A New Generation, Ultra-Efficient, High-Power DTV Transmitter

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Abstract
In this paper we discuss the implementation of the newest, and possibly the last, innovation in IOT technology, the Multi Stage Depressed Collector (MSDC) IOT. In addition to achieving up to twice the operating efficiency of a traditional IOT, other feature enhancements to the system may also be realized. To take full advantage of these improvements, a specially designed amplifier and support circuitry are required. This paper introduces a newly designed, ultra-efficient, high-power DTV power amplifier and its practical integration into a complete and working UHF transmitter system. Actual performance results are also provided.

OVERVIEW
With the industry wide acceptance of the IOT as a proven television amplifier device, combined with the rollout of DTV, the broadcaster is continually looking for ways to lower their operating costs and increase system reliability. This next innovation in transmitter technology for DTV promises to do just that.

HISTORY
Approximately 4 years ago, the idea of "marrying" a multi stage depressed collector to an IOT was being looked at seriously for the first time. The initial calculations showed that a substantial, increase of operating efficiency could potentially be realized by doing this. At this point the IOT manufacturers independently set out on their own unique paths to develop this technology into a real product. Here it is 4 years later, and as seen at this past NAB show there were 3 different implementations of a multi-stage depressed collector IOT. Each of these has their own unique features, and the operation of these devices varies from type to type. Because of the added complexity of the extra collector stage(s), coupled with the need for a "pure" cooling loop, along with the extra monitoring and control required to properly care and feed one of these new devices, it made sense to design a supporting amplifier cabinet to run one of these devices in the most reliable, efficient, and safe manner, instead of "modifying" an existing IOT amplifier and potentially compromise features, functionality, operator safety and reliability. The development engineering team at Thales Broadcast and Multimedia has designed just such an amplifier as shown in figure 1.

Figure 1
MSDC IOT High Power Amplifier

THE DESIGN PROCESS
When the design process started, there were a number of features that the design team wanted to incorporate into this amplifier. These include the ability to take full advantage of any of the various MSDC IOTs, an internal pure cooling loop, a user-friendly operator interface, and optimized mechanical ergonomics to aid serviceability. Maximum reliability has been achieved by removing certain complex and unnecessary components. This design also allows for retrofit to previously implemented Thales system control interfaces.

In order to take full advantage of all the MSDC IOTs the industry has to offer, the team quickly came to the conclusion that they needed to design for the most electrically complex version of these tube types, and "scale down" for the others. This being the case they looked at the five-stage device developed by Northrop Grumman. This MSDC IOT has a maximum DTV operating efficiency of approximately 60%. It is most complex electrically as it requires five different high voltage power supplies that need control, monitoring, and protection. Although this tube is the most electrically complex device it is also the most efficient. This creates a situation in the front end of the amplifier design that requires allowance for the least efficient devices operating at just above 45%. Because of this, the AC distribution and switchgear needed to be sized appropriately for the higher levels of power consumption at the same levels of maximum RF power output.

COOLING

Another key feature of the HPA is the internal "pure" cooling loop. All MSDC IOT devices require the use of various sources of high voltage at different values on the collector stages. These stages are liquid cooled due to their relatively high dissipation. Because of these two factors a "pure" type coolant needs to be used to both cool and insulate these stages. The traditional method was to use pure, de-ionized water with an active filter purification system and conductivity monitoring. This technology is in widespread use in the broadcast industry on devices such as triodes, tetrodes, diacrodes, and MSDC klystrons. The new innovation from the design team was to utilize a dielectric, synthetic oil as the coolant. This type of coolant is used in modern oil filled transformers and power supplies. In this application the oil is simply pumped as if it were water or a water / glycol mixture in a standard IOT based transmitter system. The first MSDC IOT to utilize this system is the five-segment device developed by Northrop Grumman Electron Devices. The E2V Technologies three-segment tube also incorporates this cooling methodology. Because there are different potentials of high voltage on the various collector segments, these stages will also contain a finite amount of RF energy. This RF energy needs to be de-coupled to ground and the collector segments need to be shielded to contain any RF radiation. The high voltage surfaces must also be covered for safety purposes. When oil is used as a coolant, both of these shielding features can be easily accomplished through the use of a conventional, one-piece coolant jacket over all of the collector stages. This places all of the stages in the same oil bath utilizing the dielectric properties of the oil to insulate between collector segments. In the pure water system, the high voltage isolation between segments is accomplished via a length of hose between individual water jackets on each collector segment. The entire collector end of the tube is then covered with a safety shield to prevent contact with the collector. This adds unnecessary complexity. In either case, the HPA needs to be able to supply the proper quantity of the coolant of choice to the collector of the tube. In this new design, the primary cooling loop has been incorporated directly into the HPA cabinet. This is advantageous for a number of reasons. The quantity of "pure" coolant is kept to a minimum, reducing the risk of contamination, and optimizing the required filtering of the coolant. It also allows the re-use of a secondary water / glycol based cooling system that may already be in place at the transmitter building if this HPA were used as a replacement, expansion, or upgrade unit to an existing system. There is no need to replace a perfectly good cooling system when installing one of these amplifiers. In the case of the oil-cooled system, Thales' patent pending design incorporates a number of key features to increase reliability and longevity. This system is shown below in figure 2.

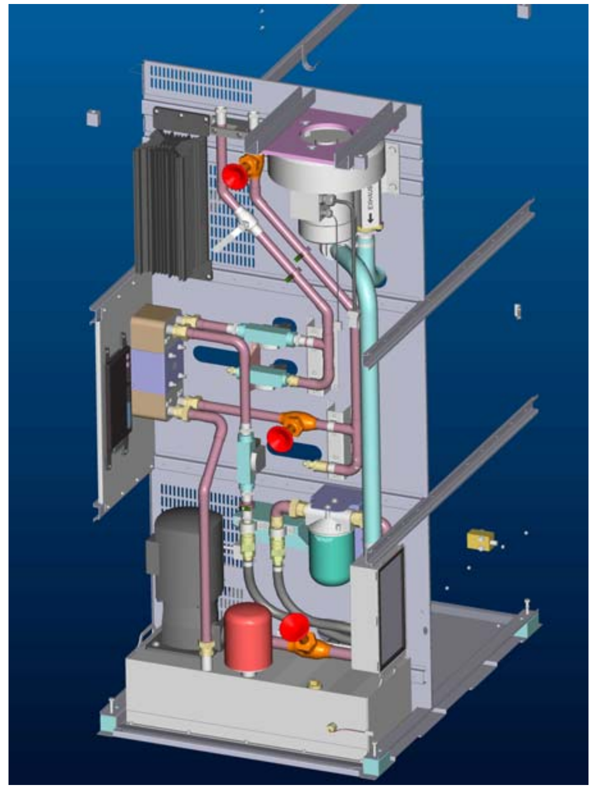

Figure 2
3D Solid Model Representation of the Internal Oil Cooling System

A stainless steel submersible pump with ceramic-based seals is used to feed a desiccant filled oil filter not only to remove any particulate contaminants but to also remove any moisture, as the oil is hydroscopic. From the filter the oil passes through the tube's collector section and back through a viscosity compensated flow meter, then on through a plate-style liquid-to-liquid heat exchanger. The waste heat can then be taken away by the secondary water / glycol cooling system utilizing a liquid-to-air heat exchanger. From the plate-style heat exchanger, the cooled oil is then returned to a sump tank that is vented to the atmosphere through a desiccant filled "breather". This device prevents the oil from ingesting moisture from the outside air. The coolant used in this system is Alpha 1 fluid manufactured by Dielectric Systems Inc. (DSI). This fluid is a synthetic-based oil with a flash point of 308 degrees Celsius. The oil is also fully biodegradable. A minimal 7 gallons is required to fill the system.

CONTROL AND MONITORING

The user interface control panel for the amplifier is the key component used to operate and troubleshoot the HPA. The design team used the same basic approach to this control panel as they had used in their earlier DTV IOT transmitter line with some enhancements to create a more user-friendly interface. Figure 3 shows this new user interface panel.

Figure 3
User Interface Panel

The enhancements include ergonomically grouping the various functions of Stop, Standby, Beam, and RF modes with the particular status and overload LEDs that are pertinent to that particular section. Another enhancement places the operating parameter metering directly on this panel instead of on a separate panel in the amplifier or, more traditionally, across the top section of the amplifier. The meters are also arranged in a similar fashion to the LEDs, as they are located in the appropriate section for measuring the pertinent parameters for that particular section. For example, the meters located within the "Beam" section are to measure exclusively the beam operating parameters of the tube. The scales on the meters are simple, easy to read with no more than two scales per meter. Another key feature enhancement is contained in the multi-line text display. It will include all of the same menu functionality as its predecessor and additionally will provide troubleshooting information in the event of a fault. For instance, in the case of an HPA utilizing the five-segment tube, the high voltage power supply has 5 outputs. Each one of these can potentially have a fault to ground. In the case of a standard IOT this would result in a crowbar event. With 5 power sources, there is the need to know which one of the five sources caused the fault. The multi-line display will state which source had the fault simplifying the troubleshooting process. Additionally, the screen will be able to display the amplifier operating voltages and currents (up to 5) simultaneously, allowing the engineer to optimize the operating parameters of the tube for greatest efficiency.

The control system is based on a concept of distributed I/O gathering, connecting to a central embedded processor via a Controller Area Network (CAN) bus. CAN is widely used in many harsh industrial and commercial environments including the automotive industry. This infrastructure allows the data to be gathered physically near each of several modules and then passed to the central processor for action. From the overall transmitter system perspective, the control interface is compatible with all previous Thales DTV tube transmitter products via a dedicated I/O module that communicates with the system level PLC (Programmable Logic Controller). Thus, this HPA can be used as an upgrade or replacement for currently operating, less efficient HPA technology.

IOT PROTECTION

The design team also wanted to eliminate a key component in the amplifier system that has received widespread criticism throughout the life of IOT based transmitter products. This component is the shunt crowbar mechanism. The job of the crowbar is to limit the energy that can be transferred to the inside of an IOT when a high voltage fault occurs. IOT protection has previously been accomplished in one of two ways. The most common method utilizes the previously mentioned "shunt" mechanism that actually short circuits the output of the high voltage power supply in the event of a fault. The other method requires the use of a complex, low storage, switch-mode power supply.

Triggered Spark Gap

The first generation of IOT based transmitters utilized a triggered spark gap type crowbar system as shown in figure 4.

Figure 4
Triggered Spark Gap

This system proved to be less than reliable as the triggered spark gap "aged" with each firing. Because of this, the system needed to be tested on a regular basis. The problem is that testing would also "age" the triggered spark gap even to the point of failure. Because of the required design for this system, there was no other way to tell the health of the system, causing an operator to have to "test it to death" at times and potentially it could leave the IOT unprotected.

Hydrogen Thyratron

Because of the lack of reliability with triggered spark gaps, in the early 1990's, transmitter manufacturers started using a hydrogen thyratron based crowbar system. See figure 5.

Figure 5
Hydrogen Thyratron Crowbar

This system was touted as being failsafe. Grid priming current, if measured, would be able to show that the thyratron tube was ready for action. There are also a few detriments that go with this benefit. First of all, the thyratron is yet another vacuum tube. It can and will wear out. Additionally, a thyratron system places more components at high voltage requiring that they be isolated from ground by means of fiber optics and power transformers which presents the opportunity for further problems.

Switch-Mode Power Supplies

There is another way that transmitter manufacturers have tried to tackle the protection of the IOT from high voltage faults. This system involves the use of a medium to high frequency switch-mode power supply configured in various ways to allow it to have a small amount of output capacitance coupled with a higher speed turn-off capability due to the operating frequency. These supplies have been tested by a number of manufacturers to be capable of protecting the IOT. Because of their nature they require a feedback signal allowing for regulation of the high voltage. Although this is nice from a laboratory operating perspective, the sheer amount of electronics involved, both at low and high voltage, coupled with the frequency at which these operate, cause them to be very costly to design and build. Because of the number of components required to make them operate, reliability is again compromised. Also, from the broadcasters point of view, this is now a critical transmitter part that contains unnecessary sophistication and is complicated to service.

Soft Arc Technology SAT™

The innovative approach taken with this new HPA was one of simplicity. The team took a long hard look at the real signal requirements for DTV and realized that the traditional specifications for beam power supplies were no longer required.

Traditional Beam Power Supplies

Until now, all of the manufacturers have simply "applied" their analog HPA technology to their DTV product. Because of this, the typical, widely used, choke input type power supply with 8 to 12 microfarads of output capacitance was utilized. This configuration contains a substantial amount of stored energy. These power supplies have been designed to exceed a -60dB AM noise requirement. This represents the hum and ripple specification for the traditional supply. There was also the need to pass the relatively long duration, high peak power vertical interval of the NTSC analog TV signal. Due to standard IOT efficiencies, power output capabilities, and the aforementioned specifications, these supplies were rated in the range of 100kW with impedance factors of less than 5%.

Traditionally the AC mains connection to this type of supply was via an electro-mechanical step-start or a vacuum contactor system. When coupled to a transmitter with a shunt type crowbar circuit, a high voltage fault will create a very violent impact to the AC power source as shown in figure 6.

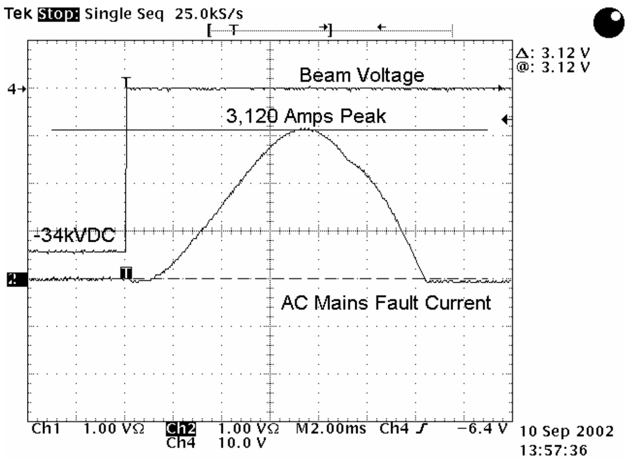

Figure 6
AC Mains Fault Current with Shunt Crowbar and Mechanical Step-Start

Additionally, the DC fault current that flows from the power supply through the crowbar mechanism during one of these events (figure 7) can represent a substantial amount of energy. This violent release of energy is known to contribute to sympathetic failures of many system components. These failures can be random and insidious throughout the life of the equipment.

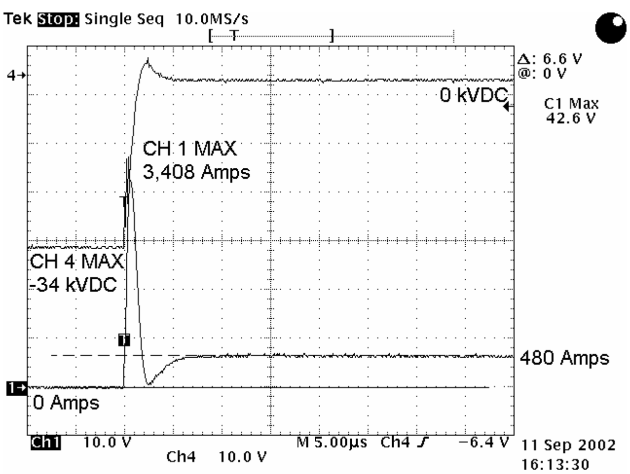

Figure 7
DC Fault Current from Power Supply with Shunt Crowbar System

New Switchgear Technology

Recently, the power electronics industry has introduced semiconductors in various forms that are suitable for use as switches for large amounts of AC. Since these are electronic, they are much faster acting than anything with physical moving parts. Using these semiconductor devices to control the AC to the high voltage power supply primary could, at the least, reduce the AC line disturbance caused by a crowbar event. The result of using such a system as applied in the Soft Arc Technology SAT™ system is shown in figure 8.

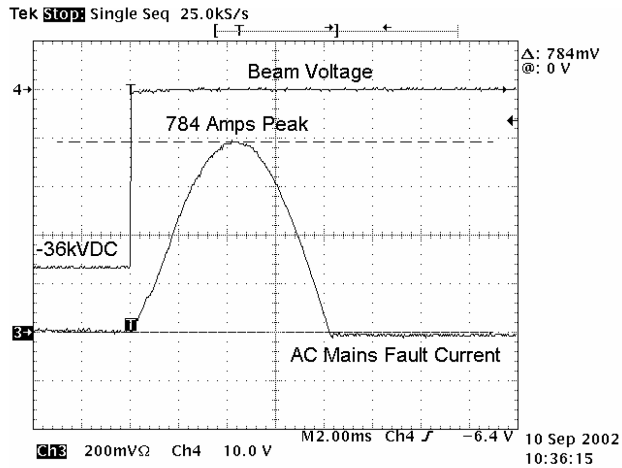

Figure 8
AC Mains Fault Current with SAT™

Since the -60dB or better AM noise spec did not exist in the DTV world, the team looked at what the limiting factor would be in terms of designing a power supply strictly for DTV service. With the peaks in the 8VSB signal being of such a very short duration, the real limiting factor was SNR (Signal to Noise Ratio). With a minimum specification of 27dB being a far cry from the old 60dB specification, there was quite an opportunity to redesign the output filter of the power supply.

The Thales patent pending Soft Arc Technology SAT™ system utilizes a solid-state switch on the AC mains of the beam supply. This solid-state switch serves two purposes. First, it is actually two sets of switches and a set of resistors configured as a "standard" resistive type step start. Using the solid state electronics as switches avoids the potential system resonance problems experienced in previous designs with phase angle fired SCRs configured as a "ramp on" type control. The second purpose is to remove the AC mains from the power supply in less than 12mS. This greatly reduces the "follow-on" energy supplied by the power supply during a fault condition. This solid-state switch is driven directly by HV current fault sensors eliminating any potential processing time required by a control system. This system is coupled to a conventional linear power supply that was carefully designed to the amplifier design team's specifications. This supply has a minimal amount of stored energy but will still pass a ripple spec of -40dB. Most critical, this would allow for a system that could naturally pass the most stringent of the IOT manufacturers "wire tests" with margin to spare. And, it could be done without the use of any series or shunt-type high voltage switch (crowbar)! Figure 9 shows the fault current in the IOT using SAT™. This is also the total fault current from the power supply unlike the crowbar-based system.

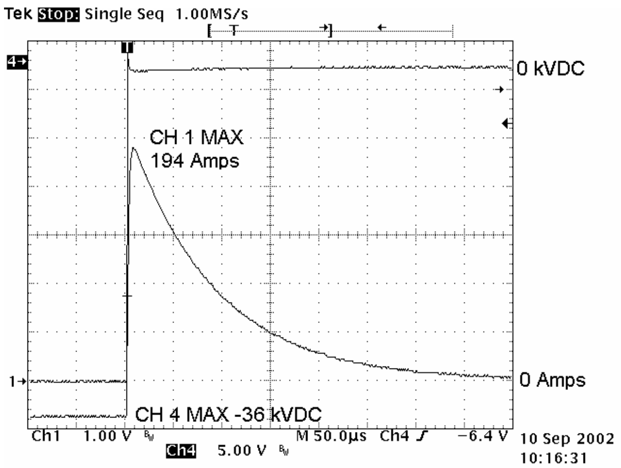

Figure 9
IOT Fault Current with Soft Arc Technology SAT™

The other goal of this design was to produce an amplifier that was extremely easy to maintain and repair. No matter how robust a design is, sooner or later it will need to be repaired or at the very least will require regular preventative maintenance. The last thing a maintenance technician wants is a piece of equipment that is difficult to service. As any experienced transmitter engineer knows, the work that takes place on these units is not always under the best of conditions. Failures can occur at the worst possible times and can be most difficult to troubleshoot and repair. Some of the features that have been added in this design make troubleshooting easier. Any piece of gear with 35,000 to 40,000 volts in it will, sooner or later, have a high voltage induced failure. Because we now have a situation with a tube requiring up to five different high voltages, we need to be able to troubleshoot high voltage problems easily and safely. The first item is a key part of the Soft Arc Technology SAT™ design. There is a sensor incorporated on each high voltage line to sense an arc of the high voltage to ground or to a different voltage source. The user interface has an indicator light that will display a high voltage fault, and, the multi-line text display on the user interface will indicate which sensor(s) detected the fault. This eliminates the need for guesswork in this troubleshooting process. Another key high voltage troubleshooting aid is a high voltage isolate / connect plug system for the MSDC IOT. This can handle up to a 5-collector device and allows disconnection of the IOT from the high voltage sources and reconnection to ground. This allows the isolated operation of the power supply system to determine if the fault is in the transmitter or the IOT. Figure 7 shows the layout of the high voltage compartment as configured for the Soft Arc Technology SAT™ system.

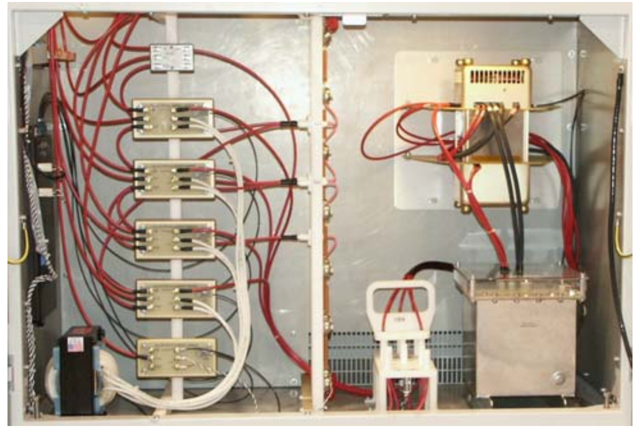

Figure 10
MSCD Amplifier High Voltage Compartment

OVERALL CONSTRUCTION

Other key features of the amplifier are modularization, and connectorization. All of the major sub-assemblies are in modular form and are connectorized to allow easy removal and replacement. The cabinet itself is designed to allow access to any of its inner sub-assemblies without having to reach more than half way into the cabinet, or approximately 18 inches. For standard preventative maintenance items such as air filters for the cabinet blower and cavity blower, standard HVAC and automotive type air filters are utilized. The oil filter is a standard hydraulic oil filter available at various major supply houses and through the Internet. Making these items readily available from other sources is helpful in insuring that they are changed at regular intervals.

For access behind the 19-inch front panels, a locking quick release catch system was incorporated. This system allows the panels to be “locked” in place by using a Philips screwdriver on the integral ¼-turn fastener making them IEC-215 compliant for safety while still allowing a quick release for ease of access without the risk of lost hardware.

PERFORMANCE

Notwithstanding all of these innovative features, what is the most significant argument for owning these amplifiers instead of another type of transmitter system? The answer to this question is in the cost to operate the transmitter. A standard IOT transmitter’s beam efficiency is on the order of 35% to 40% efficient at full rated output power. An IOT’s efficiency also decreases drastically as the power output level is decreased. The beam efficiency of a five-segment MSDC IOT is upward to 60% at full power, and only drops off to about 50+% at ½ power! Table 1 contains operating parameters obtained from the five-segment device in the Thales factory.

Table 1. Five-Segment Operating Data

Parameter	Voltage to GND (kV)	Effective Voltage (kV)	Current (A)	Power (kW)
Cathode	34.2	34.2	1.82	64.24
Collector # 1	0.0	34.2	0.458	15.67
Collector # 2	7.5	26.7	0.409	10.92
Collector # 3	14.2	20.0	0.290	5.81
Collector # 4	18.1	16.0	0.274	4.41
Collector # 5	24.3	9.9	0.389	3.84
Sums (1 - 5)	-	-	1.82	40.65
RF Output	-	-	-	23.3
IOT Eff. %	-	-	-	36.3
MSDC Eff. %	-	-	-	57.3
Eff. Increase	-	-	-	57.9

As shown below, a two-tube standard IOT equipped system operating at a 50kW level on a 24-hour per day basis from an electric source with a rate of $0.10 per kilowatt-hour will produce a monthly electricity bill of almost $12,000. By equipping this transmitter with five-segment MSDC IOT tubes, the added beam efficiency now yields a power bill on the order of $8,000 per month. This is about a 33% savings. Based on these figures, and the MSDC IOT type chosen an annual electricity bill savings on this transmitter should range from $29,000 to $48,000! This gives a transmitter of this type a very favorable return on investment. As they say, "your actual mileage may vary", based on electric rates, hours of operation and MSDC tube choice. Table 2 contains a comparison of typical two-tube transmitter electricity costs versus various amplifier types.

Table 2
Electric Cost and Savings for Various Transmitters

Amplifier Type	Efficiency	Monthly Electric Bill	Annual Savings
Standard IOT	37%	$ 11,880	$ 0.00
5 Collectors	60%	$ 7,920	$ 48,180
3 Collectors	53%	$ 8,784	$ 37,668
2 Collectors	48.5%	$ 9,504	$ 28,908

Signal Quality

Since an MSDC IOT is simply a standard IOT with a modified collector assembly, signal quality can be expected to be equivalent to previous IOT systems. Figures 11 and 12 show fully corrected amplifier output signal performance under the conditions documented in Table 1.

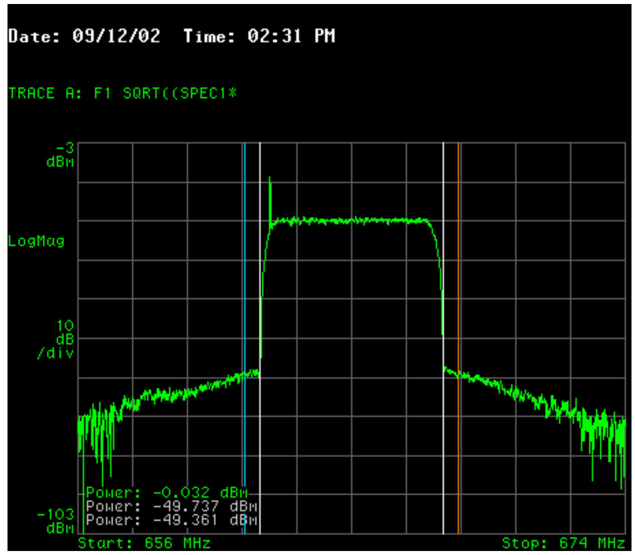

Figure 11
Output Spectrum Performance

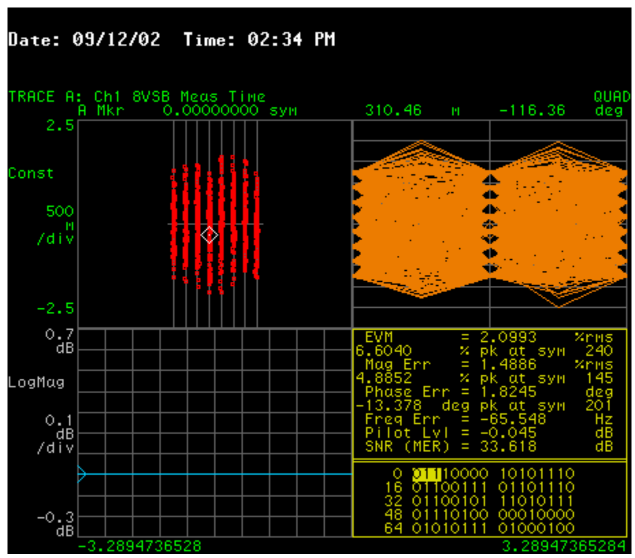

Figure 12
Output 8VSB Signal Performance

CONCLUSION

All in all, this may be the final step in efficiency enhancements for vacuum tube based television transmitters and will eventually obsolete standard DTV IOT systems. These transmitters will begin to be installed during the fall of 2002, and there should be a number of them on the air saving money by 2003.

ACKNOWLEDGEMENTS

- High Power Amplifier Design Team at Thales Broadcast and Multimedia, Inc.
- Dielectric Systems, Inc.
- E2V Technologies
- EG&G, Inc.
- Northrop Grumman Electron Devices
- NWL Power Systems
- Thales Electron Devices

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