ABSTRACT

M/A-COM, Inc. has previously developed a highly integrated transmitter chip set for wireless telemetry applications for the military L and S band frequencies and the commercial 2.4GHz ISM band. The original chip set is comprised of a voltage controlled oscillator (VCO), a silicon phase locked loop (PLL), and a family of power amplifiers (PA's). Using these components, M/A-COM has produced a miniature IRIG-compliant transmitter module, which has been flight-tested by the U.S. Army’s Hardened Subminiature Telemetry and Sensor System (HSTSS) program. Since the initial offering, several product enhancements have been added. The module performance has been improved by tailoring the VCO specifically for direct frequency modulation applications. In addition to improving noise performance, these enhancements have produced improved modulation linearity, decreased lock time and increased carrier stability. Modulation rates in excess of 10Mbps have been demonstrated. High efficiency power amplifiers operating at 3V have also been added to the family of amplifiers (PAE > 50%). This greatly enhanced efficiency allows higher RF power output while maintaining the same miniature form factor for the transmitter. Further, M/A-COM has added a silicon-on-sapphire PLL to the chip set, which operates at frequencies up to 3.0GHz. This paper details the enhancements to the components within the chip set, and the improvement in performance of the transmitter module. Test data is presented for the transmitter modules and individual components.

KEY WORDS

Transmitter, telemetry, munitions, high-g,
voltage controlled oscillator, power amplifier, phase-locked loop
INTRODUCTION

M/A-COM has developed a very rugged, small, low cost, low power transmitter module for ballistic telemetry applications. The module is comprised of a chip set developed specifically for the Hardened Subminiature Telemetry and Sensor System (HSTSS) program. The chip set architecture approach allows for embedded instrumentation solutions as well as retrofitting existing munitions with on-board measurement systems. Although some commercial transmitters exist for these types of applications, they typically are large in size, fixed in form factor, limited in performance, and expensive. In order to provide greater packaging and system design flexibility, a highly integrated transmitter chip set is required. The chip set is comprised of four major subsystems: a phase locked loop (PLL) chip, voltage controlled oscillator (VCO), a crystal reference oscillator, and a family of power amplifiers (PA’s). This paper briefly reviews the chip set and transmitter architecture. Enhancements and optimizations to subsystems are then discussed. The resultant performance improvements of the integrated transmitter module are then presented.

TRANSMITTER SYSTEM SPECIFICATIONS

The transmitter system design was driven by the contract specifications developed by the HSTSS integrated product team (IPT). General specifications come from the IRIG 106-96 Telemetry Standards. A listing of these major parameters can be found in reference [1].

COMPONENT REVIEW

The M/A-COM transmitter chip set is comprised of a PLL, VCO, and a family of PA’s. For maximum versatility, the chip set components are available in both die and surface mount packages.

The initial offering of PA’s include devices with 100mW, 250mW, 1W, and 2W power ratings. The lower power amplifiers (100mW, 250mW) are fabricated using M/A-COM’s heterojunction bipolar transistor process (iHBT™) requiring only a single 3V positive supply voltage. The power amplifiers with higher power ratings (1W, 2W) are MESFET devices, and operate with a drain voltage of 5V and 8V respectively.

The VCO is the primary frequency source and is available in L band, S band, and ISM band. This device is fabricated using iHBT™ technology (thus requires only a 3V positive supply). The output stage of this device is a 10dB amplifier, which buffers the output, and produces a minimum output power of 10mW. The tuning linearity has been measured to be approximately 6%. VCO test data is presented later in this paper.

The PLL originally developed for the project was fabricated in 0.35μm CMOS, and operates with a 3V supply voltage. This device has a parallel band and channel select interface, with sixteen channels available in each of three bands (L, S_LOWER, and S_UPPER bands). These sixteen channels are contiguous, spaced in increments of 1MHz. Although fully functional, extensive testing has shown that the device is sensitive to power supply variations over the –40°C to +85°C temperature range. A commercial PLL has been
selected which offers the capability of more channels and greater programming flexibility. This device will be discussed in another section of this paper.

The task of meeting the IRIG 106-96 ±20ppm frequency stability over temperature requirement is the duty of the reference oscillator. However, providing small, reliable, and affordable quartz crystal reference oscillators for high shock applications has been an on-going challenge. The Statek Corporation has developed a quartz crystal oscillator specifically for high-shock telemetry applications. This component provides frequency control for the HSTSS transmitter and potential clocking for the HSTSS data acquisition chip set.

Further information on the crystal oscillator and a summary of all the initial component offerings can be found in references [1,2].

**TRANSMITTER MODULE REVIEW**

A block diagram of the transmitter system is shown in figure 1. This type of modular architecture allows the telemetry engineer to optimize the transmitter based on the system requirements. The module can be configured to operate in either free running or phase locked mode, for L or S band operation, and can be configured for 10mW, 100mW or 250mW output powers. The operating voltage range of the module is 2.85V – 3.15V. The VCO is directly frequency modulated, decreasing the number of components required, thus enhancing miniaturization.

For free running operation the VCO is coupled directly with a PA. This inexpensive configuration can be used for extremely limited volume applications. The Army Research Laboratory at Aberdeen Proving Ground has implemented this type of configuration on modules less than 15mm in diameter for kinetic energy (KE) and small caliber projectiles. In free running mode, stability of +0.005% is met after the system has been allowed to warm up for approximately 5 seconds.

Figure 1. Frequency Source Block Diagram
The second configuration is the phase locked VCO with reference oscillator. The form factor of the module was chosen to fit into a standard NATO artillery fuze housing. The module dimensions are 1.125” (28.6mm) in diameter and 0.2” (6.0mm) in height with RF shield. The transmitter module was designed using both surface mount and chip & wire technology. The module is built on FR-4 substrate material and uses coplanar waveguide for controlled impedance lines. In this configuration, the $\pm 0.002\%$ stability requirement is easily met, and modulation bandwidths of over 10MHz have been demonstrated. Turn-on time is predominantly determined by the loop filter; for a 10kHz loop filter, turn-on times of the order of 0.5ms have been recorded. Both free running and phase locked configurations have been successfully flight tested by the HSTSS program on numerous platforms [1,2].

PRODUCT ENHANCEMENTS

In the past year, several improvements and/or additions have been made to the transmitter chip set. A high efficiency 500mW PA has been added to the family of power amplifiers, offering even more design options to the telemetry engineer. The original 2W MESFET PA is currently being replaced with a much smaller, more efficient $i$HBT$^\mathfrak{TM}$ device. A tailored silicon-on-sapphire PLL, provided by our partners at Peregrine Semiconductor, has been added to the chip set to provide greater stability over a broader range of temperatures. Finally, the M/A-COM $i$HBT$^\mathfrak{TM}$ VCO is being modified for dual port operation, which will yield better performance at lower (< 1Mbps) data rates.

500mW Power Amplifier: M/A-COM has tuned a commercially released 2.4GHz ISM power amplifier for operation in the military S band. The MA02303GJ has a saturated output power of 500mW and is designed on M/A-COM’s proprietary Multifunction Self-Aligned Gate (MSAG) MMIC process. This process offers significant benefits for defense and space applications. MSAG is an excellent choice for power amplifiers, delivering performance comparable to the more expensive PHEMT processes through X band. Because MSAG uses selective ion-implantation, it is also a true multi-function process: low noise, power, switch, and digital FETs and circuit functions can be integrated onto a single MMIC. MSAG is highly reliable and allows single supply voltage operation.

The MA02303GJ operates at supply voltages between 3V and 5V, and is been tuned with external components for S band frequencies. At a 3V supply, this device exhibits a linear gain of 30dB, and has a minimum saturated output power of 27dBm. The amplifier consistently yields power added efficiencies (PAE) of greater than 55%. Figures 2a and 2b show device performance with a 3V supply voltage.
New 2W Power Amplifier: A new 2W PA is being developed on M/A-COM’s \( \text{iHBT} \) process. This is an InGaP/GaAs HBT process based on a 3\( \mu \)m emitter dimension. The \( \text{iHBT} \) technology is ideal for portable wireless telemetry applications where efficiency, and ultimately battery size and runtime, is of primary concern. Saturated power performance of a typical \( \text{iHBT} \) 1080\( \mu \)m\(^2\) cell, operating at a supply voltage of 3V demonstrates a power density of 425mW/mm with PAE > 50%. Using M/A-COM’s \( \text{iHBT} \) process with patented heat spreading layout topology to ensure low thermal resistance, a very small (4mm\(^2\) plastic FQFN-16) microwave packaged amplifier is possible.

For reference, several 2W power amplifiers for handset applications in PCS (1.96GHz) and CDMA (836MHz) frequency bands have been designed and demonstrated using the aforementioned architectures. These power amplifiers are designed for use on an 8 mil thick first dielectric substrate FR-4 board. Figure 3a shows output power and PAE vs. input power for the commercial CDMA packaged amplifier. Figure 3b shows the uniform heating profile from an actual CDMA device under test conditions. At the time of writing, the commercial PCS device is being scaled for optimum performance in S band. This device will have a nominal 2W output, require a 3V single supply, and yield a PAE better than 50%. The amplifier circuit will include a digital control line, to power down the device for battery power conservation.
**New Phase Locked Loop (PLL):** To improve transmitter performance over temperature, M/A-COM has selected a Peregrine Semiconductor phase locked loop (PLL). This PLL is an integer-N device, fabricated using CMOS silicon-on-sapphire (SOS) technology (thus potentially rad hard). This new PLL die has a larger form factor (2526 x 2526µm) than the original PLL (1930 x 2311µm), and requires more external support circuitry. However, the new PLL provides advantages of frequency synthesis up to 3GHz and operation with a range of reference frequencies. Additionally, this device contains a programming interface select pin which enables the user to choose between parallel or serial programming. An on-board charge pump may be enabled for use with a passive loop filter, or disabled, allowing the phase/frequency detector to provide input directly to an active loop filter. M/A-COM has verified complete transmitter functionality over temperature on a test board using the new PLL. At the time of writing, a new layout is underway, of the 1.125” diameter module with the Peregrine PLL.

**Voltage Controlled Oscillator (VCO) Enhancements:** The architecture of the original transmitter module directly modulated the VCO. The modulation stream was added to the output of the PLL loop filter and both signals were input to the VCO tune port. This approach has distinct advantages in miniaturizing the transmitter, and reducing the number of requisite components. However, modulation data always has certain requirements for peak performance, especially in terms of peak frequency deviation. In order to satisfy optimum performance requirements within this architecture, special attention must be paid to the VCO. The next generation transmitters utilize an improved VCO to optimally transmit a wide range of data rates.

To optimize the VCO for direct frequency modulation applications, certain modifications had to be made to the architecture of the device. The same VCO chip is used, but is configured differently, allowing separate modulation and DC tune voltage ports. This allows the user to tailor the frequency deviation of the transmitter to the data rate of the system. The new configuration improves the transmitter performance of direct frequency modulation systems in a number of ways. First, isolation is increased between the modulation and loop filter circuits. This allows for a greater loop bandwidth, even for the lower data rates. Additionally, the user is given more control over the modulation characteristics, resulting in improved modulation linearity and noise performance especially at the lower data rates.

**NEXT GENERATION TRANSMITTER TEST DATA**

The IRIG-compatible transmitter module was enhanced with the features described previously in this paper. The following test data was obtained from a test board with complete transmitter functionality. At the time of writing, this functionality was being implemented onto a 1.125” diameter module. This transmitter module form factor is shown in figure 4.
The IRIG standard specifies all spurious output to be below $-25\text{dBm}$. The three (unwanted) spurious emissions generally seen in this system are 500kHz (PLL comparison frequency), 20MHz (oscillator reference frequency), and the harmonics at the output of the amplifier. The spurious output resulting from the PLL operation is shown below. As the choice of output amplifier power is dependent upon user application, figures 5 and 6 show the resultant spurious output of the phase locked VCO with oscillator operation (without output amplifier). It may be seen that the 20MHz spurs are less than $-65\text{dBc}$, and the 500kHz spurs are approximately $-65\text{dBc}$. It is clear, using simple addition, that for a 100mW (20dBm), 250mW (24dBm), 500mW (27dBm) or 2W (33dBm) system, both the measured 500kHz and 20MHz spurs would meet the IRIG specification.

The output amplifiers are all operated in saturation, and have been optimized for high PAE. This means that the harmonic output from any amplifier will not meet the specification without an output filter. For this reason, an output filter has been implemented on the module. Figure 7 shows the typical output from a 500mW transmitter (with output filter), which can be seen to meet the IRIG specification.
The stability of the module was examined over temperature. Figure 8 shows the frequency variation over time. The y-axis displays frequency and shows a variation of 90kHz (+0.002% of carrier frequency). At a given temperature, the stability is approximately an order of magnitude better than the IRIG specification of +0.002%. This measurement was performed with a 1kHz loop filter bandwidth. As the loop bandwidth increased, it is expected that stability will improve.

The modulation characteristics of the module were also examined. The modulation bandwidth was measured, and the response of the transmitter module from 25kHz to 10MHz is shown in Figure 9. The roll-off at the lower end is due to the dc blocking capacitor on the modulation input. It can be seen that there is less than a 2dB variation between 125kHz to 10MHz. Operation over 10MHz has also been demonstrated.
It is expected that the demodulated receiver output will accurately reflect the amplitude of the input to the transmitter. This behavior is characterized by modulation linearity. Modulation linearity is the maximum deviation from a best-fit straight line of the demodulated output amplitude vs. input amplitude curve, and is expressed in percent (%). The modulation linearity demonstrated by this transmitter was measured using a 10kHz sine wave over temperature. The modulation linearity was measured to be a maximum of 1.0% over temperature. The temperature variation is displayed in figure 10.
SUMMARY

M/A-COM has produced a transmitter module with a number of enhancements for improved performance and increased flexibility. Direct frequency modulation is the architecture of choice, due to fewer required components. The VCO has been tailored specifically for this application: separating modulation and DC tune ports on the VCO allows for each port to be optimized. This flexibility will improve overall transmitter performance, especially noise performance. Additionally, the flexibility of the transmitter may be enhanced by augmenting the family of amplifiers in the chip set operational at 3V. New PA’s at 500mW and 2W output power have been developed, with high PAEs. The new M/A-COM transmitter uses a PLL, capable of locking to all frequencies within L, S and the 2.4GHz ISM band, and frequency selection can be hardwired or serially loaded to the chip. When this chip set is used with a 20-ppm resonator the transmitter is IRIG 106-96 compatible.

This development effort represents a major advancement in the area of ballistic telemetry. The flexible architecture allows munition developers to integrate the instrumentation system with the on-board guidance, navigation and inertial measurement systems, thus providing an embedded instrumentation system. In addition to munitions testing, the transmitter chip set is ideally suited for vehicle, airframe, and soldier training applications.

REFERENCES


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