A Low Noise, High Linearity Lossless Feedback Amplifier for LWA Applications

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Abstract

We have developed a discrete component amplifier that is intended for use in Long Wavelength Array applications. The device is a lossless feedback amplifier that exhibits $\sim$ 8 dB of gain and a noise temperature of 70 – 80 K in the LWA frequency band of 20 – 80 MHz. This amplifier can be integrated into an active balun circuit that would achieve improved gain and noise temperature relative to the current LWA baseline design. Details on amplifier circuit layout, characterization, and plans for future applications are detailed in this document.

I. INTRODUCTIONS

A. Motivation for Work

The Long Wavelength Array (LWA), currently in the design phase, is an instrument intended to study the universe at frequencies below 100 MHz. It is required that the LWA exhibit a minimum 6 dB Galactic noise dominance in the 20 – 80 MHz frequency range. Utilizing an active balun at the antenna feedpoint that has a low noise temperature is critical to achieving this specification. This active balun must also exhibit enough gain to overcome losses in cables and other passive components in the overall electronics chain.

Currently, the existing LWA baseline active balun design is the Hicks balun, characterized in [1]–[3]. This balun utilizes a *Minicircuits* Gali-74 MMIC as the amplification stage and exhibits 24 dB of gain (per polarization) with a noise temperature of 250 K in the LWA frequency band.

There is concern that 24 dB of gain will not be sufficient to overcome the anticipated levels of cable loss in an LWA station. In addition, a lower noise temperature could prove instrumental in improving Galactic noise dominance levels particularly at the high frequency end of the LWA band. These two primary factors have motivated the need to explore alternate balun designs.

As a precursor to a new balun prototype, we have developed a single, low noise, high linearity amplifier. This amplifier exhibits roughly 8 dB of gain in the LWA frequency band, and could be used either as a stand alone device or as a component in a larger system. This amplifier could be used in a new balun prototype either by cascading multiple 8 dB stages, or some combination of 8 dB stages, and MMIC's to achieve the desired levels of gain for the LWA. The topology of this amplifier follows that of the lossless feedback common base amplifier, the background of which is given in section I-B.

B. Design Background

The lossless feedback common base amplifier was introduced in 1975 by David E. Norton and Allen F. Podell who patented and described the circuit in a series of journal publications [4]–[6]. This circuit employs a magnetically coupled feedback network which introduces negligible loss; consequently the noise temperature of the amplifier is essentially equivalent to that of the transistor used. In addition to the remarkable noise performance of this amplifier, the linearity of also admirable. It is possible that the patent, which is believed to have expired, contributed largely to the lack of widespread acceptance of this novel circuit.

This amplifier topology was first used in an active balun circuit developed by Bradley and Parashare of the NRAO Dynamic Spectroscopy Laboratory for use on the Green Bank Solar Radio Burst Spectrometer

(GBSRBS–L 10–70 MHz)) [7]. The GBSRBS–L balun employs a 2N5109 transistor and has operated continuously since January, 2004 without any failures or degradation. A revision of this balun used the NE461 transistor (chosen for its more compact size and improved gain-bandwidth product) and was adopted for GBSRBS–M (70–300 MHz) and the Precision Array to Probe the Epoch of Reionization (PAPER) projects [8]. In order to facilitate future integration of the 8 dB amplifier presented in this document into a larger circuit (such as an active balun), a compact layout for the overall circuit needed to be maintained. The NE461 transistor was therefore also chosen for our application.

NRL and NRAO have collaborated to produce the design presented here which is optimized for performance and mass production. We were initially deterred by the cost and availability of a suitably packaged transformer optimized for the LWA frequency range because of the large quantities needed for the LWA. We worked with the *Tele-Tech* Corporation to make such a part (TX60-27) available [9]. Assembly instructions for the TX60-27 transformer can be found in the appendix. Our efforts have subsequently focused on optimizing the circuit and PCB layout for compactness and manufacturability for use in a new balun prototype as well as variety of other LWA applications.

II. CIRCUIT SCHEMATIC AND PCB LAYOUT

The amplifier test circuit schematic is shown in Figure 1. The corresponding PCB layout depicted in Figure 2 was intended specifically to test the 8 dB amplifier, which occupies a rectangular region in the center of a board of approximately 6 cm^2. Additional components such as the connectors, initial bypass capacitors, and a protection diode add to the size of the test layout shown. The populated PCB is shown in Figure 3, and the component costs for a single amplifier are given in Table I. A detailed bill of materials for an LWA station can be found in the appendix. To enable accurate noise measurements, the test board was designed to form the lid of a metal box with the components facing down and the connectors facing out (Figure 4).

Considerable care was taken in this design to ensure proper ground distribution and avoid resonant features. Previous versions employed a hand-wound transformer for T1 and additionally involved structures that left the plane of the circuit board. The present design has been completely flattened and is suitable for production with automated assembly equipment.

This 8 dB amplifier features 50 Ω ports, but because it is based entirely on discrete components, the impedance characteristics can be precisely modelled and tailored for specific applications. It is a straightforward process to place this amplifier block within a more complex layout.

III. AMPLIFIER CHARACTERIZATION

The 8 dB amplifier was characterized at the NRAO Dynamic Spectroscopy Laboratory in Charlottesville, VA. S-parameters (including gain and input and output return loss), noise temperature, 1 dB compression point, and intermodulation distortion measurements were performed on this device.

The most notable result is the noise temperature, shown in Figure 5. The noise temperature of this amplifier ranges from 70 – 80 K in the LWA band. Using this amplifier in a full balun circuit could result in a significant improvement in noise temperature relative to the Hicks balun.

Figures 6 and 7 show the measured magnitudes and phases of the transmission and reflection coefficients. The gain of this amplifier ($|S21|$) is approximately 8 dB and the input match ($|S11|$) is -15 dB or less across the LWA band. Figure 8 shows that the amplifier reaches its 1 dB compression point at an input power level of almost 7 dBm. Figure 9 shows the output IP2 and IP3 results. The second order intercept occurs at an input power of 27 dBm and the third order intercept occurs at an input power of 0 dBm. These results are summarized in Table II.

IV. FUTURE WORK AND CONCLUSIONS

We have reported on an amplifier that can be used for the LWA and other radio science applications with stringent requirements on noise performance and linearity. We have addressed critical PCB layout concerns and have resolved significant manufacturing concerns.

Based on the results of this work, we are developing a cost effective candidate LWA balun that will inherit the positive traits of this amplifier. We are also exploring the possibility of incorporating this circuit into the initial gain stage of high-sensitivity, low-noise receivers. These efforts will be detailed future LWA memoranda.

ACKNOWLEDGMENTS

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[2] K. Stewart, B. Hicks, N. Paravastu, R. Bradley, C. Parashare, W. Erickson, C. Gross, E. Polisensky, P. Crane, P. Ray, N. Kassim, and K. Weiler, "Recent Progress in Active Antenna Designs for the Long Wavelength Array (LWA)," *Proceedings of the URSI General Assembly, New Delhi, India*, October 2005.

[3] P. Ray, S. Ellingson, R. Fisher, N. Kassim, L. Rickard, and T. Clarke, "A Strawman Design for the Long Wavelength Array (LWA Memo 35)," *LWA Memo Series*, April 2006.

[4] D. Norton and A. Podell, "Transistor Amplifier with Impedance Matching Transformer," *U.S. Patent 3,891,934*, June 1975.

[5] D. Norton, "High Dynamic Range Transistor Amplifiers Using Lossless Feedback," *Proceedings of the 1975 IEEE International Symposium on Circuits and Systems*, pp. 438–440, 1975.

[6] ——, "High Dynamic Range Transistor Amplifiers With Lossless Feedback," *Microwave Journal*, pp. 53–57, 1976.

[7] "Green Bank Solar Radio Burst Spectrometer," *http://www.nrao.edu/astrores/gbsrbs/*.

[8] R. Bradley, D. Backer, A. Parsons, P. C., and N. Guggliucci, "PAPER: A Precision Array to Prove the Epoch of Reionization," *207th AAS Meeting (Poster Presentation)*, January 2006.

[9] Tele-Tech Corporation, *http://www.tele-tech-rf.com/*, 2050 Fairway Drive, Bozeman, MT 59715 USA.

TABLE I

PARTS COST FOR 8 dB AMPLIFIER (A MORE DETAILED BILL OF MATERIALS IS GIVEN IN THE APPENDIX.)

Designation	Value	Type	Manufacturer	Unit Cost
L1	4.7 μH	Inductor	JW Miller	\$0.16
C1, C2, C3, C5, C6	0.1 μF	Capacitor	Panasonic	\$0.06
R1	8.2 $k\Omega$	Resistor	Panasonic	\$0.04
R2	100 Ω	Resistor	Panasonic	\$0.04
R3	51 Ω	Resistor	Panasonic	\$0.04
R4	2 $k\Omega$	Resistor	Panasonic	\$0.04
Q1	NE461 M02	NPN Transistor	NEC	\$0.80
T1	TX60-27	Transformer	Tele-Tech	\$8.00
Total for above parts				\$9.36
C4 (needed for test circuit only)	10 μF	Tantalum Capacitor	Nichicon	\$0.26
D1 (needed for test circuit only)	MBRS2040	Diode	ON Semi	\$0.30

TABLE II

SUMMARY OF 8 dB AMPLIFIER CHARACTERISTICS IN LWA BAND (20 – 80 MHz)

Current Draw (at +12 VDC)	20 mA
Voltage Range	+/- 1%
Noise Temperature	70 – 80 K
Gain	$\sim$ 8 dB
Input Match (for 50 Ω load)	$\leq$ -15 dB
Output Match (for 50 Ω load)	$\leq$ -20 dB
1 dB Compression Point (Input Power)	$\sim$ 7 dBm
Input IP2	0 dBm
Input IP3	27 dBm

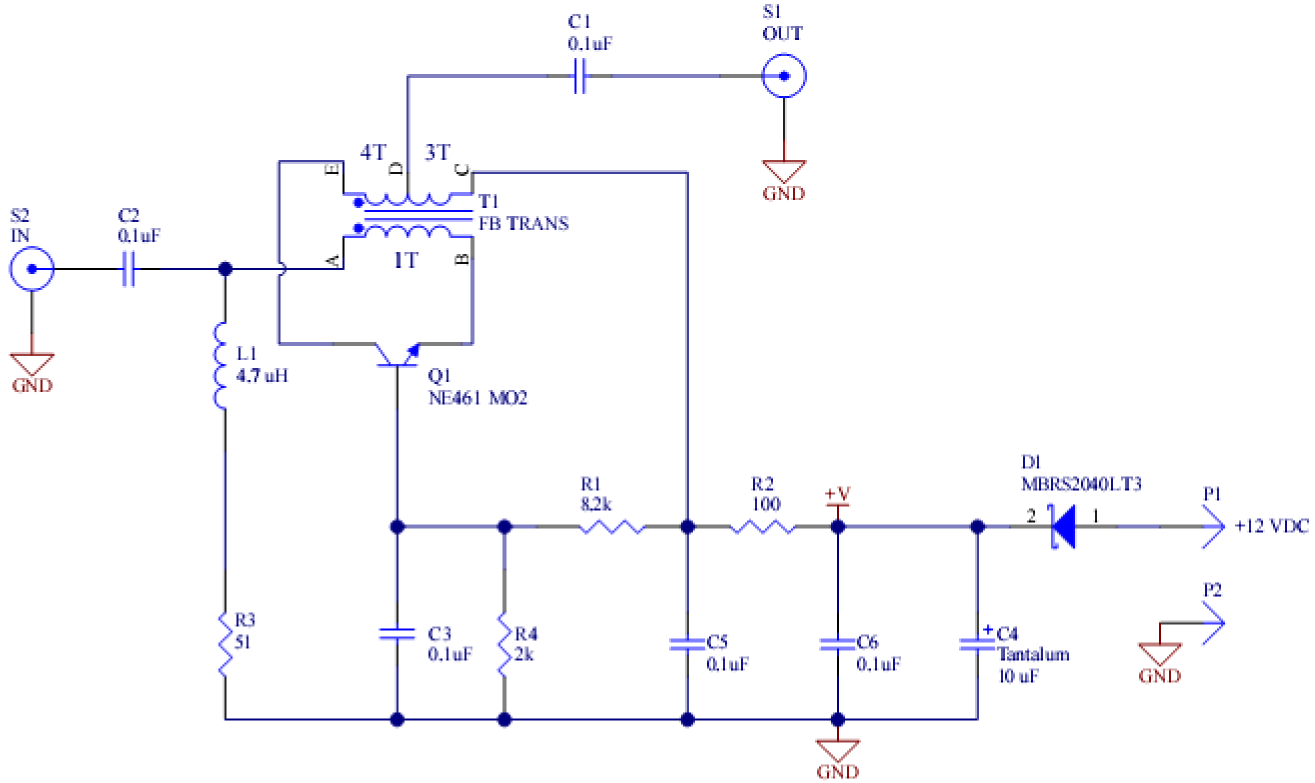


Fig. 1. The schematic of the 8 dB amplifier circuit. The turns ratio for the transformer (T1) is indicated next to its circuit symbol.

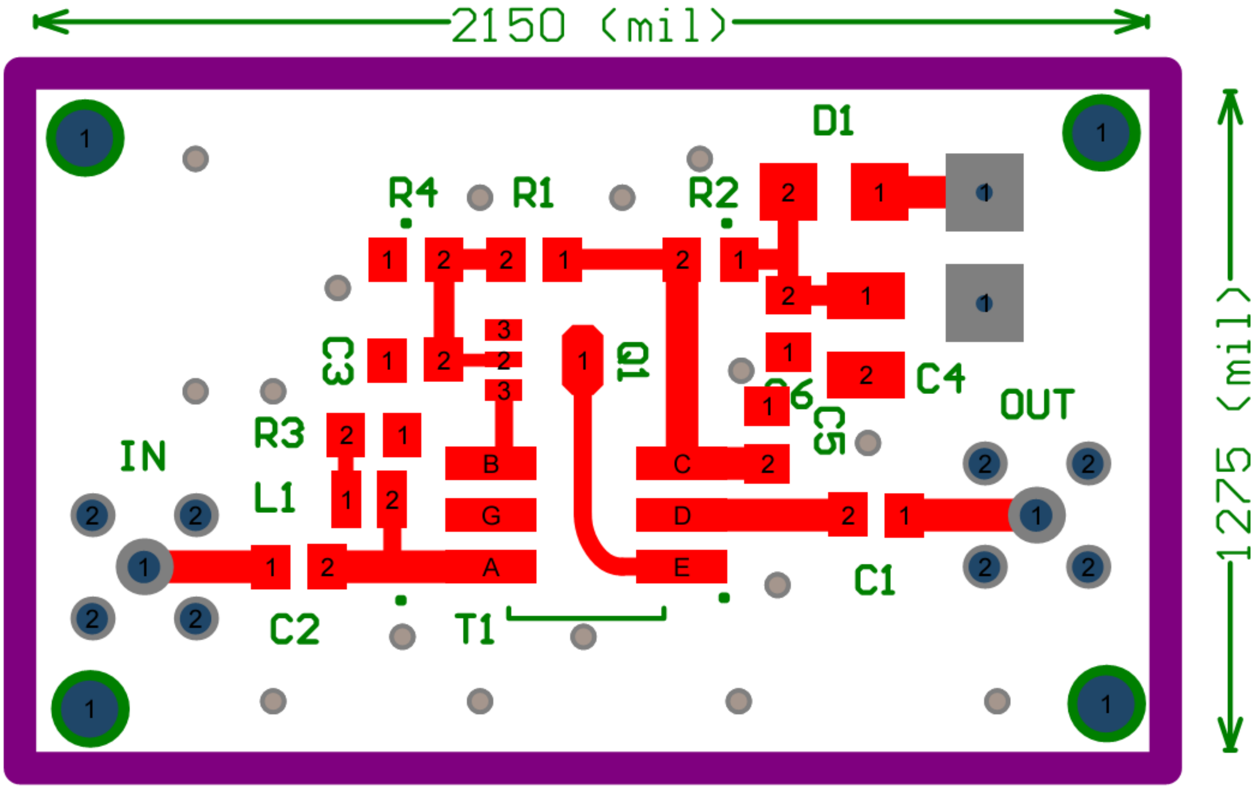


Fig. 2. The PCB layout of the 8 dB amplifier circuit. The dimensions of the board are indicated (1 mil = 0.001 in).

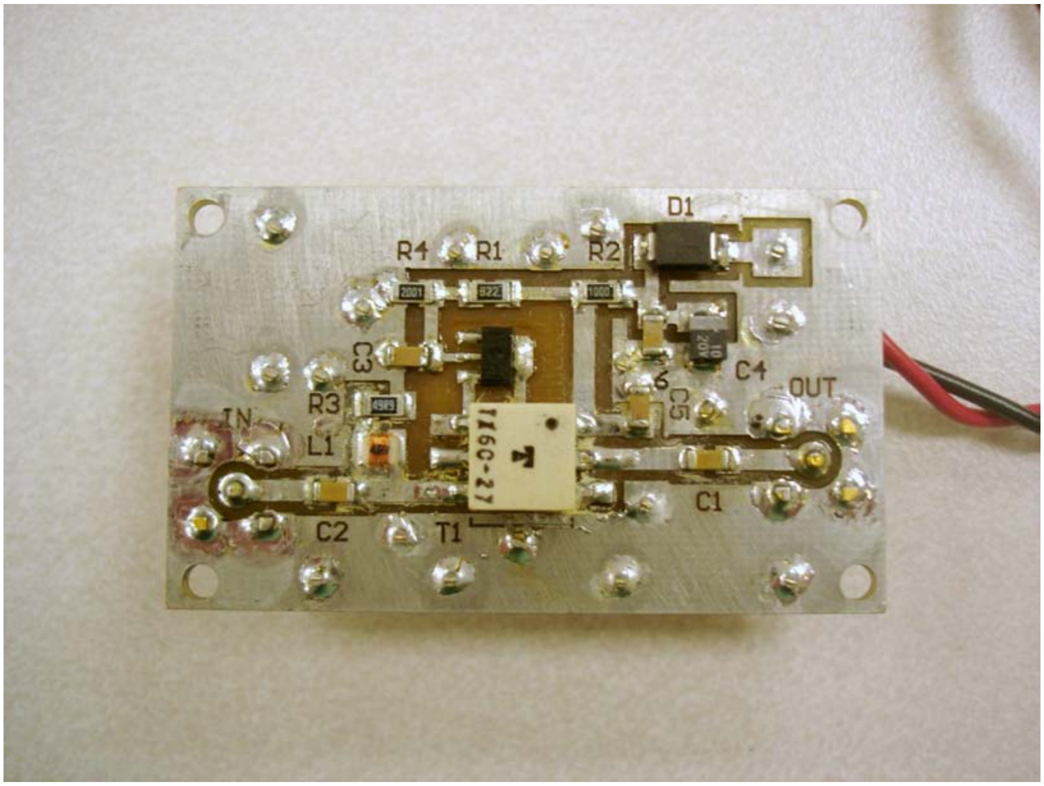


Fig. 3. A photograph of the 8 dB amplifier circuit. The white package (T1) near the center of the board is the *Tele-Tech* TX60-27 transformer mentioned in section I-B.

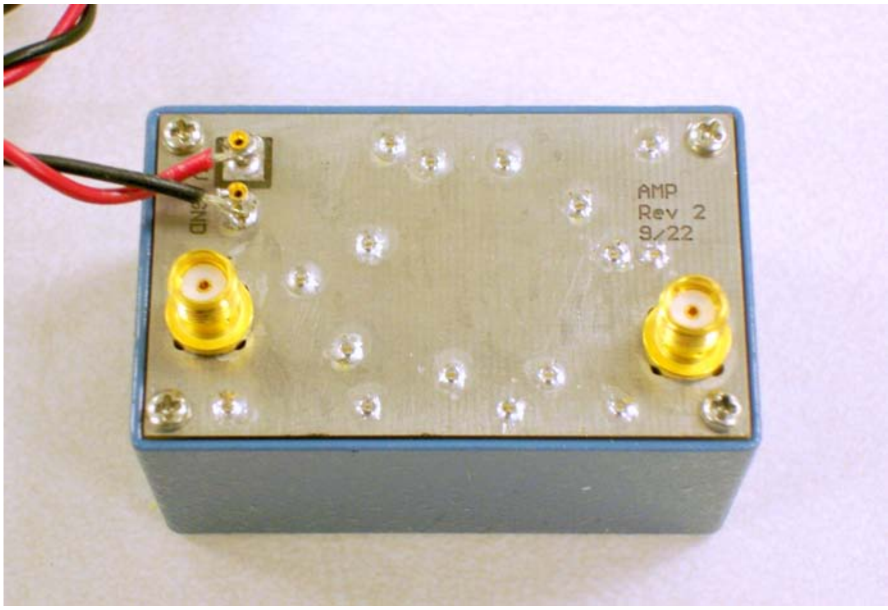


Fig. 4. A photograph of the fully packaged 8 dB amplifier prototype.

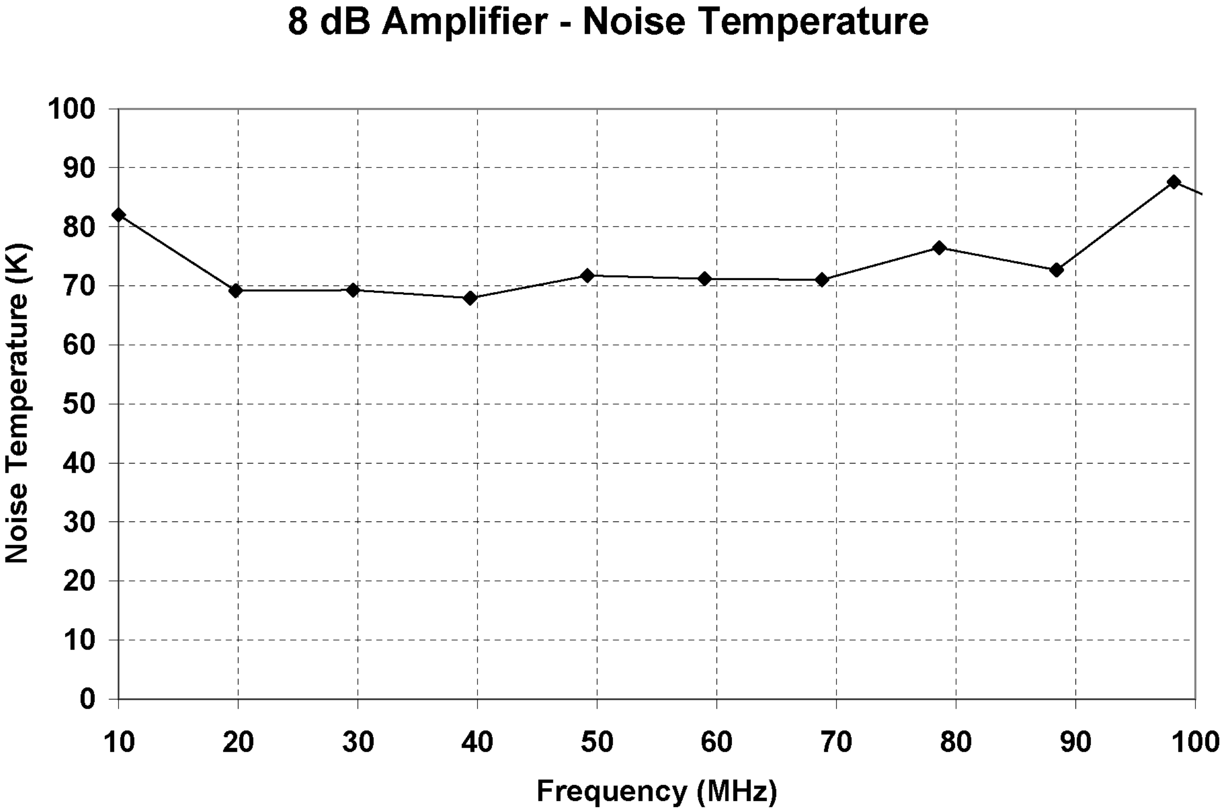


Fig. 5. The noise temperature of the 8 dB amplifier stays between 70 and 80 K in the LWA band. Using this amplifier in a full balun circuit would yield an improvement in noise temperature of approximately a factor of two over the Hicks balun.

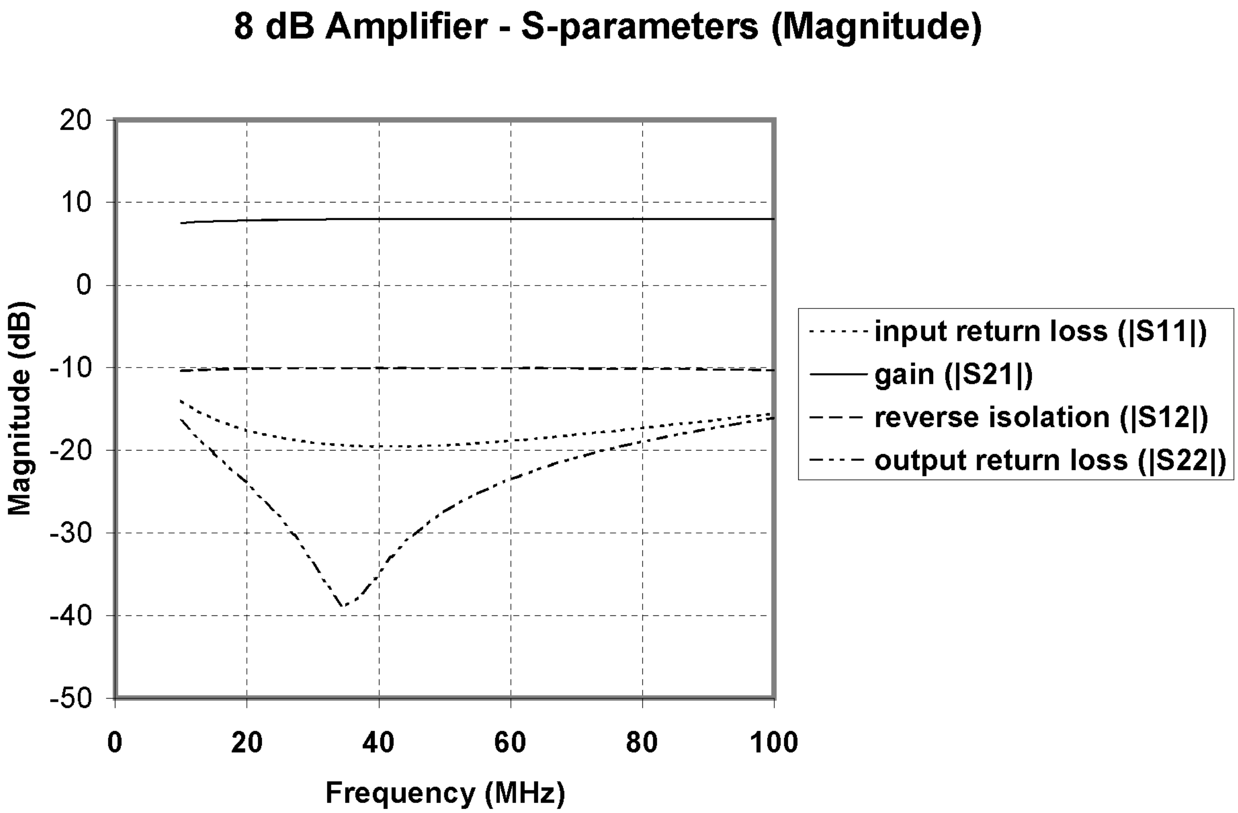


Fig. 6. The magnitudes of the reflection and transmission coefficients of the 8 dB amplifier.

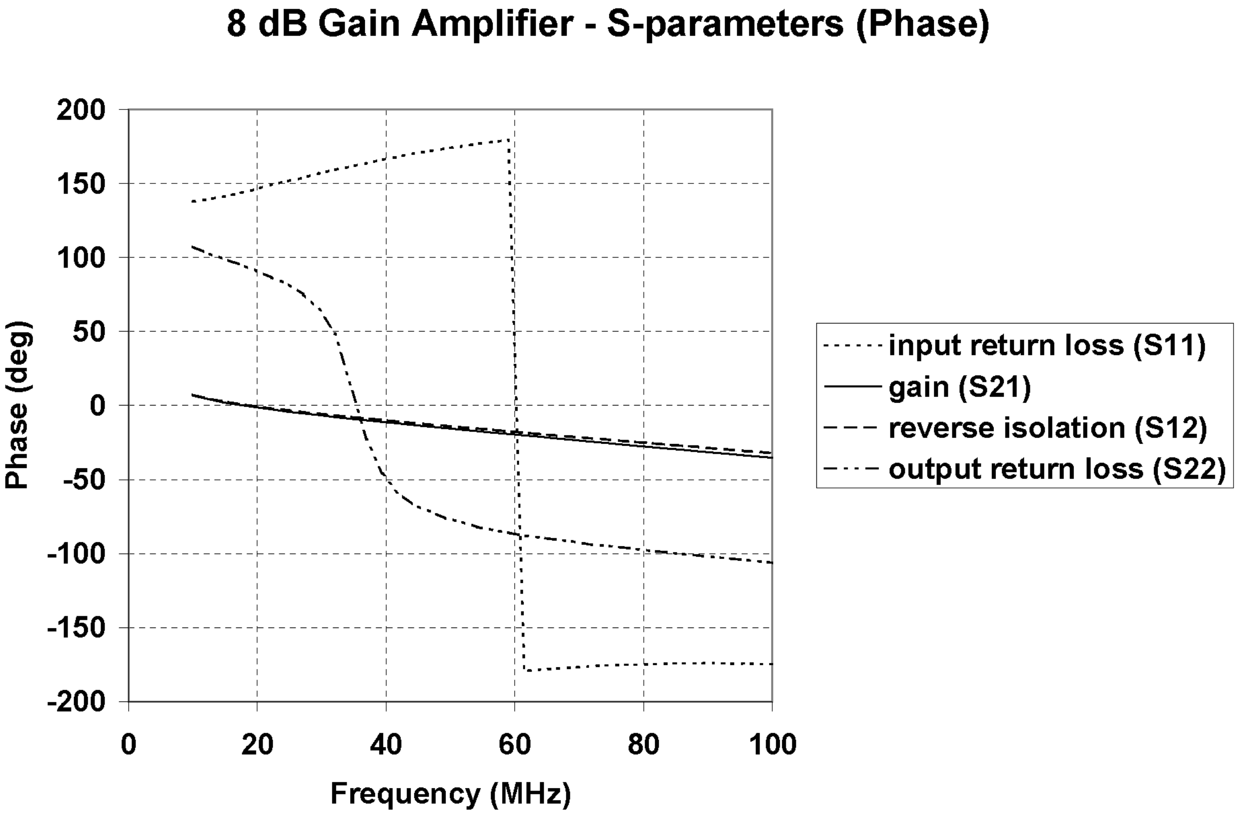


Fig. 7. The phases of the reflection and transmission coefficients of the 8 dB amplifier.

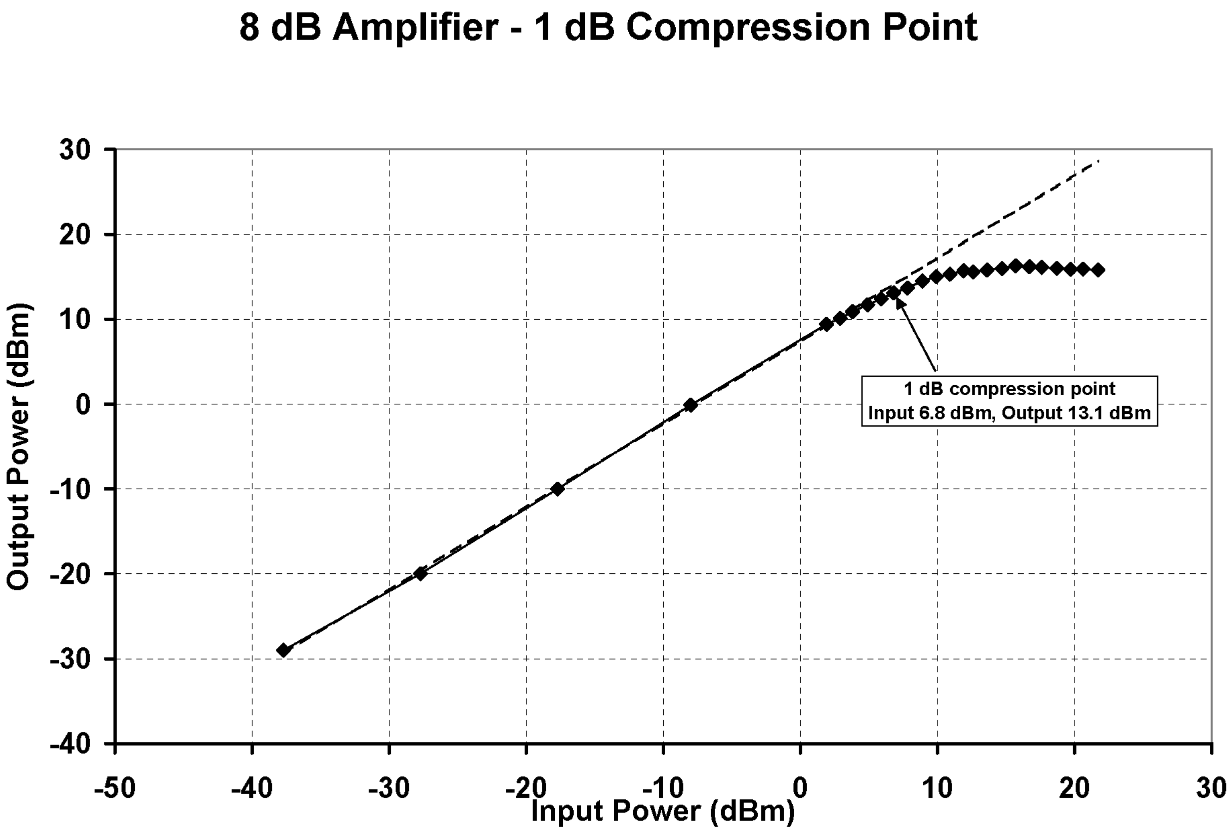


Fig. 8. The 1 dB compression point of the 8 dB amplifier.

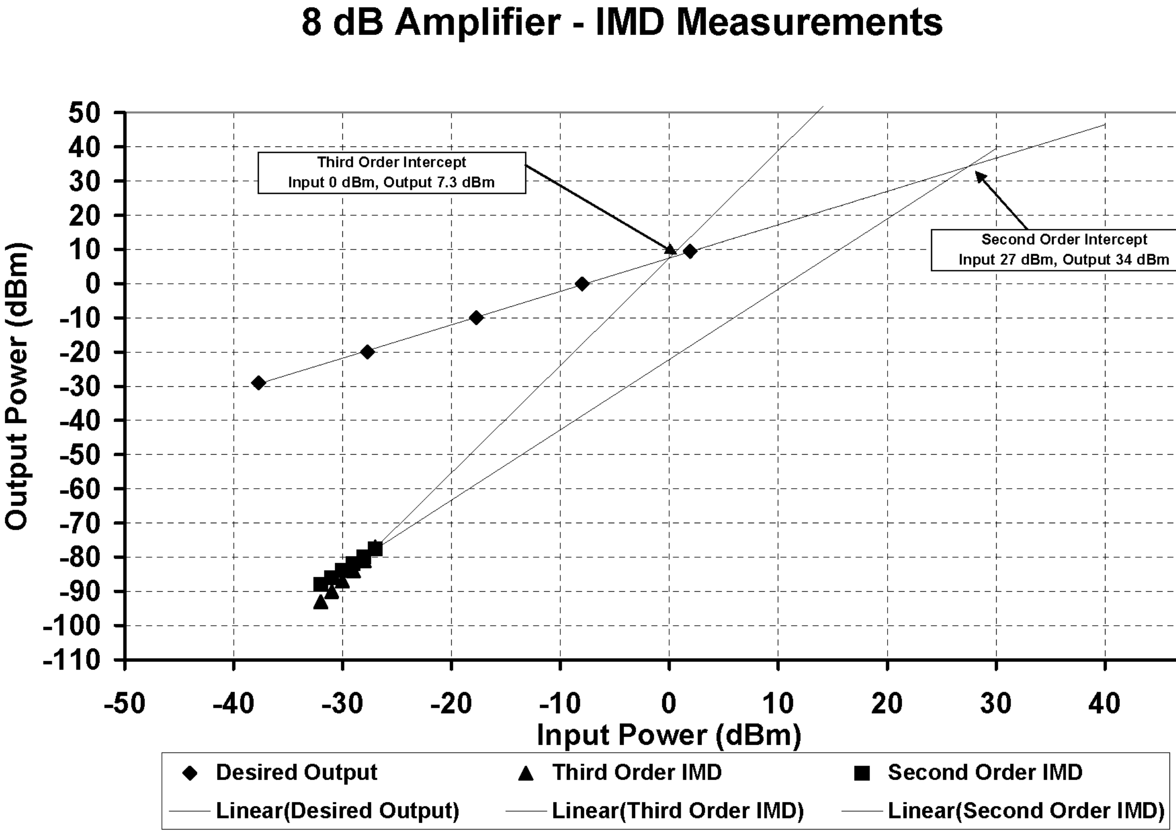
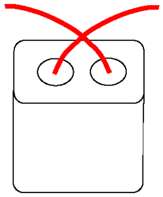


Fig. 9. The second and third order intermodulation products of the 8 dB amplifier.

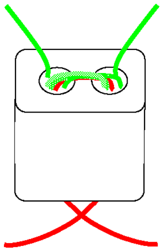
APPENDIX

Assembly Instructions TX60-27
October 16, 2006, drawn by Gib Curtis
PRELIMINARY

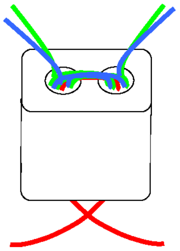
Substrate	21-4860-00	TX60-27	(1)
Cover	60-1132-11	Plastic .3x.3x.15	(1)
Core	50-1024-20	Balun “Fair-Rite” 2843002302-0	(1)
Wire	65-1360-02	#36 HPN blue	(3.0”)
Wire	65-1360-02	#36 HPN green	(3.0”)
Wire	65-1360-02	#36 HPN red	(2.0”)
Clip	59-9820-01	Substrate SMD	(6)



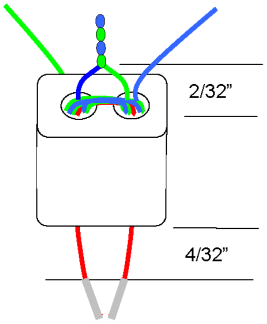
Making the beginning tail 7/8” long, wind 1 turn with 2” of #36 RED wire in the 2 hole core as shown. Red tails cross. This wire must be wound on the core first.



Turn the core over, end for end. Making the beginning tail 7/8” long, wind 4 turns with 3“ of #36 GREEN wire over the 1 turn of red wire as shown.



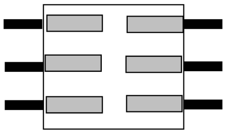
Next, making the beginning tail 1” long, wind 3 turns on the core with 3” of #36 BLUE as shown in the figure.

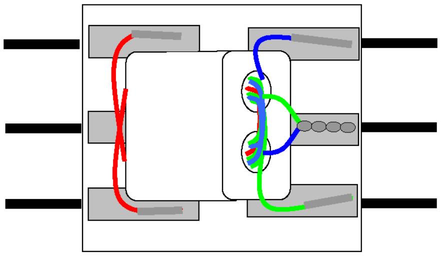


Center tap the core by winding one blue wire with one green wire as shown in the figure. Make the center tap 2/32” from the core body.

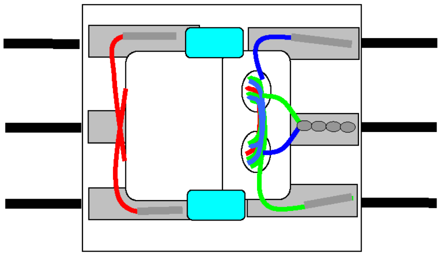
Tin wires using dimensions shown in the figure.

Assemble the Clip leads to the strip of 5 substrates using the lead bender and clencher tools.

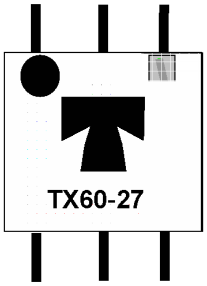




Use High Temp Sn96 solder. Mount the core to the header as shown in the figure. All wires surface mount. Red wires cross.



Encapsulate with white RTV as shown in the figure.



Adhere the cover to the substrate using high temp epoxy. Orientation is as shown in the Figure.
Cut the leads using the lead cutting fixture.

Bill of Materials
8 dB Discrete Gain Block
12/12/2006

Designation	Value	Tolerance	Type	Manufacturer	Manufacturer's Part Number	Digi-Key Part Number	Package Style	Unit Cost	Quantity	Extended	Cost Bracket (*)
L1	4.7 µH	10%	Inductor, Ceramic Core	JW Miller	PM1008-4R7K-RC	M8483TR-ND	PM1008	$ 0.12	1	$ 0.12	>2000
C1, C2, C3, C5, C6	0.1 µF	10%	Capacitor, Ceramic, X7R	Panasonic - ECG	ECJ-3VB1E104K	PCC1883TR-ND	1206	$ 0.06	5	$ 0.28	>4000
R1	8.2 kΩ	5%	Resistor, 1/4 Watt	Panasonic - ECG	ERJ-P08J822V	P8.2KALCT-ND	1206	$ 0.04	1	$ 0.04	>1000
R2	100 Ω	1%	Resistor, 1/4 Watt	Panasonic - ECG	ERJ-8ENF1000V	P100FCT-ND	1206	$ 0.03	1	$ 0.03	>1000
R3	51 Ω	5%	Resistor, 1/4 Watt	Panasonic - ECG	ERJ-P08J510V	P51ALCT-ND	1206	$ 0.04	1	$ 0.04	>1000
R4	2 kΩ	1%	Resistor, 1/4 Watt	Panasonic - ECG	ERJ-8ENF2001V	P2.00KFCT-ND	1206	$ 0.03	1	$ 0.03	>1000
Q1	NE461 MO2	N/A	Transistor	NEC	NE461M02-AZ	NE461M02-AZ-ND	SOT-89	$ 1.35	1	$ 1.35	>1000
T1	TX60-27	N/A	Transformer	Tele-Tech, Corp.	TX60-27	Must Buy Directly	0.3 x 0.3 x 1.5 inches	$ 8.00	1	$ 8.00	>1000
									Total Cost:	**$ 9.88**	
C4 (needed for test circuit only)	10 µF	20%	Tantalum Capacitor	Nichicon	F931E106MCC	493-2388-1-ND	SMT-C (6.0 x 3.2 mm)	$ 0.52			>10
D1 (needed for test circuit only)	MBRS2040	N/A	Diode, Schottky, 40 V, 2A	ON Semiconductor	MBRS2040LT3G	MBRS2040LT3GOSCT-ND	SMB (5.59 x 3.81)	$ 0.39			>10

* Cost bracket was selected on the assumption that four 8 dB gain blocks would be used for each stand, with 256 stands per station.
Pricing and availability was verified on 12/12/2006