AN1225
APPLICATION NOTE

RF POWER TRANSISTOR BALLASTING IMPROVES PERFORMANCE OF SURVEILLANCE RADARS

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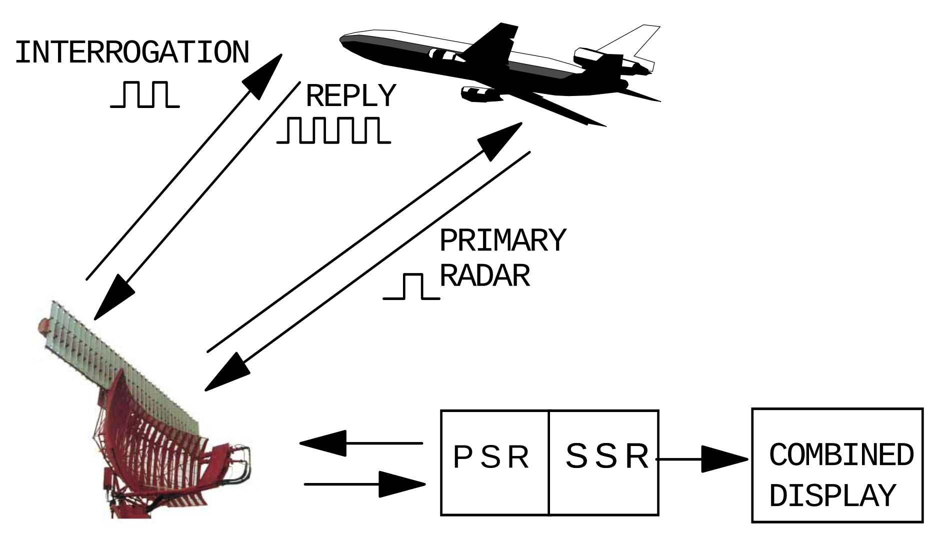
1. ABSTRACT

By designing in high levels of emitter ballasting, power transistors can achieve good thermal stability without reducing the collector efficiency. This is important for the interrogators and transponders used with the new generation of secondary surveillance radars that employ Mode-Select (Mode-S).

One of the major requirements for interrogators and transponders in surveillance radars is delivering sufficient levels of power, while maintaining an efficiency and gain that allows the final amplifier to be as efficient and small as possible. Historically, power transistors capable of short pulses and higher power levels have been derated in output power by reducing the collector in order to substain the longer pulse widths. This results in solid-state transmitters that are often criticized by tube advocates as being marginal, claiming that systems must be designed around the devices rather than vice versa. However advances in die processing and device manufacturing have produced a family of power transistors that can reliably satisfy the requirements called for in new Modes-S type Air Traffic Control Radar Beacon Systems (ATCRBSs). Mode-S techniques add a method of addressing interrogations to a particular aircraft without ambiguity or confusion such as exists in congested air traffic corridors, to present surveillance radar systems. To appreciate the case for Mode-S it is essential that some level of understanding exist in the principles of secondary surveillance radar and how it operates alongside the primary radar.

2. OPERATION OF SURVEILLANCE RADARS.

Figure 1: Primary and Secondary Surveillance Radar



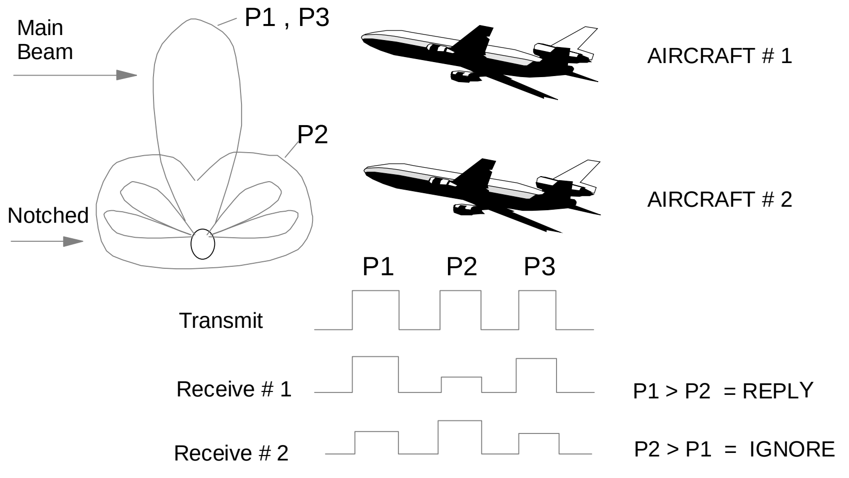
Secondary surveillance radars operate in conjunction with a primary surveillance radar to provide air traffic control information, as shown in Figure 1. However, rather than timing the received echo with respect to the transmitted pulse, as it is in the case of primary radar, secondary radar transmits a pulse train that triggers an on-board transceiver to reply. Therefore there are two parts to the system: the interrogator and the transponder.

The interrogator asks each target to identify itself. The aircraft transponder replies with flight number, destination and altitude (range and bearing having already been ascertained by the primary radar). Presently, Secondary Surveillance Radars or SSR systems interrogate targets based on spatial selection enhanced by ISLS (Interrogation Side-Lobe Suppression) and mono-pulse techniques. The SSR antenna is normally mounted above that of the primary. It too, of course, must be a directional antenna because high gain antennas produce side lobes.

Interrogation side-lobe suppression is employed to prevent interrogation via these lobes. The side lobes of the primary radar do not present such a big problem, as range is proportional to the fourth root of power as opposed to the square root in the case of SSR.

There are three different antennas for transmitting the interrogation: directional, main beam and omnidirectional (Figure 2). If pulses P1 and P2 are transmitted, P1 on the main beam and P2 on the omni, and an aircraft that receives those pulses compares the respective power levels of the two, it can discern whether it is in the main beam and whether or not a reply is warranted. By use of a notched antenna, rather than an omni for transmitting P2, the effective beam width can be controlled by varying the transmitted power level of P2 with respect to that of P1. However a situation can still occur that two aircraft in close proximity are triggered so that their replies overlap in time and thus cannot be decoded. This is known as "garbling". Confusion also arises from "fruit”. This is the term given to replies received by an aircraft that was triggered by a different air traffic control center. The Mode-S system addresses this problem specifically and enables each aircraft to be observed distinctly. They are able to time interrogations so that the replies do not overlap. "Fruit" can still occur, but since a Mode-S transponder replies with its address code the system is aware that it is "fruit" and can ignore the erroneous responses.

Figure 2: Interrogation Side-Lobe Suppression

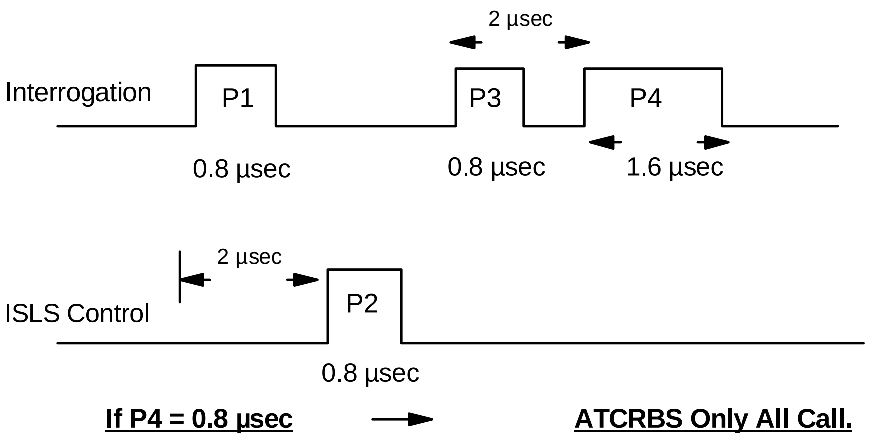


Interrogation side-lobe suppression allows transponders to discern whether or not they are in the main beam of the SSR antenna.

3. ADDING MODE-S SYSTEMS.

Mode-S maintains absolute compatibility with present radar surveillance systems. The interrogation frequency is, as always, at 1030 MHz and the reply frequency is at 1090 MHz with the interrogation signal being transmitted as phase shift keying and the reply signal as pulse position modulation. When an aircraft first enters airspace surveyed by a particular control site its address is unknown. Unless transferred verbally from one site to another the address is obtained by an "all-call".

Figure 3: ATCRBS Interrogation Scheme



In order to maintain compatibility, Mode-S systems must be capable of interrogating ATCRBSs type transponders.

Three types of "all-call" are employed:

1. ATCRBS and Mode-S all-call
2. ATCRBS only all-call
3. Mode-S only all-call.

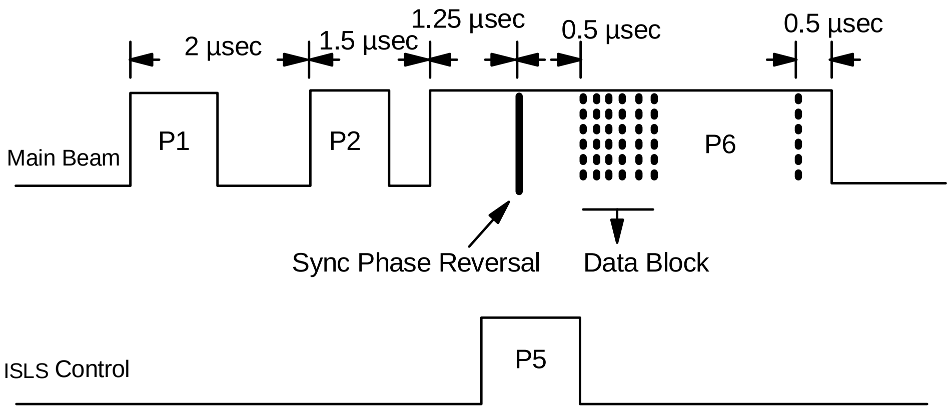
Case number 2 is the usual Air Traffic Control Radar Beacon System (ATCRBS) interrogation. All pulses P1, P2, P3 and P4 are 0.8 µsec. Mode-S transponders will not reply to this sequence. However, if P4 is lengthened to 1.6 µsec., as shown in Figure 3, both Mode-S and ATCRBS type transponders will reply.

In the third case of Mode-S only all-call, P2 is transmitted via the main beam and so surpasses all ATCRBS transponders. In other words, it fools them into "thinking" that they are being interrogated via a side lobe. A further pulse P5 is transmitted on the control channel at the same time as the sync-phase reversal such that it masks it from any targets not in the main beam; thereby, producing a side-lobe suppression for Mode-S transponders.

Once the ATC site has an address for a Mode-S type transponder it can be addressed individually. However, P2 is still transmitted on the main beam to prevent random triggering of ATCRBS type transponders, as shown in Figure 4 (Pulse P5 is also transmitted on the control channel although the latter is somewhat superfluous).

The data block P6 in a Mode-S interrogation (Figure 4) is either 16.25 µsec. or 30.25 µsec. long. The phase-sync reversal occurs 1.25 µsec. into the block. Data is transmitted 0.5 µsec. after the sync reversal.A phase reversal can take place every 0.25 µsec. If a phase reversal occurs, then logic zero appears. As a result, one bit of information occupies 0.25 µsec. A 0.5 µsec. guard band is maintained at the end of each data block to ensure that the trailing edge of the pulse does not interfere with the processing. Therefore, with a 16.25 µsec. pulse, 56 data bits occur and with a 30.25 µsec. pulse 112 data bits will result. The first 24 bits of both interrogations and replies are used for the address. Mode-S also has the capability to transmit an Extended Length Message (ELM). This consists of a maximum of 32 P6 pulses with a 50 µsec. pulse spacing. A second format of this transmits 96 P6 pulses with a 60 µsec. pulse spacing.

Figure 4: Mode-S Interrogation Scheme



Phase shift keying is used for data transfer in the Mode-S interrogation.

Mode-S transponders employ PPM or pulse position modulation. The data block is either 56 µsec. or 112 µsec. long. One bit of information occupies 1 µsec. time. The pulse width used are 0.5 µsec. The logic is:

SPACE - BAR = 0
BAR - SPACE = 1

As before, there are data blocks consisting of 56 or 112 bits of information.

4. DESIGNING THE INTERROGATOR TRANSMITTER.

With this background in mind, consider now what specifications such a system places upon the transmitter. There are, in fact, three types of transmitters required. One for the transponder and two for the interrogator. The second transmitter in the interrogator is necessary because P5 is transmitted at the same as P6. This transmitter is used for all pulses transmitted on the control channel. While the power levels required are somewhat higher than those of the primary channel, the pulse conditions are very light.

STMicroelectronics currently supplies single-ended devices for this application that deliver in excess of 750 Watts typically.

As transistor designs for such applications are very mature, this transmitter design need not be considered further. The real challenge lies with the transmitter requirements in the primary channel of the interrogator and transponder. Consider a typical interrogator of the form shown in Figure 5. Assume an output of the oscillator/modulator of 0.5 Watts and let the required output of the E channel amplified be 3

KW. To achieve modularity the amplifier is split into two sections; a driver and a High Power Amplifier (HPA). This allows the HPA to be a uniform corporate-structure design, providing the required output power level with the most reliability and smallest number of power transistors. Obviously, the design of such an amplifier requires a knowledge of the performance that can be expected from the transistors selected. This in turn will determine the "fan-out" ratio and thus the total number of devices required. The most important transistor specification is that the output power can be reliably delivered, consistent with high efficiency and gain. This will allow the final amplifier to be as efficient and small as possible.

Figure 5: Mode-S Interrogation Block Diagram

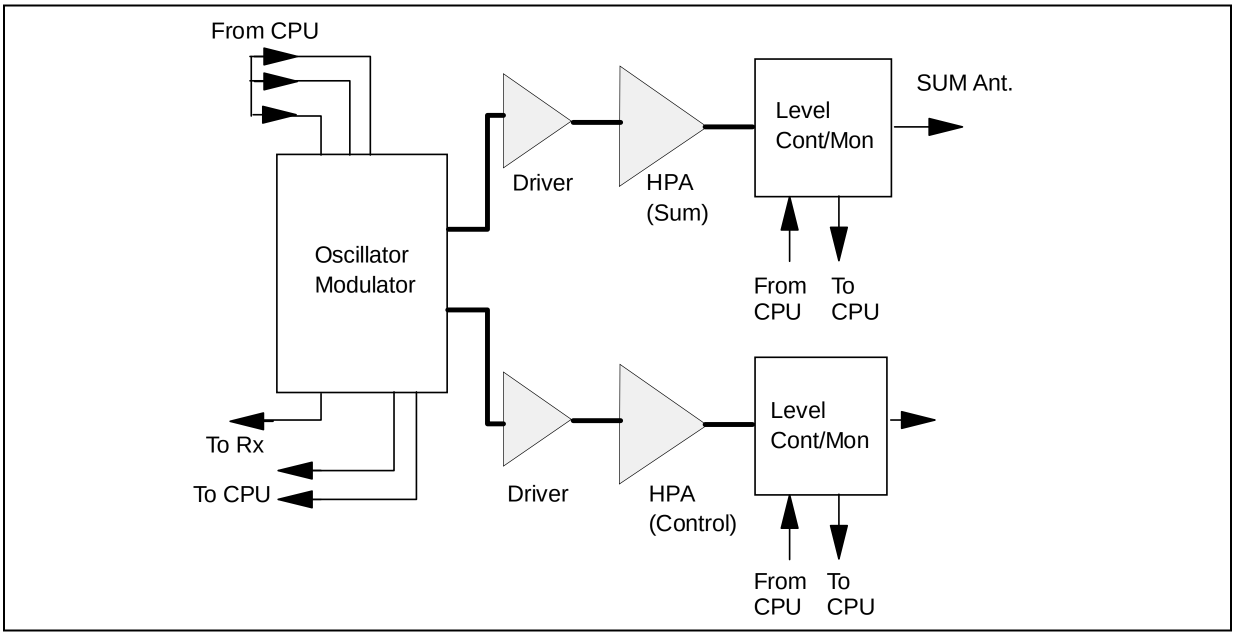
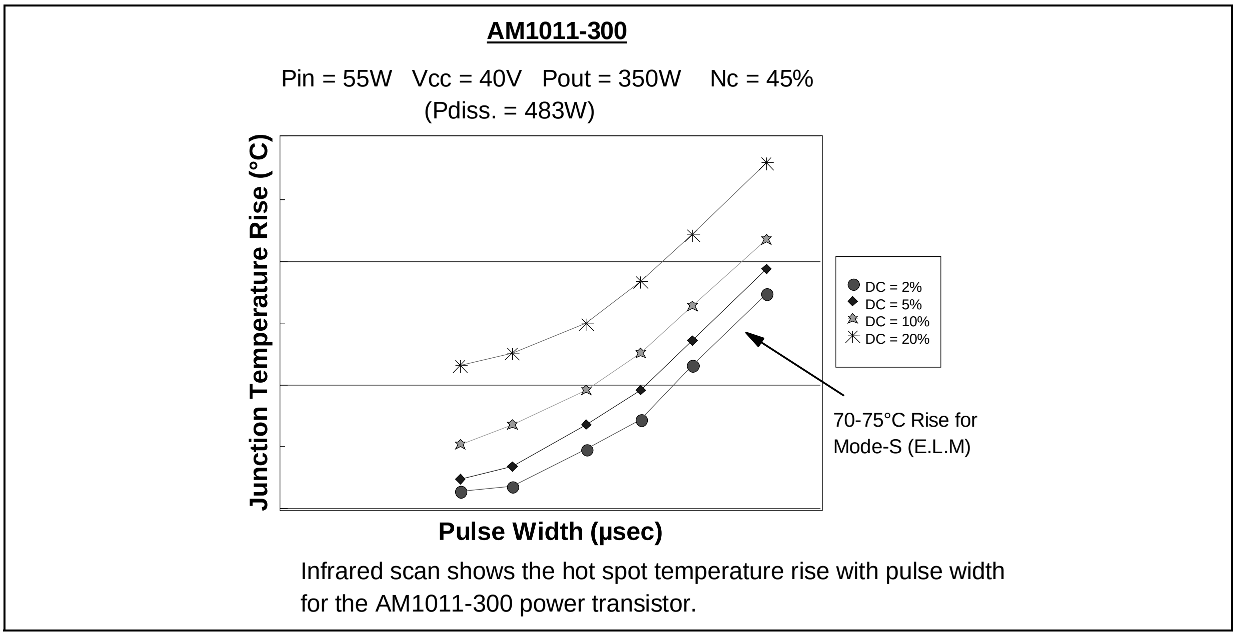


Figure 6: Junction Temperature vs. Pulse Width



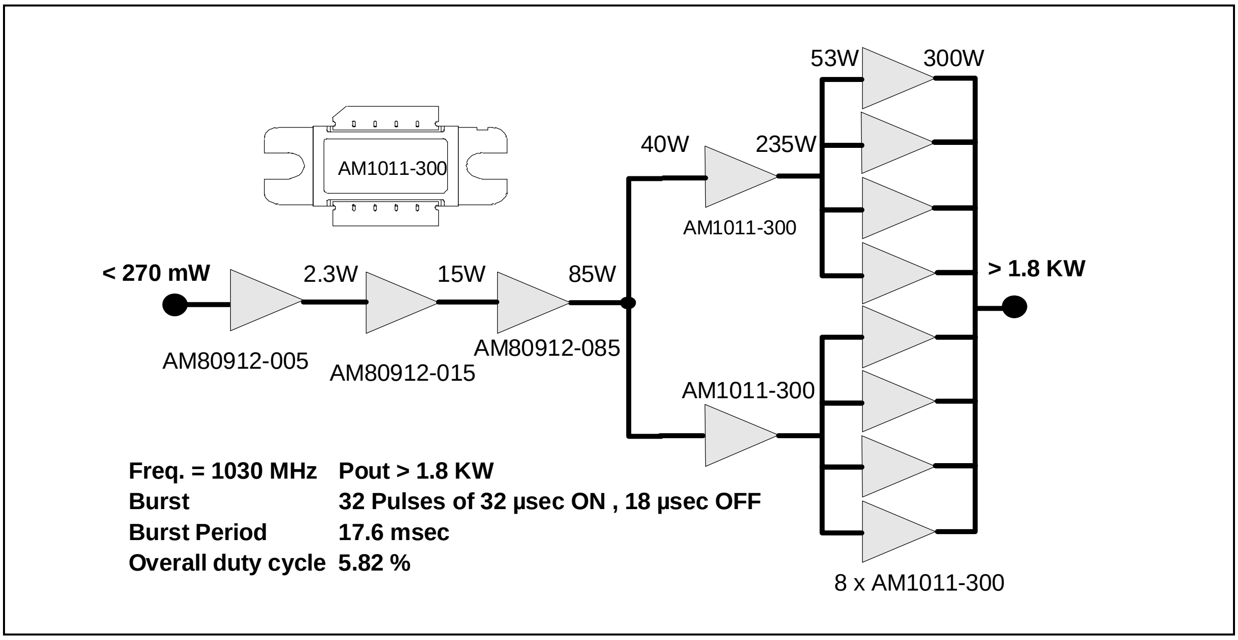
Infrared scan shows the hot spot temperature rise with pulse width for the AM1011-300 power transistor.

The Extended Length Message (ELM), as discussed earlier, has two formats: 32 P6 pulses with 50 µsec. pulse spacing or 96 P6 pulses with 60 µsec. pulse spacing. It is these pulse conditions that present the biggest problem to power transistor manufacturers since the die must be very rugged and thermally stable.

Typically, transistors capable of short pulses and higher power levels must be derated in output power by reducing collector voltage to meet these conditions. This method provides the transistor with so called collector ballasting. The level of this ballasting is inversely proportional to the collector potential (by a square root function) and it is determined by the amount of undepleted epitaxial material. In other words, the undepleted epi acts as a resistor in series with the collector. The biggest drawback to this approach is the loss of the collector efficiency.

At STMicroelectronics a die has been developed that uses a very high level of emitter ballasting. This allows it to attain thermal stability without a reduction in efficiency. In fact, efficiency is actually enhanced. The emitter ballasting does, of course, reduce the gain by increasing the emitter-base time constant. However, by using a die with an inherent Ft in excess of 2.5 GHz, 8.0 dB of gain is achieved at 1030 MHz. This very high level of emitter ballasting cannot be obtained using normal processing techniques. An overlay geometry is used with poly silicon site ballasting. In addition to this, there is emitter finger ballasting performed also with poly silicon. By using poly silicon to ballast the emitter fingers as well, it is possible to attain the high level of ballasting required and maintain a low current density to achieve desired levels of reliability.

Figure 7: Mode-S Interrogator - Typical Line-Up



Freq. = 1030 MHz **Pout > 1.8 KW**
Burst **32 Pulses of 32 µsec ON , 18 µsec OFF**
Burst Period **17.6 msec**
Overall duty cycle **5.82 %**

Infrared thermal scans show this die to be extremely stable over severe pulse conditions. These IR scans were taken from the device under various pulse lengths (in addition to the Mode-S Extended Length Message -ELM- format). Both formats were tested. It was found that the first condition of 32 P6 pulses at 50 µsec. pulse spacing (64% duty) is the most severe. As illustrated in Figure 6, a 70-75 °C temperature rise is obtained with the ELM conditions. Further, it can be seen that the device may be safely operated with much longer pulses. Also note that the ELM is equivalent to a single pulse around 200-250 µsec. This equivalence is only dependent on the thermal time constant of the die and not purely a function of thermal resistance.

The test results of this device, now known as the AM1011-300, indicates that the die is very suitable for long pulse, single frequency applications. AM1011-300 is both input and output matched.

It typically delivers 350 Watts with 8.0 dB gain. The lowest efficiency that was recorded was 40% (45% typical) and the highest temperature rise, the hot spot, was 70-75°C, measured off a 30°C flange. In designing an interrogator amplifier with these transistors, a minimum specification of 300-325 Watts with 7.7 dB gain was used. This means an input drive of 55 Watts minimum was required. If the output stage had used 8 transistors, the Corporate Structure Amplifier (CSA) design would have the form shown in Figure 7. This provides for a combining loss of 1.0 dB per eight-way splitter/combiner and a final isolator at the output.

The driver stage can easily be designed around the line-up of a AM80912-005 driving AM80912-015 followed by AM80912-085. This would then produce a 1.8 KW minimum at the output of the transmitter.
In the system, however, there are further losses associated with the switching networks and band-stop filters.

4.1 Interrogator designs.

In order for both Air Traffic Control Radar Beacon Systems (ATCRBSs) and Mode-S systems to function with minimum error it is necessary to ensure that the rise time of the transmitted pulse is less than 100 nsec., (as measured between the 90% and 10% voltage amplitude points) and the fall time is less than 200 nsec. Also, to comply with spectrum confinement requirements these rise and fall times must be greater than 50 nest. The problem that circuit designers face is trying to reduce rise time and increase the fall time. In transponder applications this can be achieved by collector modulating the transistors. However, in the interrogator (where the power levels are concerned) the number of output transistors is much higher, such a method becomes impractical. Here it is necessary to reduce the rise time to approximately 60 nsec., allowing the fall time to be 15 nsec. and then employing a spectrum confinement filter so that both rise and fall times will be increased in order to meet the system specifications. The problem then becomes, how to attain a rise time of 60 nsec. There are many circuit dependent factors that affect rise time. The closer a device is to saturation the faster the rise time will be. Also the emitter-base return choke and collector feed, associated with the video circuitry, must be kept to a minimum. On the collector, it is necessary to use at least three decoupling capacitors. The RF decoupling is best affected with a ceramic chip capacitor of around 100 pF and there is a main reservoir capacitor that supplies the current for the duration of this pulse. A third capacitor (commonly an axial lead chip) supplies the current for the duration of the rise time, or a percentage of it. When mounting this capacitor it is imperative that the leads are as short as possible to reduce the parasitic inductance, like any inductance in this network will serve to increase rise time. It also impedes the switching and can introduce pulse ripple. The value of the main reservoir capacitor will depend upon the power level, efficiency and allowed voltage, related pulse droop. One must ensure that this capacitor has a low series resistance and series inductance.

The compromise is that the larger the capacitance the larger the physical size. It is important, therefore, when evaluating transistors for such applications to consider the dependency of power level on applied voltage such that a figure for the maximum allowed voltage droop can be obtained. The final droop will be a function of both voltage and thermal droop. In order to meet often restrictive space constraints, it is advantageous to employ a device with minimal thermal droop. Thermal droop is, of course, related to junction temperature and a device's performance over temperature. Efficiency is again the key to the problem of droop. By keeping high efficiency, the power dissipated is reduced as well as the junction temperature. Further, less power is required from the power supply and so there is less voltage droop. The response of the complete video network must be carefully considered to ensure that it allows the transistor to exhibit a smooth transition both on rising and falling edges and that it does not introduce any instabilities. Instabilities are often caused by poor grounding of the decoupling point. This allows for signals at both RF and video frequencies to penetrate the power supply lines and couple back to the input. This will then manifest itself as oscillation on top of the RF pulse, or in severe cases, regeneration.

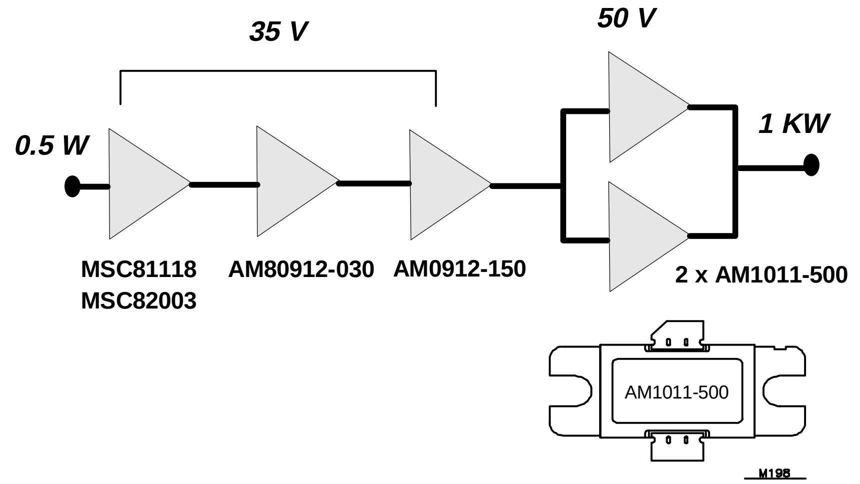
4.2 Transponder designs.

Transponders pose a different set of problems. They must be compact and capable of operation over severe temperature ranges. Because size is so critical, power transistors selected for this application must offer very high gain so that overall transistor chain will be small. Since the pulse conditions for this part of the beacon system are much reduced in comparison to that of the interrogator, the high levels of ballasting such as those used in the AM1011-300 are not required. The pulse burst length is only 112 µsec. but only at 50% duty cycle for this duration. If a transponder with an output of 800 Watts is required, this can be obtained with two output devices. Allowing for a 0.2 dB loss in a two way splitter/combiner, it is possible to achieve this with the line-up of the AM80912-030 driving the AM0912-150 driving two AM1011-500s in parallel (Fig.8). Collector modulating these devices will decrease the size necessary for the power supply; and as discussed earlier, will enable one to meet rise and fall time specifications.

5. CONCLUSION

The advantages of solid-state transmitters with regards to reliability and graceful degradation is well known. However, the counter claim that is laid on solid-state is that the devices, while capable of high peak power, are only useful in short pulse applications due to their thermal characteristics. Newly developed Mode-S systems allows for a great amount of data transfer in congested air traffic control situations. Although this places rigorous demands on the transistors advances in die processing techniques, device manufacturing have produced a family of transistors than can reliably satisfy this application.

Figure 8: Mode-S Transponder



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