virtue of the resistor divider network R6, R7, and Q2-A configured as a 6.8 V Zener diode. When Vcc drops, Q2-B shuts off, which in turn shuts off Q1-A and Q1-B. Q1 and Q2 are inexpensive pre-biased bipolar switching transistors available from any number of commodity semiconductor manufacturers. The simple inexpensive design insures that no bias is applied to either the Vpd or Vbias lines unless there is at least 14 V present at Vcc, thus eliminating the possibility of damaging intermediate states.

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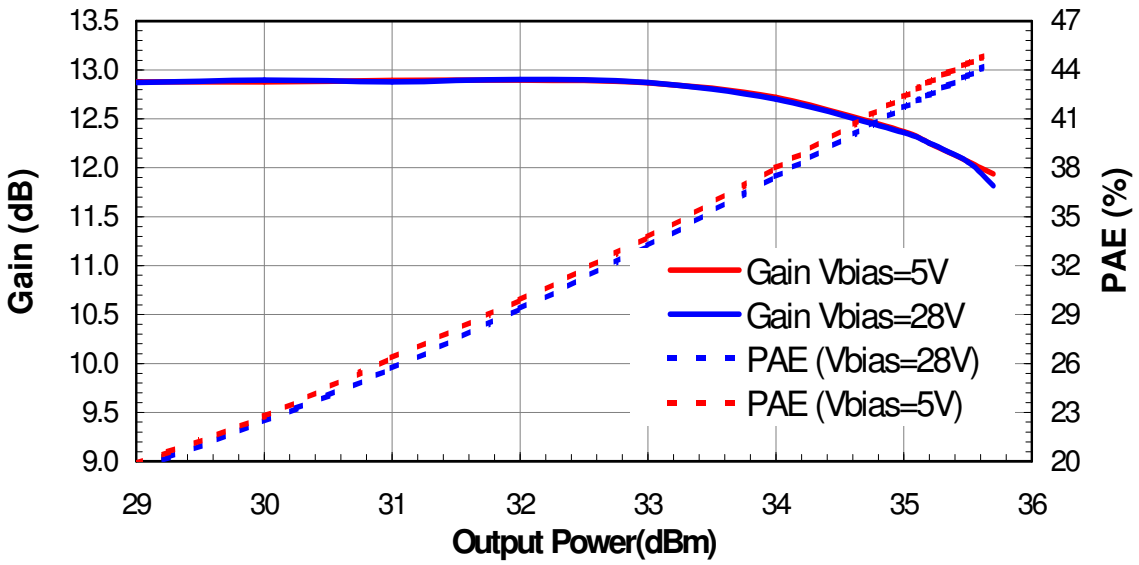

Figure 11. AP602 performance at 5 V and 28 V bias supplies voltage. Efficiency drops 0.65 % at 30 dBm when biased at 28V. Signal is CW at 2140 MHz at 25 °C. For Vbias =28 V: Rbias = 4.3 K, Rpd = 1.50 K, Icq=74 mA. For Vbias = 5 V: Rbias = 200 Ω, Rpd = 1.33 K, Icq=75 mA.

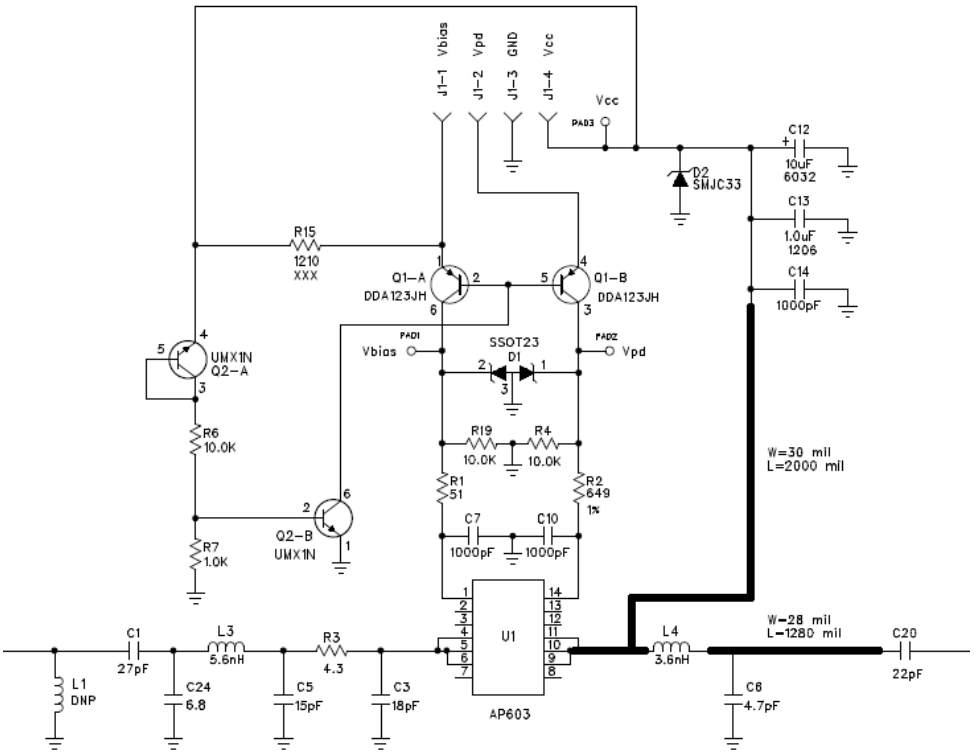

Figure 12. AP60X recommended alternate configuration for improved efficiency. Vbias=Vpd =5 V. Q1 - Q2 switching circuit removes 5V bias from Vpd and Vbias for the case of Vcc <15 V.

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RECCOMENDATION FOR EXISTING DESIGNS

The question that arises for designers who are seeing failures with existing designs is what is the minimum changes needed to insure safe operation. In particular time domain systems such as TDS-CDMA and WiMAX that continuously toggle the PA will require the improvements discussed here for reliable operation. The first step is to compare the schematics given here to the target application. Find the differences and then start changing the application circuit one step at a time, starting with the most obvious or easiest to change differences. If for example Vbias and Vpd are tied together and are being toggled to turn the amplifier on/off, then the Vbias line will need to be separated from the Vpd line and connected to a fixed 5V supply or Vcc. If that is already the case, or would be difficult to implement, then adding a 10K to ground at Vbias or Vpd might do the trick. The next step would be to add TVS diodes to the Vbias and Vpd lines. In many cases just connecting Vbias to Vcc with a series dropping resistor is all that is needed to eliminate switching failures.

CONCLUSION

The destructive forces of transient voltages can be mitigated by proper selection and application of commonly available TVS devices. Specific circuit configurations for TVS have been presented for the TQS family of HBT RF power devices. Floating grounds are a form of voltage transient that are protected by the uni-directional properties of the specified TVS devices. In many case a reliable design is as simple as connecting Vbias to Vcc with a series dropping resistor from **Table 3** and using a 10K resistor from Vpd to ground.

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