Integration of GaAs MMIC Technology in Commercial mm-Wave SATCOM and LMDS Transceivers

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ABSTRACT

This paper describes the key role that GaAs MMIC devices are playing in the development of cost-effective front-end components for mm-Wave Satellite Communications (SATCOM) ground terminal equipment, terrestrial LMDS and point-to-point / point-to-multi-point distribution systems. We present an overview of the development of two specific examples. The first is a MMIC based 19/29 GHz dual-channel transceiver for terrestrial or ground-terminal applications, and the second demonstrates how GaAs MMIC devices form the heart of a 2-Watt, 29 GHz transmit module for a specific SATCOM system currently being deployed throughout Europe.

INTRODUCTION

An ever growing demand for more bandwidth in the data communications field has led to unprecedented growth in the mm-Wave frequency bands during the past few years. Space-based and terrestrial systems are competing head-to-head to provide broadband services to the large business and consumer markets on a world-wide basis. In addition to competing with each other, terrestrial and satellite services are also competing against cable services that already offer broadband services in several large metropolitan markets, thus rapid development demands are high.

Cost is a key component in all commercial mm-Wave applications. We will outline some of the techniques used to control cost both at the MMIC design level and at the MMIC implementation (module design) level. Given the projected volumes for these systems, “Design for Manufacturability” is more than just a desire for these products. If mm-Wave commercial products are to achieve the lofty goals that current market forecasts are predicting, the overall product design – from MMIC design to final product assembly – must be compatible with high volume, low cost manufacturing methods, which we will illustrate where applicable.

In this paper we outline the development of two commercial mm-Wave products as examples to demonstrate how GaAs MMIC device technology plays a key role in practical, cost-effective design. The first is a MMIC based 19 / 29 GHz dual-channel transceiver suitable for use with K/Ka-Band satellite data and / or terrestrial LMDS communication systems. The second example demonstrates how GaAs MMIC devices form the heart of a 2-Watt, 29 GHz transmit module for a specific SATCOM system currently being deployed to distribute commercial 2-Way SATCOM services throughout Europe.

The goal in each of these two designs was to demonstrate functional modules which would be compatible with high volume, low cost manufacturing methods. Several of the “lessons learned” during the prototype construction are included, design considerations that affect low-cost manufacture are outlined, and the tradeoffs that link cost to performance are discussed where applicable.

Figure 1: Prototype Development Modules for a 19/29 GHz MMIC-Based Dual-Channel Transceiver (Top); and a 2-Watt, 29 GHz MMIC-Based SATCOM Transmitter (Bottom).

THE DESIGN CONCEPT

1. Electrical Design Considerations

Geostationary Satellite (GSO) systems such as SES Astra® (Europe), Hughes Spaceway® (North America); Medium Earth Orbit (MEO) systems, and Low-Earth Orbit (LEO) “array” systems such as Teledesic® and Skybridge® will all require ground terminals in the allocated K and Ka-Band frequency ranges. In addition, terrestrial mm-Wave point-to-point /
point-to-multipoint and LMDS / LMCS systems will require much of the same technology for both base-station as well as individual subscriber terminals. In addition to similar frequency allocations, all of these applications share one overriding requirement – High performance using high volume, low cost commercial manufacturing methods.

Figure 1 shows the completed prototype modules. The design concept was to provide for module designs that demonstrate as many technology points as possible as applicable to both terrestrial and ground-terminal applications.

Figures 2 and 3 show the block diagrams for the dual-channel 29 GHz Transmitter and the dual-channel 19 GHz receiver (respectively) that were realized in the dual-channel transceiver shown in Figure 1. Likewise, Figure 4 shows the block diagram for the 2-Watt 29 GHz SATCOM Transmitter shown in Figure 1. In both cases, the GaAs MMIC content is clearly indicated, and a study of the block diagrams shows that the MMIC devices are critical components on the high-frequency side of the frequency conversion mixer. Without MMIC devices at these locations, the indicated block diagrams would be very difficult to realize, and the time required to assemble, test and tune equivalent functions using discrete components would make the cost of these types of systems prohibitive for any potential commercial application.

A few key points that apply to all three block diagrams: (1) The integrated Local Oscillator is an important function that allows the module to function in a stand-alone environment. MMIC based Ku-Band oscillators have been available for DBS applications for a number of years, and a MMIC VCO (with an external resonator port) is probably the right choice for the LO in a fully integrated module design such as this. (2) No matter how simple the technology, it is very difficult to realize a MMIC mixer or frequency multiplier cheaper than a simple diode structure unless required gain can be integrated on the same chip. This is a desirable approach if it can increase the level of complexity at the chip level, thus simplifying and reducing cost at the module level. (3) Gain distribution is an important parameter in building a practical system. Too much gain in the wrong location can lead to linearity problems and/or can lead to stability and isolation problems. The MMIC chip set for a specific system should be optimized for that application before putting the design into volume production.

The dual-channel transceiver utilizes a sub-harmonically pumped (SHP; n=2) mixers in both the up and down-converter functions. The sub-harmonically pumped mixer is attractive in that it allows the entire LO chain to be constructed using low-cost plastic surface-mount components, and there is no need for a frequency doubler, a post-doubler filter or a post-doubler gain stage. The 29 GHz SATCOM transmitter uses a more traditional fundamentally pumped mixer to make the comparison. For the record, the linearity of the sub-harmonically pumped mixer design was still limited by the MMIC amplifier performance in both the receiver and transmitter, thus the SHP mixer is a good cost-effective alternative system design approach.

In both transmit channel designs, the post-mixer filter is a challenge, as it is required to remove the adjacent conversion “lines” separated by the input IF frequency. Since regulatory agencies typically require spurious output levels of at least –60 dBc, this requires a sharp RF bandpass filter. In the case of the designs presented here, these filters were realized on a separate alumina substrate. The spurious output requirement is helped if the MMIC amplifiers do not have unnecessary out-of-band gain, thus providing yet another reason why the MMIC chip set should be optimized for each system before high-volume manufacturing is attempted.

A similar alumina filter is required in the receiver (Figure 3) to remove the image frequency noise after the LNA. This filter requirement is not as severe, and the filter can be realized on the soft-substrate circuit board in a production design.

A dual-conversion approach was studied which would help to alleviate the filtering requirements, but the added complexity of the additional mixers, gain stages and filters made the approach undesirable from a cost standpoint.

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II. Mechanical Design Considerations

The three main goals of the mechanical design approach included: (1) The physical separation of the transmit, receive and power supply / control functions to minimize interaction and maximize isolation and stability; (2) Incorporation of a single soft-substrate approach to realize an entire transmitter or receiver function; and (3) To create a design that demonstrates compatibility with high-volume, low-cost manufacturing techniques. To these ends, the approach shown in Figures 5 and 6 were adopted for the two demonstration module designs.

In the dual-channel transceiver design, the transmit and receive functions were realized in two essentially separate modules which can function separately or can be joined to form a single module as shown in Figure 1. Both designs employ the unique feature that all RF electronics are placed on a single soft-substrate circuit board which is attached via sheet epoxy to the back-side of a “cover” plate as shown in Figure 5. The “body” of each design contains the DC bias circuitry and the compartment walls which provide needed isolation for circuit elements on each side, also as shown in Figure 5. This strictly planar RF assembly eliminates walls during the assembly process, and allows for easy assembly of all “pick-and-place” surface mount components – A proven high-volume manufacturing technique. (Note: The compartment walls were realized in the same manner in the 2-Watt 29 GHz SATCOM transmitter design, but the cover is not shown in Figure 6.)

Also visible in Figures 5 and 6 are the local oscillator (DRO) and associated cavity covers. In the 19/29 GHz transceiver design, the RF waveguide launches are printed on the substrate, and the ground plane is removed behind the launch to form a dielectric window launch, which also seals the module at the waveguide port.

In both designs, the alumina filters are seen to be epoxied into place, as are the carriers containing the GaAs MMIC devices. Eccosorb® patches were applied in the chambers above the MMIC RF amplifiers in both designs, as illustrated in Figure 5. The Eccosorb® patches prevent oscillation where RF gain is concentrated, and is a common manufacturing technique for higher-power-level microwave and mm-Wave modules. (Note: Figure 5 shows the transmitter side of the 29 GHz transceiver module. Although the receiver function on the opposite side is not shown, the circuitry and mechanical packaging is realized in an almost identical manner.)

DESIGN DETAILS

In both designs, the RF circuit boards were constructed using 8-mil (thick) Rogers® 4003 soft-substrate material. The module bodies were machined from aluminum and plated with nickel and 20µ-inches of gold. The substrate, the filters and the MMIC carriers were attached to the housing using conductive epoxy. All remaining surface-mount components were attached using a standard solder-paste pick-and-place process with a belt furnace solder reflow. The MMIC devices were eutectically attached to Cu-Mo carriers with appropriate bypass capacitors as subassemblies.

The MMIC devices employed in this design were Raytheon MMIC amplifiers as described in Table I. The up and down-conversion mixers in both designs are diode-based single-balanced ring mixers. In the 19/29 GHz transceiver, both the transmitter and receiver utilize n=2 sub-harmonically pumped (SHP) mixers. All 3 mixer designs utilize discrete beamless surface mount diodes, and in the case of the SHP mixers, the diodes are anti-parallel pairs. Both the SHP and fundamental mixer designs are tuned and matched with stubs to recycle unwanted harmonic energy to minimize conversion loss at the desired conversion frequency.

The prototype 29 GHz transceiver module utilized potentiometers to provide adjustable gate bias to the MMIC devices. In the 2-Watt SATCOM Transmitter module, an active bias circuit was developed using low-cost op-amp technology which automatically adjusts gate voltage to provide a pre-determined level of drain current. The circuit worked very well, and demonstrates yet another method of reducing test and tune time while at the same time providing more consistent performance when building modules in a manufacturing environment.

Wherever module walls are realized in the “body” of the module opposite the RF circuit board, mating metal strips with numerous via holes are provided on the RF boards in both module designs. This provides contact areas for the walls and forms RF isolation chambers. The walls can eventually be cast into a low-cost sub-cover which can be attached to the RF board at critical locations, exactly as it is presently done in numerous commercially available Ku-Band DBS LNB assemblies which are currently being manufactured at the million-unit level in offshore assembly and test facilities.
TABLE I
LISTING OF THE MMIC DEVICES USED IN THE TWO MODULE DESIGNS

<table>
<thead>
<tr>
<th>Module Design</th>
<th>MMIC Function</th>
<th>Raytheon Part Number</th>
<th>Gain</th>
<th>Noise Figure</th>
<th>PSAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>19/29 Transceiver</td>
<td>Receiver LNA</td>
<td>LN-0081-11</td>
<td>30 dB</td>
<td>2.7 dB</td>
<td>---</td>
</tr>
<tr>
<td>19/29 Transceiver</td>
<td>Transmit Pre-Driver</td>
<td>RMDA-27310</td>
<td>17 dB</td>
<td>—</td>
<td>+17 dBm</td>
</tr>
<tr>
<td>19/29 Transceiver</td>
<td>Transmit Driver</td>
<td>RMPA-29000</td>
<td>19 dB</td>
<td>—</td>
<td>+30 dBm</td>
</tr>
<tr>
<td>19/29 Transceiver</td>
<td>Transmit P.A.</td>
<td>RMPA-29100</td>
<td>16 dB</td>
<td>—</td>
<td>+31 dBm</td>
</tr>
<tr>
<td>2-Watt SATCOM Tx</td>
<td>LO Amplifier</td>
<td>RMDA-27311</td>
<td>17 dB</td>
<td>—</td>
<td>+17 dBm</td>
</tr>
<tr>
<td>2-Watt SATCOM Tx</td>
<td>RF Pre-Driver</td>
<td>LNA-0029</td>
<td>27 dB</td>
<td>N/A</td>
<td>+0 dBm</td>
</tr>
<tr>
<td>2-Watt SATCOM Tx</td>
<td>RF Driver</td>
<td>RMDA-27311</td>
<td>17 dB</td>
<td>—</td>
<td>+17 dBm</td>
</tr>
<tr>
<td>2-Watt SATCOM Tx</td>
<td>RF Power Amp. (2-Balanced)</td>
<td>RMPA-29000</td>
<td>19 dB</td>
<td>—</td>
<td>+30 dBm</td>
</tr>
</tbody>
</table>

MODULE TEST RESULTS

Figure 7 shows the measured output of one of the two receiver channels and one of the two transmit channels in the prototype 19/29 GHz transceiver module. On the receive side, the measured 1.2 GHz IF output level is -33.5 dBm in response to a 19 GHz RF input signal at -75 dBm, meaning that the receiver gain is 42.5 dB, which is within 2 dB of the design goal. On the transmit side, the output signal is +29.6 dBm, nearly the one-watt design goal, and the spurious output signal is <-50 dBc as specified. (Note: The visible spurious signal is a second-order conversion product from the sub-harmonically pumped mixer. There were no RF oscillations present.)

Figure 8 shows the measured bandwidth and output signal from the prototype 29 GHz 2-Watt SATCOM transmitter module. This module receives an S-Band (2.5-3.0 GHz) input signal at a standard cable signal level (-20 to -30 dBm) and upconverts, filters and amplifies the output signal at 29.5-30.0 GHz to the 2-Watt (+33 dBm) level. The internal local oscillator is phase-locked to a precision reference signal, which is also included in the module design.

An important consideration in the design of both of these prototype modules is the linearity of the system. In the case of the 19/29 GHz transceiver module, the receive channel third-order intercept (two-tone 3IP) was measured at +12 dBm using 19 GHz RF input signals at -50 dBm. Since +12 dBm is the rated saturation level of the IF output amplifiers, we assume these to be the limiting factor and not the mixer. It would appear that slightly larger IF amplifiers can improve the linearity performance to an even higher level if desired.

The linearity of the SATCOM transmit module was evaluated using a spectral regrowth measurement and by measuring Adjacent Channel Power Rejection (ACPR). Measurements showed that at the 2-Watt output level, the adjacent channel power is better than the -20 dBc design goal by 4.5 dB. This, in conjunction with the actual spectral regrowth measurements, shows that the prototype module meets a practical application requirement for linearity. In fact, the prototype SATCOM module was actually used to communicate with a Satellite over Europe and the transmit function worked well in delivering modulated data to the satellite system.

CONCLUSIONS

GaAs MMIC technology was employed in the development of two prototype mm-wave module products. The first design was a dual-channel 19/29 GHz satellite ground terminal transceiver module, and the second was a 29 GHz, 2-Watt SATCOM transmit module. Both of these designs were built and demonstrated. The principal electrical performance for both designs either meets the target design goals or comes very close. Some work needs to be done in optimizing the designs for high-volume production applications, but the critical aspects of the work were demonstrated in these designs.

The mechanical packaging concept for both designs is novel in that the approach is geared for compatibility with high-volume manufacturing methods. The design approach can now be applied to specific product developments because the concept is proven. In addition to the satellite ground terminal applications addressed by these efforts, the design concepts can also be applied to new products in the m-Wave radio bands at 24, 26, 28, 31 and 38 GHz.

ACKNOWLEDGEMENTS

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Figure 7 – Receive Channel Gain Flatness (Top) and Transmit Channel Power Output Signal (Bottom) from the 19/29 GHz Prototype Transceiver Module. Accounting for External Attenuation, Pout = +29.6 dBm.

Figure 8 – Output Signal from the Prototype 2-Watt SATCOM Transmit Module. Passband Gain Flatness (Left) and Spectral Output Signal at Band Center. External Attenuation = 13 dB; Displayed Power Level at +33 dBm (2-Watts).