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Evaluation of the NRL LWA Active Balun Prototype

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Abstract. This report describes the laboratory evaluation of an active balun designed and built by Brian Hicks of the Naval Research Laboratory. Measurements include S-parameters and noise temperature versus frequency over the 10-200 MHz band. In addition, the sensitivities of S_{21} to temperature and relative humidity, the signal compression point, and the intermodulation products were also measured.

1. Introduction

An active balun, based on the Mini-Circuits Gali-74 GaP HBT amplifier chip, was developed by Brian Hicks of the Naval Research Laboratory for use in Long Wavelength Array (LWA) prototyping activities. Three units (Nos. 1, 2, and 3) were evaluated at the NRAO Dynamic Spectroscopy Laboratory (DSL). A photograph of the balun is presented in Fig.1.

The nominal designed frequency band is 10-90 MHz. The design uses primarily surface mount components on an FR-4 substrate. A 180-degree hybrid junction, manufactured by Tele-Tech, Inc.(model HX-62A), is the power combining component of the balun. The supply voltage to the Gali-74 chips is controlled by an on-board voltage regulator. The bias circuit is isolated from the RF microstrip transmission line by an inductance.

Measurements stability, input and output match to 50 ohms, forward gain, common mode rejection, noise temperature, gain sensitivity to ambient temperature, gain sensitivity to relativity, 1-dB signal compression, and intermodulation products for this balun were all performed at the DSL. These are reported in the subsequent sections of this report. The dc supply for all measurements was 15 volts at 165 mA (2.48 watts). Note that gain and delay sensitivities to power supply voltage were not measured.

2. Stability

In the stability test the output port of the balun was connected to an HP 8593A spectrum analyzer operating from 1 MHz to 10 GHz. One of the input ports was terminated in 50 ohms while the other was connected to a tunable impedance.

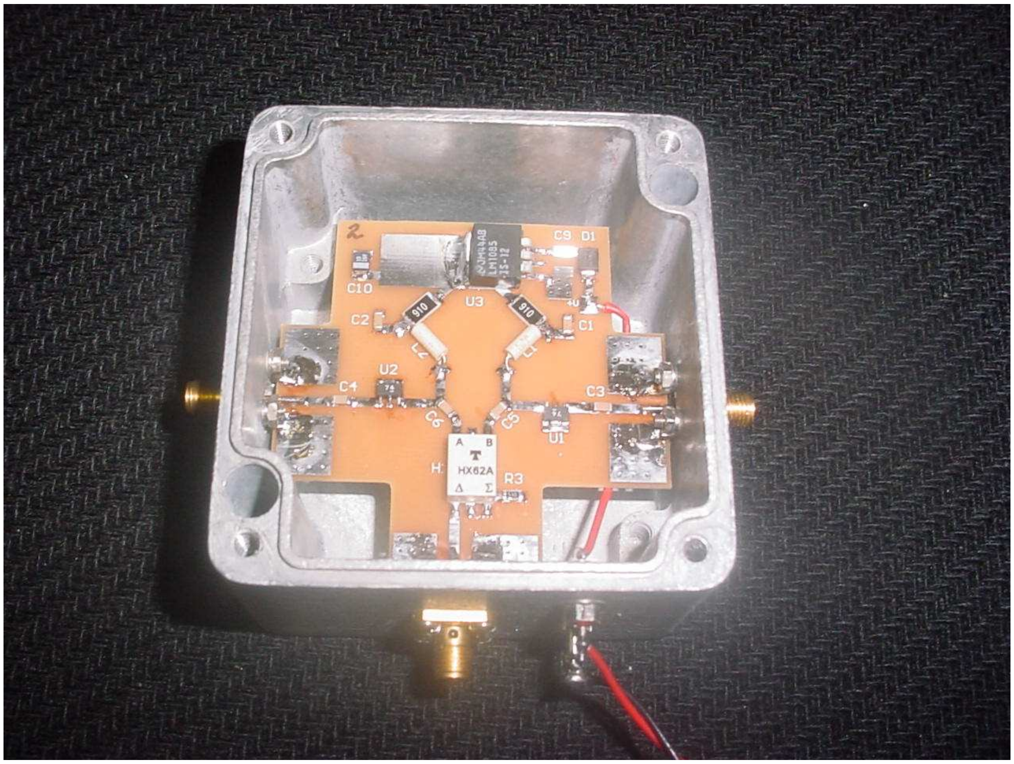

Figure 1. Photograph of active balun No. 2 with the cover removed. Input ports are on the left and right sides of the unit, as shown. The output port is at the bottom. Power supply leads are visible at the lower right

Tuning was accomplished through various combinations of a sliding short, a sliding tee terminated in resistive loads, and several lengths of coaxial line. Of the three amplifiers tested, only one side of balun No. 3 showed oscillation at 5.33 GHz while all others were unconditionally stable.

Examination of balun No. 3 under a microscope revealed no obvious abnormalities during assembly that would would have led to this oscillation. Furthermore, it was found that the oscillation was very sensitive to the cover position. The cover had to be tight with the side walls of the housing in order for the oscillation to occur. This indicates a cavity resonance which is providing a feedback path to the amplifier chip. Perhaps there is a very subtle defect to the circuit board on this side of the balun causing unwanted coupling to the cavity. The oscillation was quenched by attaching a two-inch square (approximately) piece of metalized mylar (3 mils thick) to the underside of the lid and therefore slightly lowering the Q of the cavity. With the mylar in place the amplifier is unconditionally stable.

3. Gain, Impedance Match, and Common Mode Rejection

Initial measurements were performed on both sides of the balun separately. All measurements utilized an HP 8753D vector network analyzer (VNA) calibrated in coaxial SMA connectors. Port two of the VNA was connected to the output of the balun. Excitation power at port one was set to -40 dBm to prevent any chance of saturation (dynamic range of the VNA is better than 80 dB). Frequency range these measurements was from 1-201 MHz.

All three baluns were evaluated in this manner. Results for balun No. 2 are shown here, but these results are very similar to those of the other baluns. Port one of the VNA was connected to the left side (see Fig.1) input port while the right side port was terminated in 50 ohms. The S-parameter data were recorded. The input ports were then swapped and the S-parameters measured again. Fig. 2a shows the gain or Mag[S21] versus frequency for the two sides of the balun while the Ang[S21] for both cases is compared in Fig. 2b. With appropriate loss corrections applied, the gain agrees with the manufacturer's data sheet for the Gali-74. Fig. 3a shows the input impedance plotted on a Smith Chart for both sides, while the output match, or Mag[S22], into 50 ohms is plotted in Fig. 3b. Electrically, both sides of the balun are very well matched.

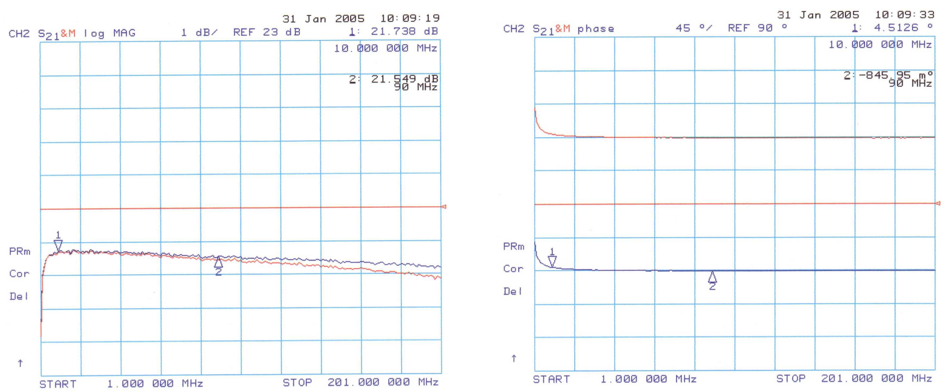

Figure 2. Plots showing the measurement of S21 versus frequency for both sides of the balun. a) Mag[S21]in dB, and b) Ang[S21] in deg.

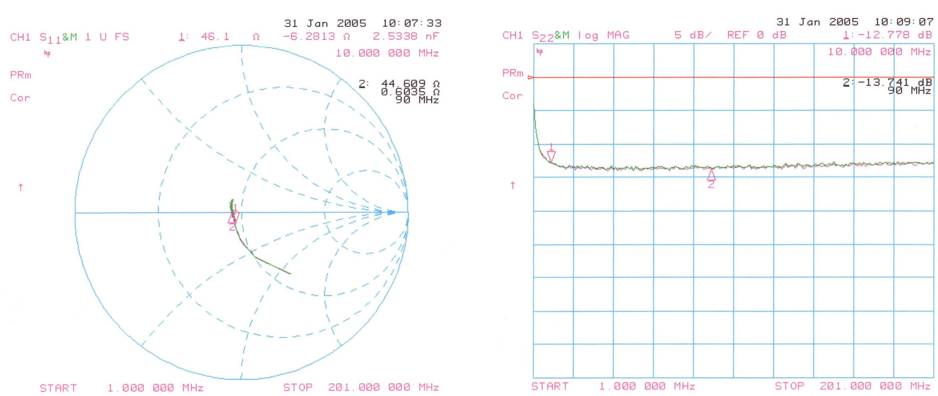

Figure 3. Plots showing the measurement of the input impedance and output match versus frequency for both sides of the balun. a) 50 ohm Smith displaying S11, and b) Mag[S22] in dB.

The entire balun was evaluated next by using an external 180-degree hybrid (Tele-Tech Inc. HX62-A) to split the signal from VNA port one into the two input ports of the balun. The loss through the external hybrid was measured by the VNA to be 0.42 dB at 1 MHz to 0.47 dB at 201 MHz. These values are better then the specification for the hybrid (loss = 1 dB) provided by the manufacturer. Measurement of Mag [S21] is shown in Fig. 4a.

The hybrid was replaced with a Mini-Circuits in-phase power divider model PSC 2-1 for measurement of the common-mode rejection. Loss through this circuit was measured by the VNA to be 0.14 dB at 1 MHz and 0.50 dB at 201 MHz meeting the manufacturer's specification for this component. Phase balance is within 3 degrees. Fig. 4b shows the common-mode rejection which is better than 44 dB at the output of the balun over the 10-90 MHz band.

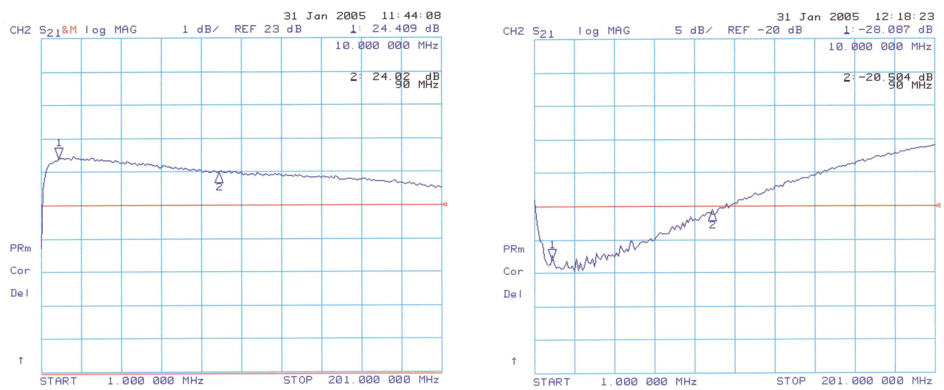

Figure 4. Plots of measured gain versus frequency for the entire balun. a) Mag[S21] in dB for balanced-mode operation, and b) Mag[S21] in dB for common-mode operation.

4. Noise Temperature

The noise temperature of the entire balun at ambient room temperature (about 25°C) was measured over the 10-200 MHz band using an Agilent N8973A and HP 346C calibrated noise diode. The external 180-degree hybrid was used in this measurement and the results were corrected by appropriate loss compensation. Fig. 5 presents the measured noise temperature versus frequency. The average value of 250 K over the 10-90 MHz band is approximately that of the typical value provided by the manufacturer (NF=2.7 dB).

5. S_{21} versus Ambient Temperature

The gain versus ambient temperature was measured for one side of balun No. 2 using the HP 8753D VNA with the amplifier mounted inside the environmentally controlled chamber (Thunder Scientific Corp., Model 2500S). The electrical lengths of the extra coaxial cables needed for this measurement were removed from the measured data during VNA calibration. A thin mylar absorber was

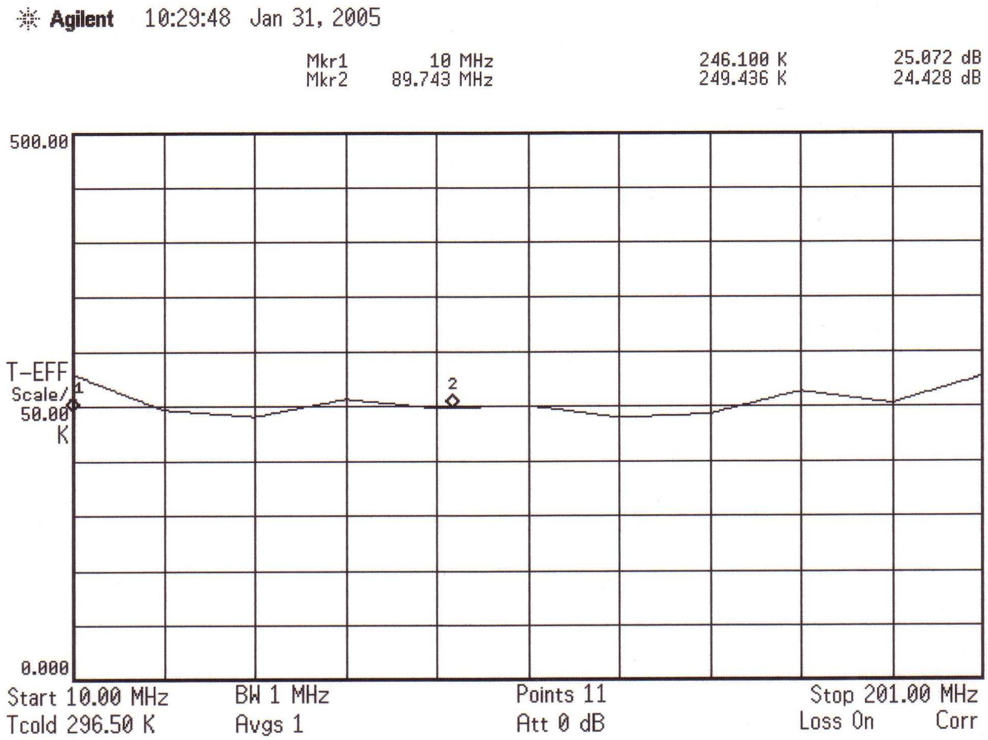

Figure 5. Plot of measured noise temperature versus frequency for the entire balun. Test fixture corrections applied.

attached to underside of the lid as a precaution against oscillation. The temperature was varied over the range 0-40°C in steps of 5 °C allowing 1.5 hours between gain readings to ensure thermal equilibrium. A plot of the gain versus temperature at several operating frequencies is shown in Fig. 6. The gain sensitivity with temperature is approximately -0.004 dB / °C.

The electrical delay through one side of the amplifier was also measured during this test and was found to be insensitive to temperature over the 0-40 °C operating range. The delay remained constant at 1.0721 nS.

6. S_{21} versus Relative Humidity

The gain versus relative humidity (RH) at an air temperature of 25 °C was measured for one side of balun No. 2 using the HP 8753D VNA with the balun mounted inside the chamber. The added cable lengths were calibrated out of the measurement. The relative humidity was varied over the range 10-90 % in steps of 10 % allowing 0.5 hours between readings to establish equilibrium. The results are plotted in Fig. 7. Estimated gain sensitivity to relative humidity is -0.0001 dB/%RH at 25°C.

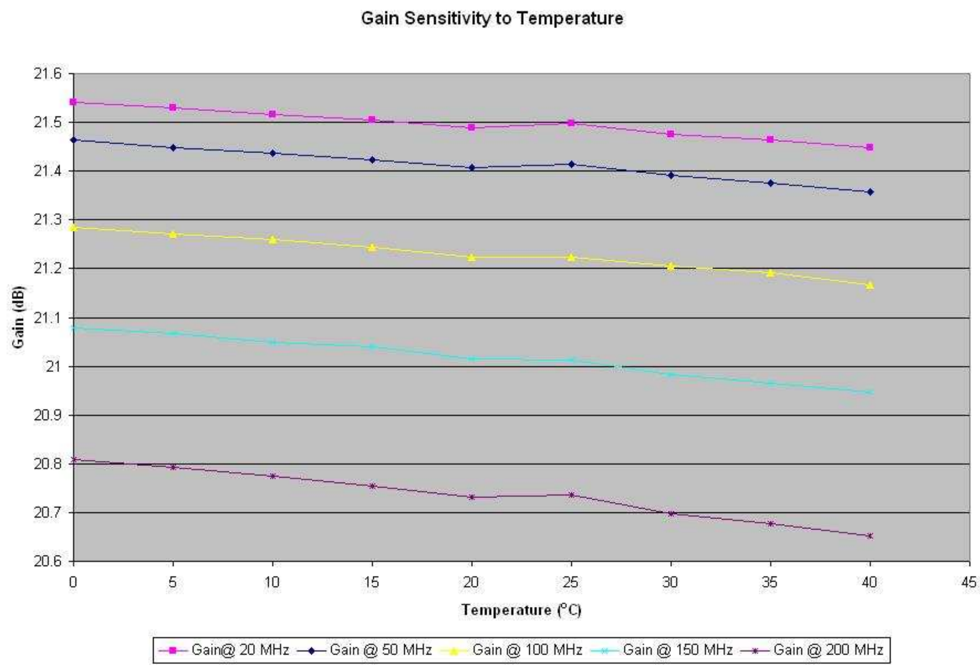

Figure 6. Graph showing the the gain of one side of the balun as a function of ambient temperature at several operating frequencies.

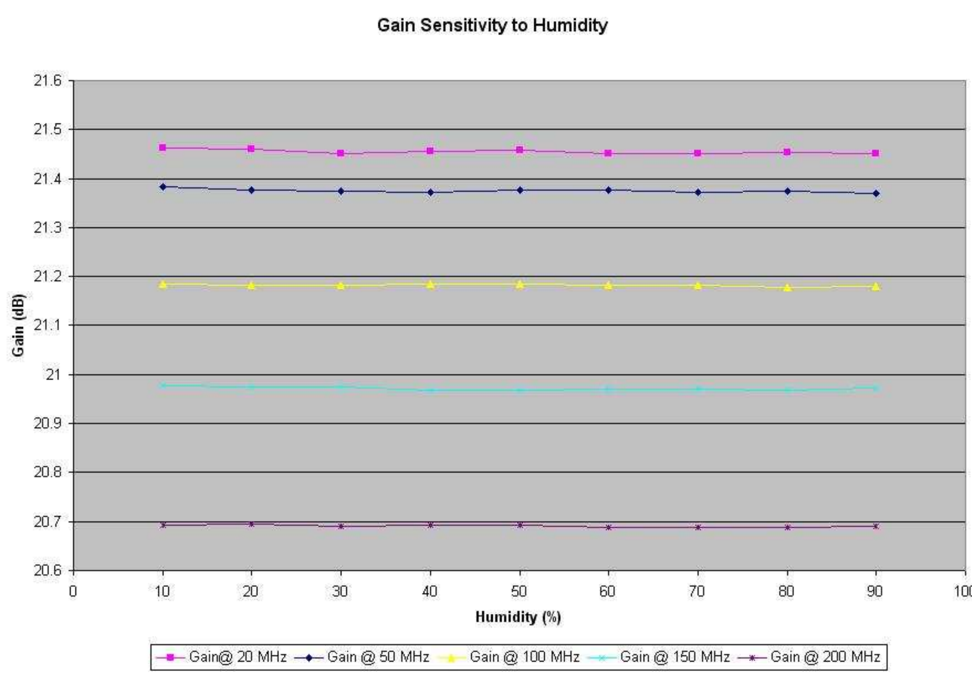

Figure 7. Graph showing the the gain of one side of the balun as a function of relative humidity at several operating frequencies.

7. Gain Compression and Intermodulation Distortion Tests

The 1-dB compression point for balun No. 2 was measured using an HP 8673D synthesized signal generator, a pair of precision attenuators (HP 8494B and HP 8495B), a Mini-Circuit Labs amplifier (ZHL-3A), and an HP 8560A spectrum analyzer. Fig. 8 is a plot of the output versus input power clearly showing the 1-dB compression point at an INPUT level of -5 dBm.

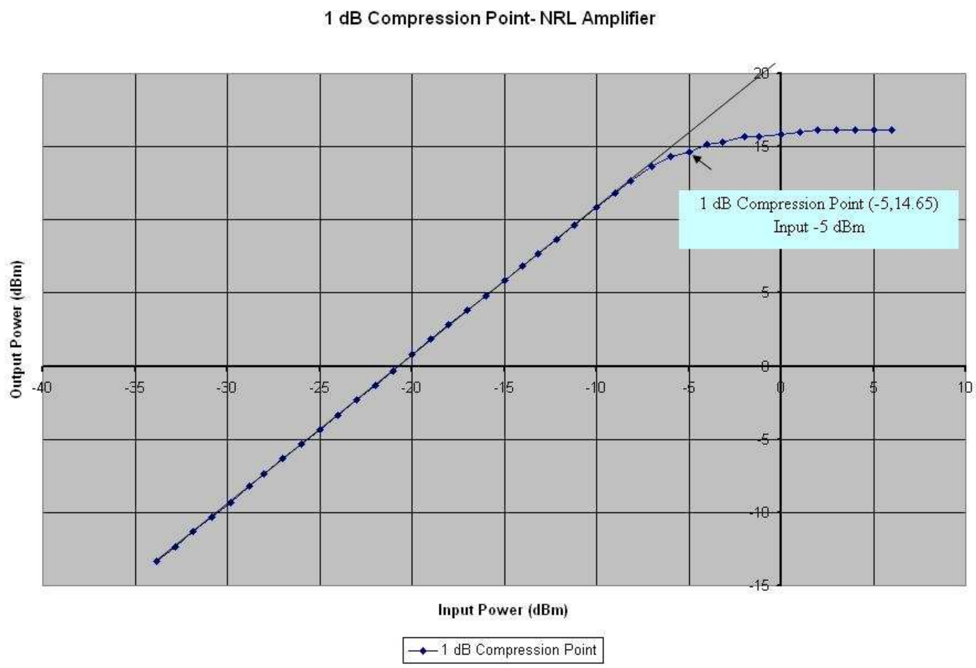

Figure 8. Plot of the output versus input power level at 50 MHz. The 1-dB compression point at -5 dBm is indicated.

The intermodulation distortion (IMD) products were measured for one side of the balun using a pair of HP 8673D synthesized signal generators with tones at 48 and 50 MHz, a 180-degree broadband hybrid coupler (Anzac), a pair of precision attenuators (HP 8494B and HP 8495B), and an HP 8560A spectrum analyzer. Results are shown in Fig. 9, where the 2nd-order intercept occurs at an INPUT level of +19 dBm, and the 3rd-order intercept at an INPUT of +7.5 dBm.

8. Discussions and Recommendations

This balun operates over the 10-90 MHz band and provides 24.5 dB gain with a noise temperature of approximately 250 K when the input is terminated in 50 ohms. These values are similar to those provided by the amplifier chip manufacturer thus indicating that amplifier's performance is not compromised by the balun design.

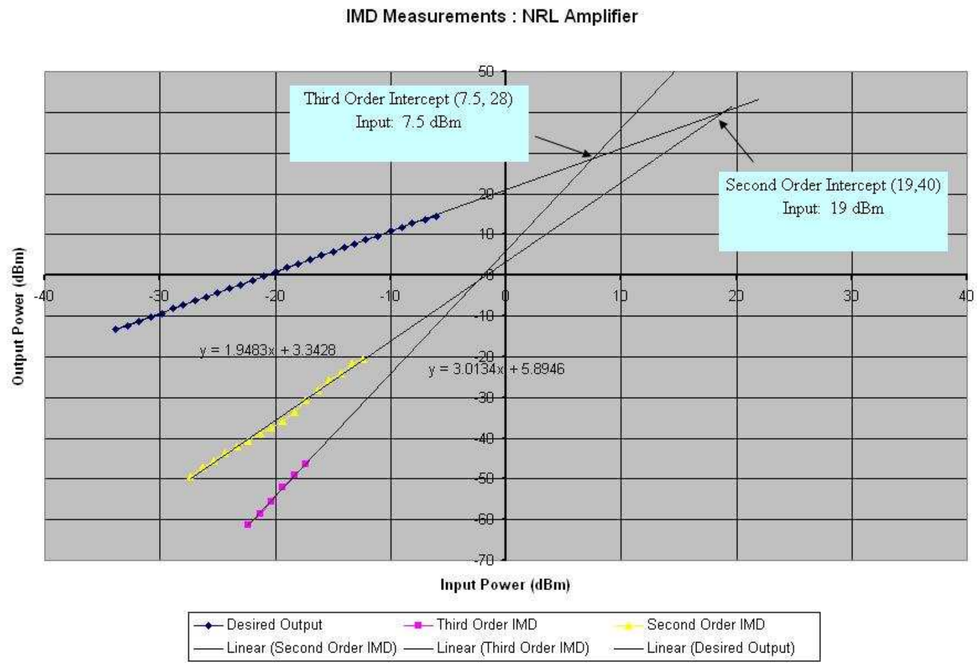

Figure 9. Plot showing the derivation of 2nd and 3rd order intermodulation products for one side of balun No. 2.

The amplifier has demonstrated unconditional stability in this configuration, but experience with the Gali-74 indicates that it's stability is very sensitive to the inductance between the chip ground tab and the RF circuit ground of the PC board. One chip (out of the six evaluated here that make up the three baluns) was found to oscillate at 5.33 GHz when the balun input port was subjected to a narrow range of input impedances far removed from 50 ohms. As a precaution, it is suggested that an inexpensive absorber be attached to the underside of the balun's cover if a housing of this size is used in the final version. Note that this material has no effect on desired balun performance.

One concern is the relatively high value for Mag[S22] (output) which is on the order of -13 dB when all ports of the balun are terminated in 50 ohms. Measurements on the hybrid indicates that it is better than -25 dB over the 10-90 MHz band thus implying that the mismatch at the output of the balun is due to either the chip's internal circuit or the bias circuit. B. Hicks noted that the -13 dB return loss meets the output VSWR=1.6 specification for the Gali-74. However, it is suggested that the bias circuit be evaluated separately from the chip and improved if it is also found to be significantly loading the 50 ohm microstrip transmission line. A value smaller than -20 dB should be attained.

A mismatch at the balun's output port can lead to undesired ripples in the receiver's passband thus making station element power combining difficult to achieve over the 10-90 MHz bandwidth. This is further complicated by the fact that the output match is strongly affected by the balun's input termination.

In other words, the dipole feed-point impedance will affect the balun's output match as a function of frequency. It should also be noted that the balun's noise temperature versus frequency will be affected by the input port termination impedance.

Measurement of the balun's performance over the temperature range of 0-40 °C has revealed no undesired effects. The balun's gain sensitivity to temperature is -0.004 dB/°C, and the signal delay through the amplifier is insensitive to temperature over this range. The balun's gain is insensitive to relative humidity. Of course, the balun should be weather sealed to prevent oxidation damage due to long term exposure to moisture.

The compression measurements show the 1-dB point at -5 dBm (input) meets the manufacturer's specification. The measured IMD-3 of +7.5 dBm (input) does not meet the specification of +13 dBm (input).

Based on the above measurements, I recommended that this balun be used for LWA prototyping. However, future improvements to the balun should focus on the noise temperature and the output match. A smaller, more compact package should also be designed.