Compact KU-Band T/R Module for Wide-Swath High-Resolution Radar Imaging of Cold Land Processes

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Abstract— The ACT program has developed a Transmit/Receive (T/R) module operating at Ku-band frequencies to enable the use of active electronic scanning phased array antenna for wide swath, high resolution synthetic aperture radar (SAR) imaging of terrestrial snow cover. For the SAR application, the electrical specifications of prime importance are the peak output power of each module and the stability of the receive gain and transmit power over extended periods of time. The T/R module described has an integrated calibrator which compensates for all environmental and time related changes and results in very stable power and amplitude characteristics. Each channel of the transmit module produces > 4 watts (35 dBm) over the operating bandwidth of 20 MHz. The stability requirements of <0.1 dB receive gain accuracy and <0.1 dB transmit power accuracy over a wide temperature range are achieved using a correction scheme which does real time amplitude calibration so that the module characteristics are continually corrected to the required values. The module was designed using advanced components and packaging techniques to achieve integration of the electronics in a 2 in (5.08 cm) by 6.5 in (16.5 cm) by 1 in (2.45 cm) package. The module size allows 4 T/R modules to feed the 16 x 16 element sub array on an antenna panel. The T/R module contains 4 transmit channels and 8 receive channels (horizontal and vertical polarizations). Each channel contains GaAs mmic amplifiers and a 5-bit phase shifter and a programmable attenuator. To meet the compact size and maintain isolation between the channels, a two-sided module approach was adapted. The broadband 4-channel highly stable T/R Module will be a useful building block for other radar and communication phased array systems operating in this band.

I. Introduction

Terrestrial snow cover, sensitive to changes in temperature and precipitation, interacts with several important climate variables through complex feedback mechanisms. Snow is an important component of fresh water resources, especially in many of the world's mountainous regions and their surrounding lowlands. High-resolution snow water equivalent (SWE) observation requirements were articulated by the Global Earth Observing System of Systems (GEOSS), Integrated Global Observing Strategy (IGOS), WMO/WCRP Climate and Cryosphere (CliC) Project, Science and Co-ordination Plan (Allison et al., 2001), National Research Council (NRC) Report on Adequacy of Climate Observing Systems (Karl et al., 1999); Intergovernmental Panel on Climate Change (IPCC) (Watson, et al., 2001). The United States Executive Office of the President, Office of Science and Technology Policy Update on Research and Development Budget Priorities (Aug 12, 2004) identifies the ability to measure, monitor, and forecast the U.S. and global supplies of fresh water as a high-priority concern.

Global measurement of terrestrial snow cover is critical to two of the NASA Earth Science focus areas, including 1) Climate Variability and Change and 2) Water and Energy Cycle. The Cold Land Processes Working Group (CLPWG), formed in 2000 by the NASA Terrestrial Hydrology Program (THP) has identified the science, technology, and application infrastructure necessary to support advanced remote sensing measurements to the terrestrial cryosphere. For radar backscatter measurements, Ku-band frequencies, scattered mainly within the volume of the snowpack, are most suitable for the SWE measurements (Ulaby and Stiles, 1984; Carver et al., 1990). Recent investigations of the coarse resolution (20Km) data from the NASA spaceborne QuikSCAT scatterometer operating at 13.4 GHz frequency have demonstrated 2-4cm SWE retrieval accuracy using Ku-band radar measurements for complex terrain (Cline et al., 2004; Yueh et al., 2007). To isolate the complex effects of different snowpack (density and snow grain size), and underlying soil properties and to distinctly determine SWE, the space-based synthetic aperture radar (SAR) system will require a dual-frequency (9.6 and 17.2 GHz) and dual-polarization approach.

Given the need for dual-frequency and dual-polarization measurements, the technology challenge is made significantly greater by a need for high-resolution and wide swath data. An objective resolution of 100-m has been identified for remotely sensed snow measurements. There are two main science drivers for 100-m resolution. The first is that the natural heterogeneity of snowpack properties (that affect both microwave and hydrometeorological response) is typically very high. The second science driver for 100-m resolution is that predictive earth system models currently have land surface components operating at 1-km spatial resolution for continental and global-scale applications. It is conceivable and perhaps even likely that this resolution will increase in the next decade. This modeling resolution is driven by a scientific need to represent relevant physical processes correctly, and to capture the natural heterogeneity of land surface processes. The need to update these models with

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observed SWE is an important driver for remotely sensed measurements of these properties, and a fundamental requirement in this regard is that the measurement resolution should exceed the modeling resolution by at least a factor of two. The electronic-scanning SAR (ScanSAR) antenna technology will achieve the swath width and high resolution for frequent repeat coverage of snowpacks.

TABLE I. KU-BAND T/R MODULE TRANSMIT MODE SPECIFICATIONS

Transmit frequencies	13-17 GHz
Transmit bandwidth	20 MHz
Transmit peak power	37 dBm (5 W)
Transmit power stability	<0.1 dB
Module input power	0 dBm
Module input power VSWR	<1.3:1
Transmit efficiency	>20%
Spurious signals	-40 dBc
PRF	8-10 KHz
Amplitude droop	<0.5 dB over 20 usec
Maximum duty cycle	10%
Pulse width	10-20 us
Power flatness over 20 MHz	<0.2 dB
Digital phase shifter	5 Bits
Phase shift accuracy	< 5deg rms
Phase switching time	< 1 us
Operating Temperature Range	-40 deg C to 70 deg C

TABLE II. KU-BAND T/R MODULE RECEIVE MODE SPECIFICATIONS

Receiver	Two parallel receive channels for each transmit channel (Vertical and horizontal polarization)
Frequencies	13-17 GHz with 20 MHz bandwidth
Gain	20 dB
Gain stability	<0.1 dB
Gain flatness over 20 MHz	<0.2 dB
Noise Figure	<2.5 dB
P in 1 dB compression	-30 dBm
Input/Output VSWR	<1.3:1
Analog attenuator range	> 15 dB
Digital phase shifter	5 bits
Phase shifter accuracy	< 5deg rms
Phase switching time	< 1 us
Isolation between channels	40 dB
Operating temperature range	-40 deg C to 70 deg C

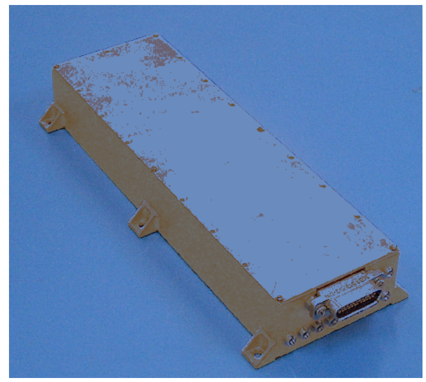


Figure 1. T/R module 4 pack housing

II. T/R MODULE DESIGN

The module was designed to meet the specifications shown in Tables 1 and 2. The photo of the complete T/R module housing is shown in Fig. 1. It measures 6 in x 2in x1.5 in and weighs 320 grams. GPPO RF connectors are used for all the RF in/out interfaces and a 25 pin miniature D connector for all digital and power connections. The T/R module housing was designed to contain 4 transmitter channels and 8 receiver channels. The module also houses the items shared by all the channels including the transmit power dividers, control and DC bias and regulation circuitry, the field-programmable gate array (FPGA) and the Random access memory (RAM).

The block diagram for the T/R module 4-pack sub-array (Fig 2) shows the configuration of the complete module package. Each element is composed of one transmit chain and two receive channels, for simultaneous V and H polarization reception. The transmit channel feeds the vertical polarization of the antenna through the circulator, which protects the power amplifier when large Voltage Standing Wave Ratios (VSWR's) are encountered during antenna scanning. The transmit channel has 38 dB of gain amplifying the 0 dBm incoming signals to 5.6 watts (+37.5 dBm) at the output. The transmit chain is composed of an analog attenuator, a buffer amplifier, a phase shifter, the driver amplifier and the power amplifier. The final power amplifier is an integrated GaAs mmic, and can supply >5 W in the frequency range of 13 to 18 GHz. It has a gain of 24 dB and is fabricated using a standard

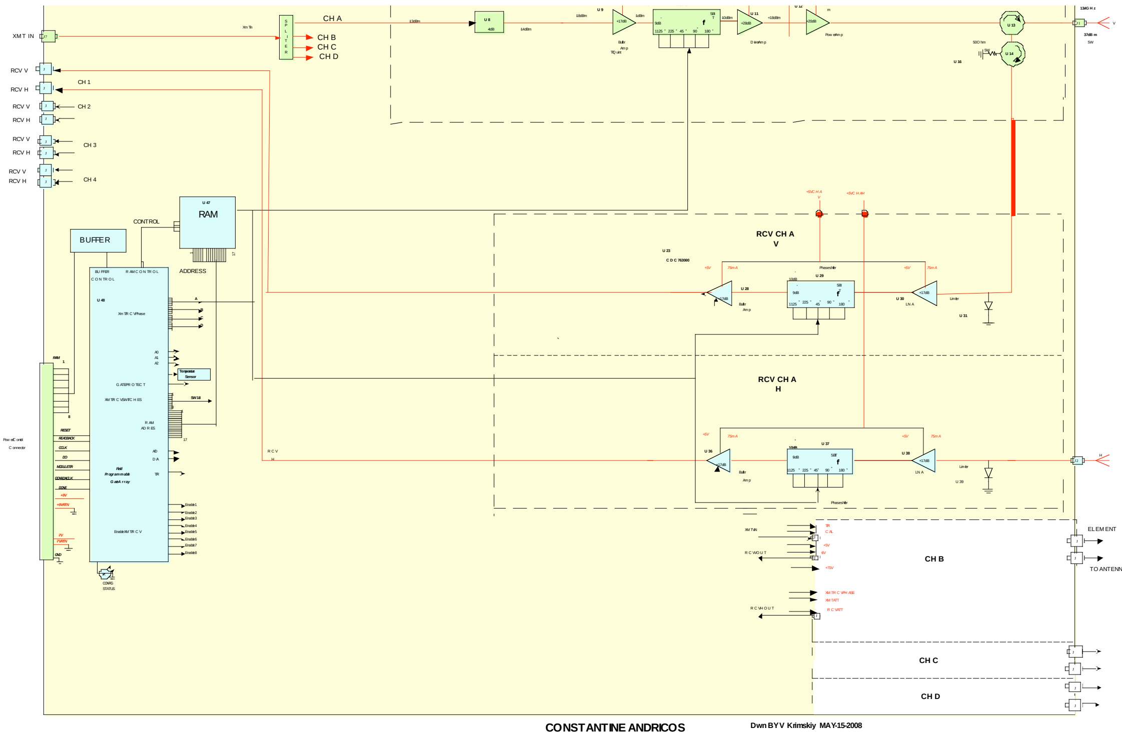


Figure 2. Simplified T/R module block diagram

0.25µm gate Pseudomorphic High Electron Mobility Transistor (pHEMT) process. The digital phase shifter is a broadband (6-18 GHz) 5-bit device using GaAs devices with an on chip Complementary metal–oxide–semiconductor (CMOS) compatible interface. Since the power amp operates in the saturated mode, the drain voltage of the GaAs power amplifier is used to control the power output and maintain constant power output over all environmental conditions.

The receiver consists of two identical channels for the separate horizontal and vertical polarization paths. The input to the vertical receive channel comes from the dual circulator in the transmitter channel. Protection to the receiver is accomplished by the limiter which reflects transmit leakage power back to the load of the circulator. Broadband highly integrated GaAs Monolithic Microwave Integrated Circuit (MMIC) chips are used for all the functions to minimize the size and parts count. The receive chain consists of the Low Noise Amplifier (LNA), the programmable phase shifter, and the variable gain buffer amplifier. The input LNA is a broadband 0.15 um pHEMT monolithic amplifier with 2 dB nominal noise figure and 17 dB of gain. The digital phase shifter, similar to the one used in the transmitter, sets the phase in each channel. An analog gain control amplifier is used to adjust the gain over a 20 dB range during calibration.

In order to achieve stable transmit power output and receive gain, calibration circuitry is included in the module. In the transmit mode the output power is sampled through a coupler, detected and converted to a digital word which is inputted to the FPGA and the RAM. The sampled signal is compared to the reference power and the loop adjusts the drain voltage on the power amplifier to maintain the RF power output at the desired level settings. In the receive mode a calibrated signal is fed through the input port to each receiver with couplers and then sampled at the outputs and digitized. The loop amplifier adjusts the gain control circuits in each channel to maintain the gain at the reference levels. A 128Kx8RAM is used to store all the receive and transmit calibration settings.

III. MECHANICAL DESIGN

The mechanical design selected took into consideration commonality of all of the power and control circuitry required for each element to achieve the required element density in a compact package. To meet the compact size and maintain isolation between the channels a two-sided module approach was adapted. The transmit side of the module houses the 4 transmit channel, the control FPGA, the RAM, and the power regulators and logic circuitry. It also contains the 4-way microstrip power splitter (Fig. 3). The 4 dual channel receivers are packaged on the reverse side of the module along with the logic and power conditioning circuits (Fig. 4). A ring frame on the receive and transmit board maintains the isolation between the channels.

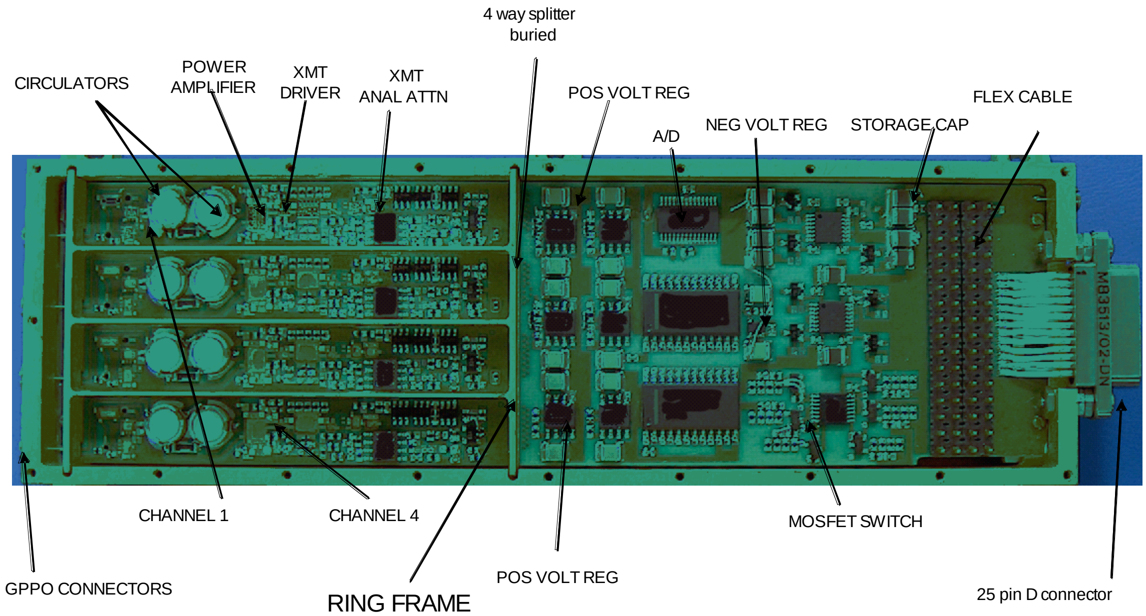
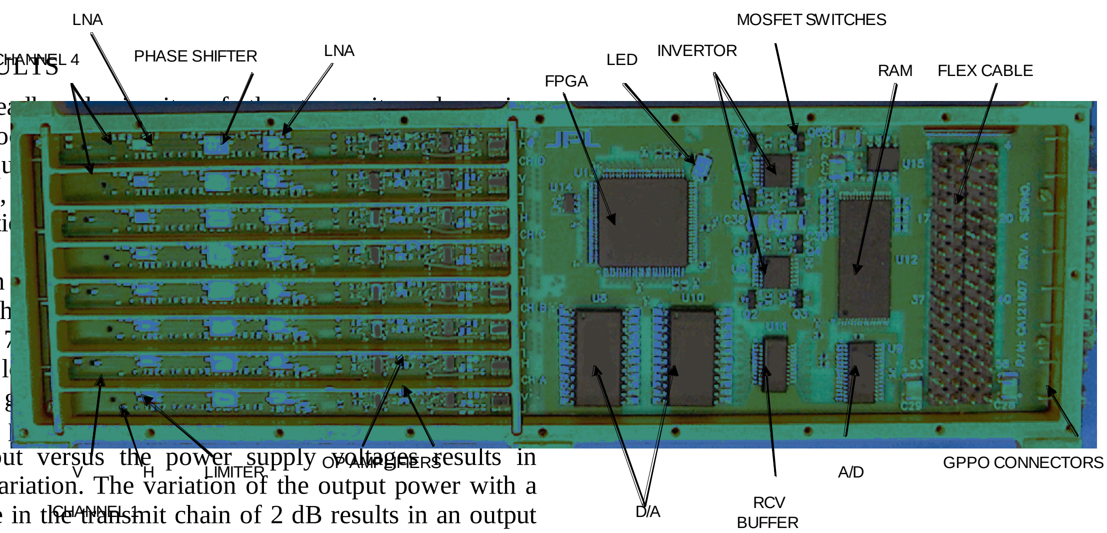


Figure 3. Transmit side of T/R module showing components.

TEST RESULTS



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power output versus the power supply voltages results in <0.02 dB variation. The variation of the output power with a gain change in the transmit chain of 2 dB results in an output power variation of < 0.1 dB (Fig. 7)

Figure 4. Receiving side of T/R module showing components

The spectrum of the output at full power output shown in Fig. 8 at different scan widths has no close in spurs or noise, and the 2nd harmonic is 40 dB down. The receiver loop was similarly tested and the results are given in Fig. 9. The feedback loop holds a variation of 3 dB of the input power to 0.03 dB at the output.

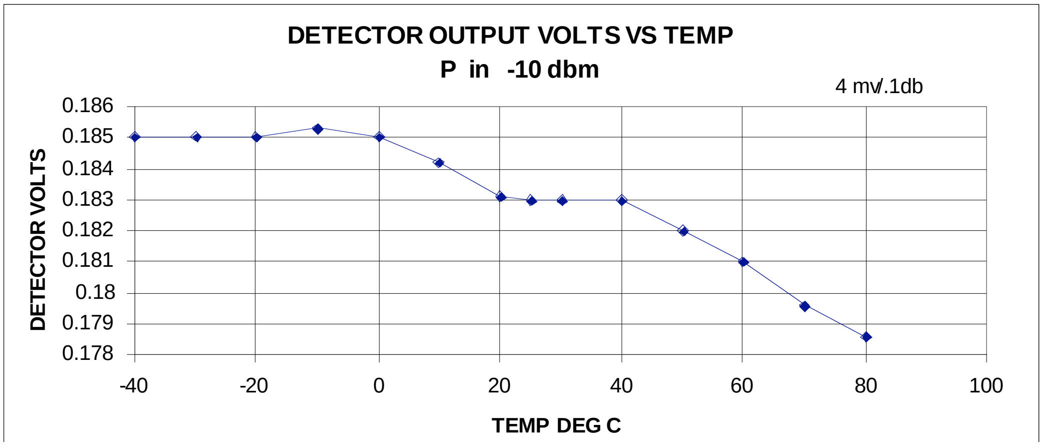

Figure 5. Power detector characteristics over temperature.

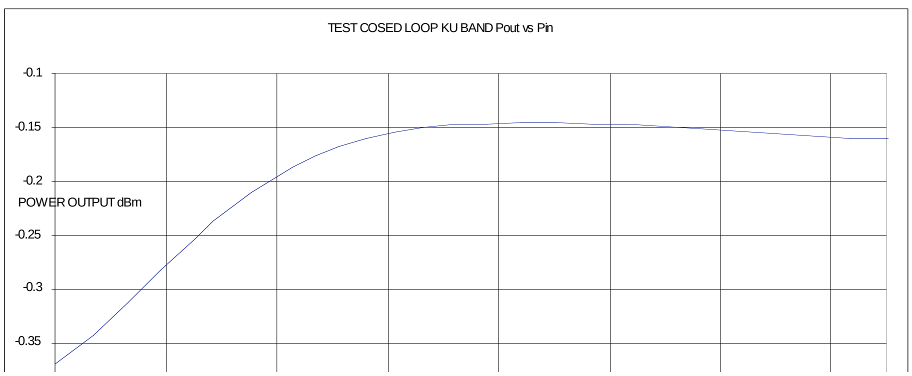

Figure 6. Transmit power output versus power input

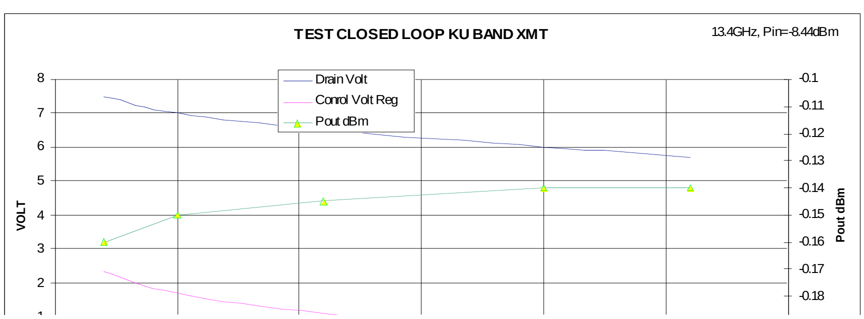

Figure 7. Transmit power output versus gain change

IV. SUMMARY

To enable the wide-swath scanning capabilities of planar phase array for synthetic aperture radar sensing of cold land processes, we have completed a T/R module design operating at Ku-band (13-17 GHz) frequencies. The module include four channels for transmit and eight channels for receiving. The built-in gain control is capable of controlling the transmit and receiver gains to an excellent stability of better than 0.1 dB over a broad temperature range. The ongoing T/R module

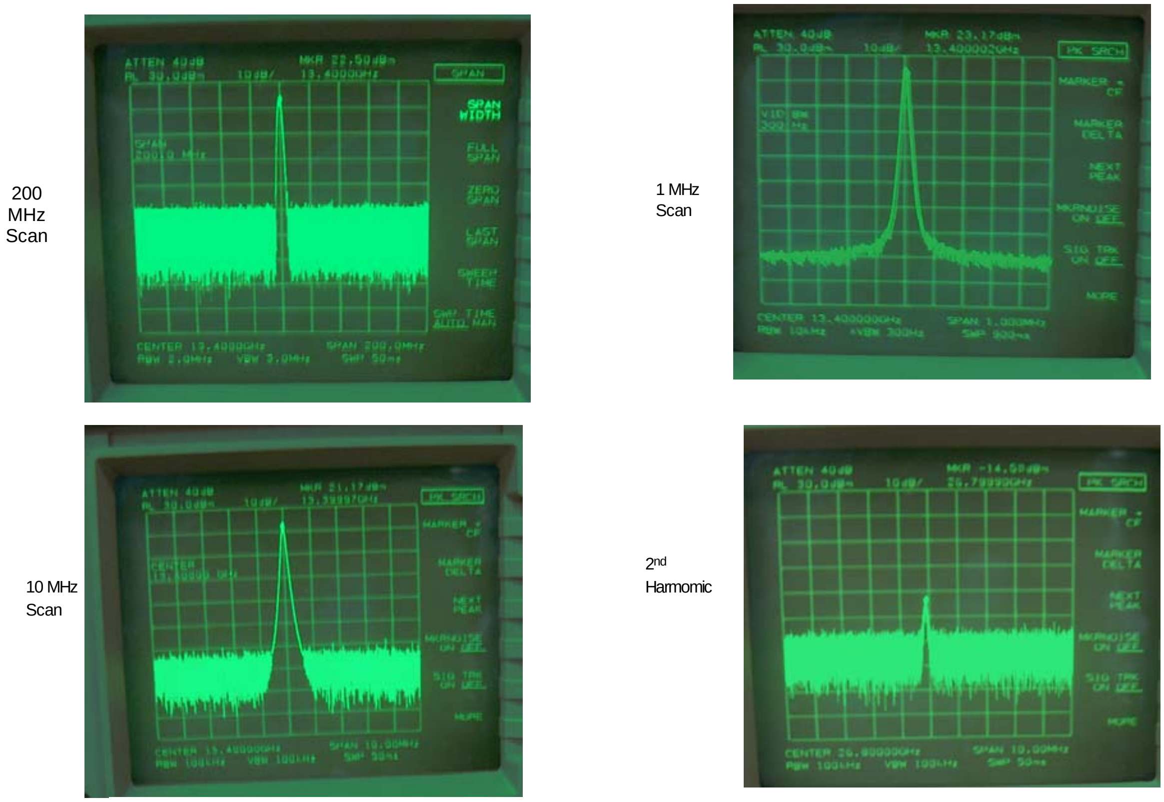

Figure 8. Power spectrum at 5 watts output

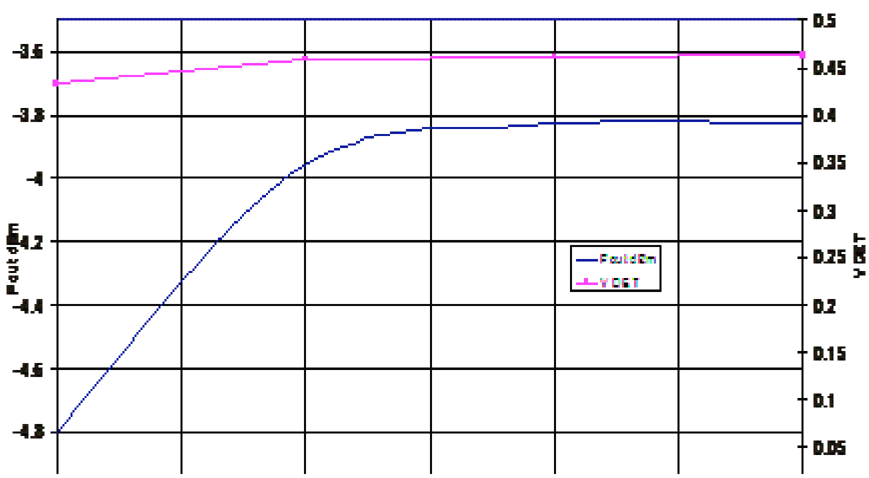

Figure 9. Receive power output versus power input

testing is expected to meet the stability requirements as verified by the breadboard tests.

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