

# Basic Rectifier Relationships and Design Considerations for use with Rectennas Part 2

Scotty Gammenthaler  
Moon Society Incorporated  
February 3, 2008

In Part 1 of this study, basic diode properties were discussed and three different rectifier/filter circuit combinations were investigated at low frequency (2.45 MHz) to explore the basic characteristics of the circuits. Part 2 will investigate the problems introduced by operation at higher frequencies (2.45 GHz) and develop final recommendations for implementation of a low power rectifier circuit.

To illustrate the problems created by the diode junction capacitance, the circuit of Figure 4 from Part 1 of this study was rescaled from 2.45 MHz to 2.45 GHz by reducing all of the inductors and capacitors (except diode junction capacitance) by a factor of 1000 and increasing the analysis frequency by a factor of 1000. The result is shown in Figure 1, where the performance graphs from the original 2.45 MHz circuit are repeated for comparison:

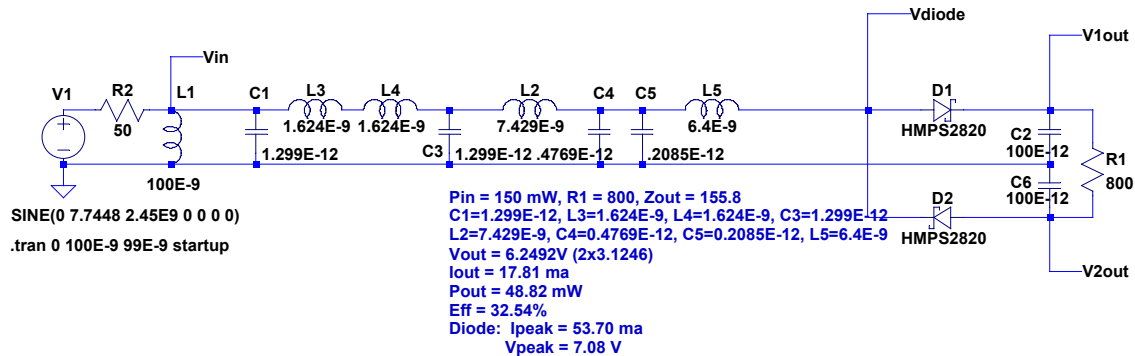
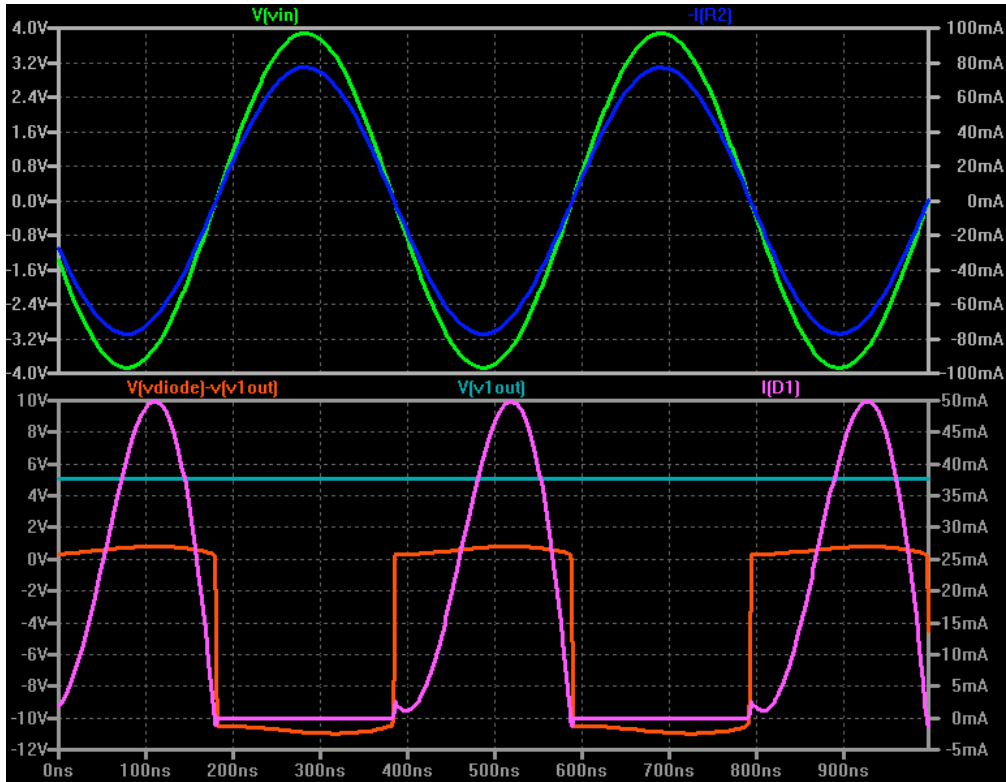
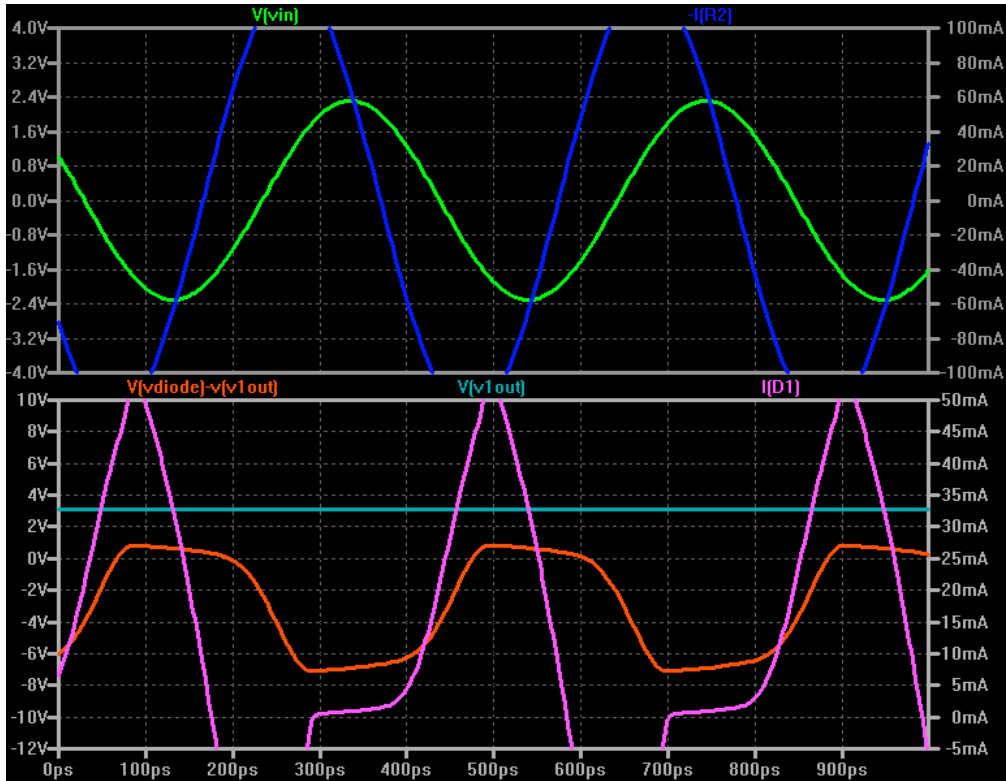


Figure 1  
2.45 MHz Circuit Rescaled to 2.45 GHz



Performance at 2.45 MHz

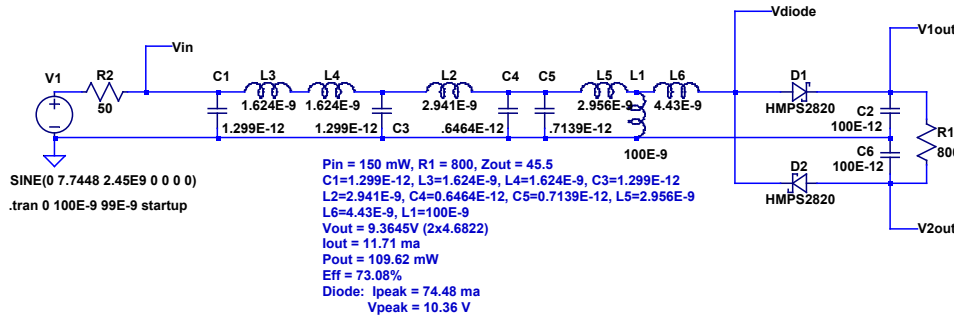


Performance at 2.45 GHz

The 2.45 GHz performance graph clearly shows the degradation produced by the diode junction capacitance:

- Input voltage and current are significantly out of phase.
- Magnitudes of input voltage and current indicate poor impedance matching. (Scale factors for the two sets of graphs were forced to be the same so this is more evident.)
- Diode voltage and current waveforms are less ideal, and significant reverse current flows to the load through the diode junction capacitance, requiring higher forward peak current.
- Efficiency is reduced from 86.19% to 32.64%.

To better understand this effect, consider that in the low frequency circuit, the filter output impedance was adjusted to 166.8 ohms for best match, indicating that this is the equivalent impedance looking into the diode. The capacitive reactance of the junction capacitance of 0.7 pF (typical) is  $X_c = 1/2\pi FC = 92.8$  ohms. This reactance appears in parallel with the diode impedance producing an equivalent series impedance of 39.4 ohms resistance in series with a 70.9 ohm capacitive reactance. Not only is the resistive component much lower than the diode impedance of 166.8 ohms, but the capacitive component is almost twice as large as the resistive component, producing a large phase difference between the voltage and current. Some of the loss in performance can be reclaimed by resonating this capacitive component with an inductor. This can be accomplished by changing the value of L6, or by addition of a shunt inductance to ground at the output of the filter. Both methods were tried and changing the value of L6 produces a better result (although this additional inductance acts with the capacitive reactance as an impedance transformer requiring readjustment of the filter impedance transformation.) During this investigation, L1 was moved from the antenna side of the filter to the diode side of the filter since it is more properly considered part of the diode termination, and L6 was split into two inductors (now L6 and L8) where L6 is part of the low pass filter, L8 is the portion used to resonate the junction capacitance and L1 is placed at the junction of L6 and L8. The values of L2, C4, C5, L6 and L8 were adjusted to provide best impedance matching and bring the input voltage and current in phase. The result is shown in Figure 2:



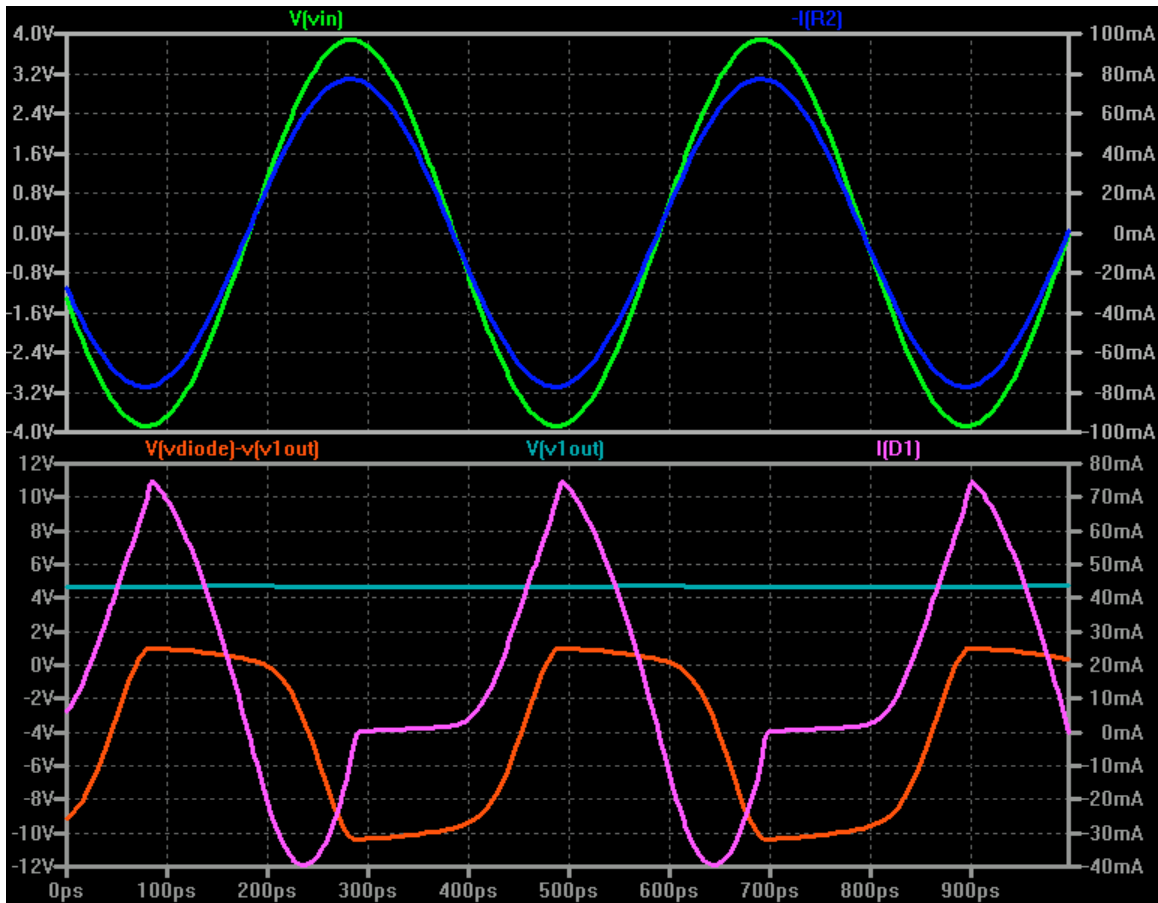


Figure 2  
2.45 GHz Rectifier with PI-T Low Pass Filter and Series Inductor

Performance is greatly improved over Figure 1 but is still well below the performance of the low frequency circuit:

- Input voltage and current are in phase.
- Magnitudes of input voltage and current indicate good impedance matching.
- Diode voltage and current waveforms are still non-ideal, and significant reverse current flows to the load through the diode junction capacitance, requiring higher forward peak current.
- Efficiency is improved from 32.64% in Figure 1 to 73.08% in Figure 2, but is still well below the 86.19% obtained at low frequency.
- Little change in efficiency was seen with 600 or 800 ohm loads when the matching was readjusted to compensate for the change in load. Efficiency begins to decrease outside this range but at a slow rate, so the choice of load impedance is not very critical.

The primary cause of the loss of efficiency at high frequency is because the source impedance driving the rectifier is no longer a high impedance at harmonics of the fundamental frequency. Even though the junction capacitance is part of the diode, the

circuit behavior is as if the capacitance was shunted across the input as discussed above. This circuit “tunes out” the capacitance at the operating frequency, but at the (higher) harmonic frequencies the impedance will be a low capacitive reactance. Because the junction capacitance is internal to the diode, it is not possible to isolate this capacitance from the diode. The author does not believe that much improvement is possible with a lumped-element circuit unless diodes with lower junction capacitance can be found.

Some additional work was done studying an implementation using Gallium Arsenide (GaAs) diodes that shows efficiencies around 80% at 2.45 GHz with a lower capacitance diode. This work has not been included because the author has not been able to locate a source for this diode. Another source for a silicon diode (Infineon Technologies BAT-62 series) was located that has lower junction capacitance (0.35 pF) than the Avago Technologies part used in Figure 2. Simulations were not performed with this part because a Spice model was not available.

All of the previous simulations were performed with ideal lossless inductors and capacitors. In addition to the above problems with junction capacitance, it is also difficult to fabricate discrete inductors and capacitors that provide good accuracy and performance at microwave frequencies. Capacitors have series resistance and inductance and inductors have series resistance and parallel capacitance that become more significant as frequency is increased, and connecting leads add significant unwanted inductance. These effects are difficult to predict analytically and it is generally necessary to measure the characteristics of the actual components to be used. A circuit fabricated from the above design will produce poorer performance than the simulations predict because of the component losses. (In the author’s judgement the loss in performance will be on the order of 10%.) Because of these difficulties, microwave circuits commonly use transmission line elements in place of discrete inductors and capacitors.

There are many forms of transmission lines including coaxial cable, waveguide, stripline and microstrip. The easiest form to work with is the microstrip, where transmission lines are formed by placing thin copper conductors on the top side of an insulating material (dielectric) and a thin uniform copper ground plane on the bottom side of the dielectric. Such circuits can be fabricated to a high degree of accuracy and provide good performance provided that an appropriate dielectric material is chosen. The most commonly used dielectric is fiberglass reinforced epoxy material known as FR4. Dielectric losses in this material are moderately low at 2.45 GHz (Better performance can be obtained with fiberglass reinforced ceramic-teflon dielectrics but these are significantly more expensive and more difficult to work with.).

With a given dielectric material and thickness, the characteristic impedance of a transmission line is determined by the width of the line, and the line will be characterized by having this characteristic impedance, an electrical length proportional to the physical length, and a certain loss per unit length. Junctions of lines of different width and/or of multiple lines will have non-ideal properties at the junctions. These non-ideal characteristics are very complex and are usually handled by using microwave simulator

software. In the following work, simulations were performed with Agilent's Genesis software package (formerly Eagleware).

Transmission line elements can be made to produce characteristics similar to discrete inductors and capacitors at specific frequencies but over a wide frequency range the characteristics are quite different. In some circuits (such as low pass filters), this limits the frequency range over which the desired behavior is obtained, but in others it introduces an additional degree of freedom that can be useful. In particular, the behavior of a transmission line will repeat at  $\frac{1}{2}$  wavelength increments of line length. For example a line that is  $\frac{1}{4}$  wavelength long at a frequency of  $F$  will be  $\frac{3}{4}$  wavelength long at  $3F$ , but will behave like it is  $\frac{1}{4}$  wavelength since  $\frac{3}{4} - \frac{1}{2} = \frac{1}{4}$  wavelength. In addition, a mismatched transmission line will pass through regions where it behaves as either a capacitor or inductor as the line length is changed so a transmission line can be designed that behaves like an inductor at the fundamental while behaving as either a capacitor or inductor at a specific harmonic.

The first step in designing an implementation was to design the low pass filter. The filter was implemented as two cascaded filters, one optimized to attenuate the second through the fifth harmonics and the other optimized to attenuate the fifth through the tenth harmonics. Each filter is constructed of alternating sections of high impedance (narrow) and low impedance (wide) lines. Figure 3 shows the frequency response of this filter predicted by the Genesis simulation software:

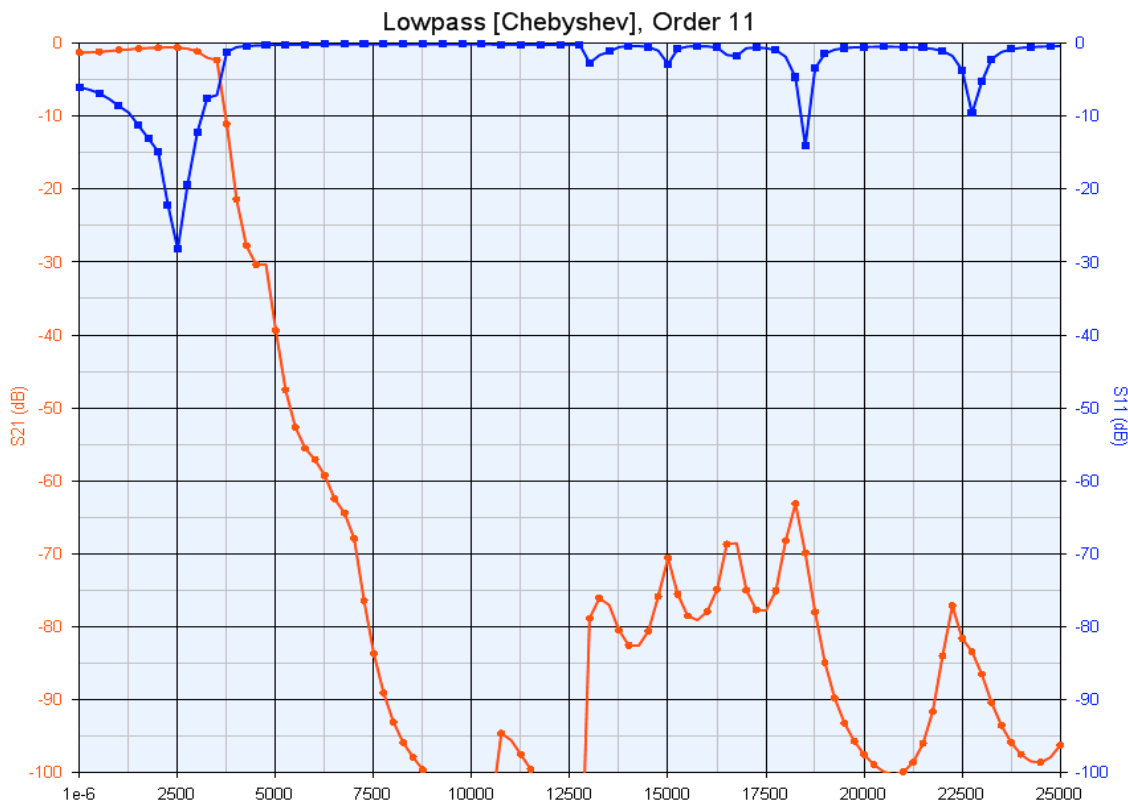
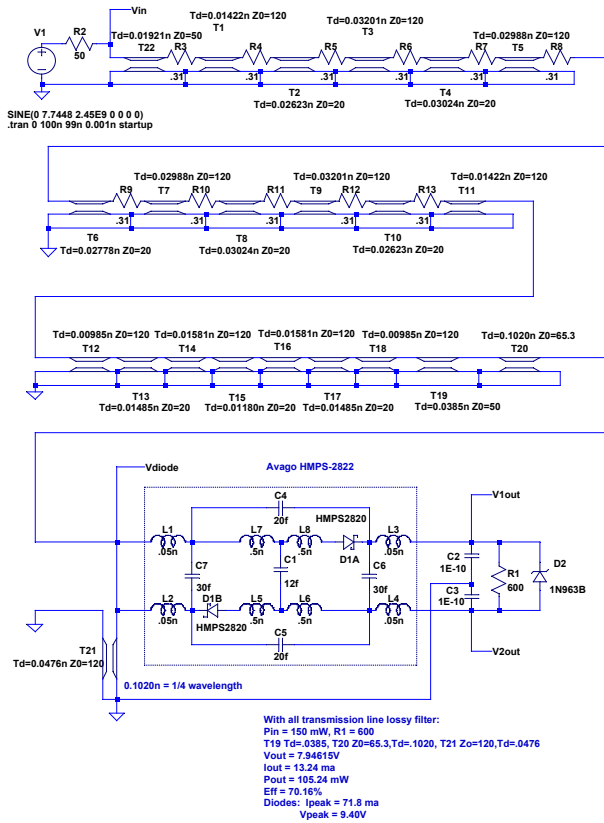


Figure 3  
Low Pass Filter Performance

S21 (red graph) is the transmission coefficient plotted through 25000 MHz (25 GHz). Attenuation is about 37 dB at the 2<sup>nd</sup> harmonic (4900 MHz), and better than 60 dB at the 3<sup>rd</sup> through 10<sup>th</sup> harmonics, and attenuation at the fundamental (2450 MHz) is about 0.5 dB (9%) due to dielectric and copper losses. S11 (blue graph) is the input reflection coefficient and is -30 dB at the fundamental while being generally near 0 dB across the stop band of the filter. The “spiky” characteristic in the stop band is due to high frequency resonances in the small elements used to make the filter and is an unavoidable characteristic of this type of filter.

Figure 4 shows an implementation of the complete rectifier circuit using transmission lines with the above filter. The diode model was enhanced to include the effects of package lead inductance and capacitance. Two designs were done, one with ideal lossless sections of transmission line with small resistors added between sections to simulate loss, and the second with .059 thick FR4 dielectric material that includes losses and the non-ideal effects of step changes in line width.. This was done because the Spice simulator is unable to handle non-ideal transmission lines. The ideal Spice model is as follows:



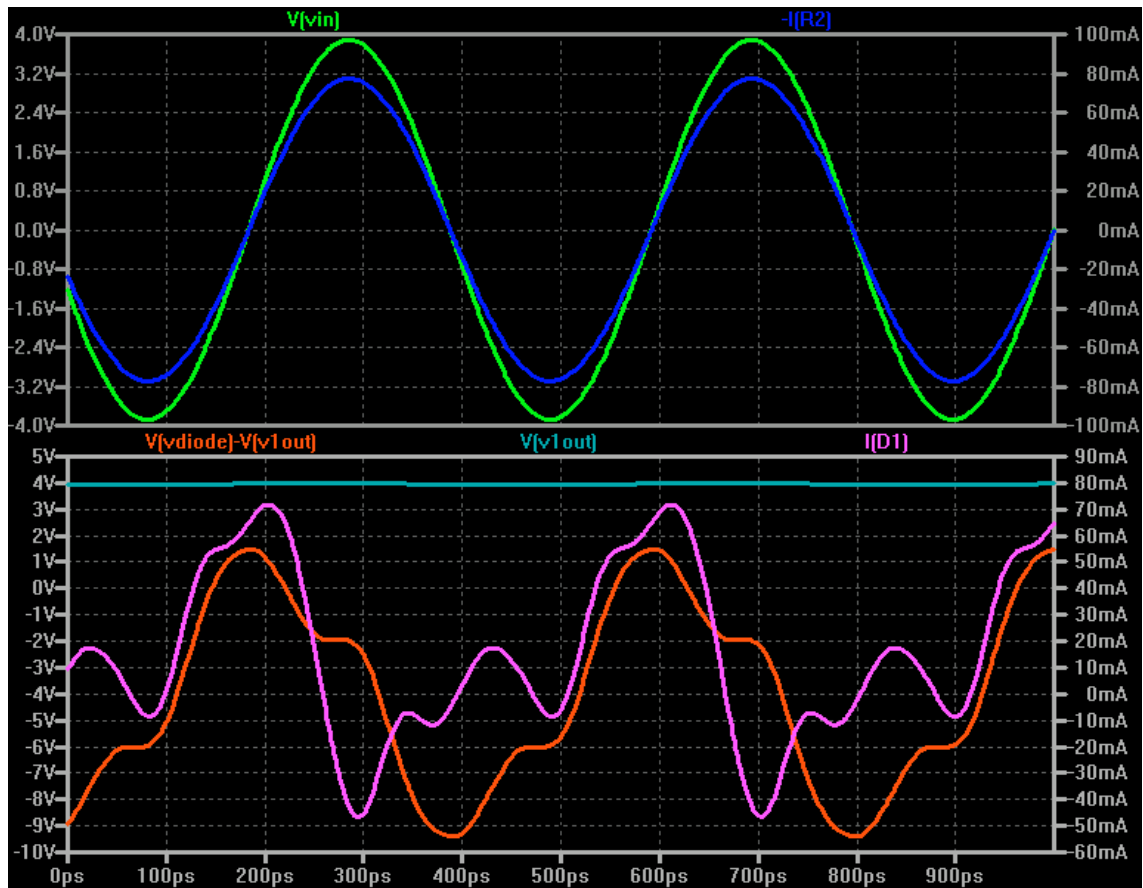


Figure 4  
Shunt-Tuned Transmission Line Implementation

While this circuit appears complex, all components except the dual diode and output filter capacitors are copper shapes on the circuit board and the circuit only has three individual parts plus input and output connectors.

- Transmission line T22 is a short length of 50 ohm line to permit the interface to a coaxial connector. Length of this section is non-critical and may be adjusted to meet mechanical requirements.
- Transmission lines T1 – T11 implement the low pass filter for the second through fifth harmonics.
- Transmission lines T12 – T18 implement the low pass filter for the fifth through tenth harmonics.
- Transmission line T19 is used to adjust the 3<sup>rd</sup> harmonic impedance presented at the filter output to the lowest possible value. (Near zero ohms.)
- Transmission line T20 is a ¼ wavelength impedance transformer to match the 50 ohm filter impedance to the diode impedance and transform the low 3<sup>rd</sup> harmonic impedance at the filter output to a high impedance at the diode.
- Transmission line T21 resonates the diode capacitance at the fundamental and 3<sup>rd</sup> harmonic.



- Diode voltage and current waveforms show evidence of ringing at the third harmonic due to this resonance. This characteristic will be seen when the matching circuit permits third harmonic voltages and currents but blocks higher harmonics.
- Efficiency including transmission line losses is 70.16%.
- Transmission line losses are about 9%, so the efficiency of the diode portion of the circuit is about 77%. This is a modest improvement over the 73.08% efficiency obtained in the discrete component implementation. The 9% transmission line loss can be reduced by use of lower loss circuit board material. (2% loss was obtained with Roger 3003 material.)
- A 12 volt zener diode (D2) was added across the output as a protective measure in case the rectifier is operated without a load. In this case the output voltage will tend to rise to a value high enough to exceed the reverse breakdown voltage rating of the schottky rectifiers. D2 will clamp the output at 12 volts, limiting the rectifier diode reverse voltage to about 13 volts.
- As previously noted, efficiency varies slightly with load resistance (R1). Best efficiency was obtained with a load of 600 ohms and the schematic and waveforms are shown for this case. While efficiency decreases for other values of R1, efficiency remains good for loads from 400 to 1000 ohms showing that the choice of load resistance is not highly critical.
- The power beaming demo system will use LED's as the load and the only choices are how many LED's to connect in series. Typical LED's have a forward voltage around 2.2 volts and these results suggest that the load should be four LED's in series for a total voltage of 8.8 volts. This will produce a load impedance of about 738 ohms in Figure 4.
- Efficiency improves a little (about 1%) in the circuit of Figure 4 as the power level is increased from 150 to 300 milliwatts. At 300 milliwatts the peak reverse voltage is near 14 volts so any increase in power level beyond this point will require reduction of the load impedance to reduce the diode voltage.

The following Figures 5-9 show the board layout, Figures 10 and 11 are drawings for an enclosure, and a parts list for a complete rectifier module based on Figure 4 follows the drawings. The board layouts were captured by taking screen shots from the circuit board design software and are not to accurate scale. The green dots that show on these layouts are the "handles" used in editing and will not appear in the actual artwork. Gerber files containing the board layouts are available and should be used for board fabrication.

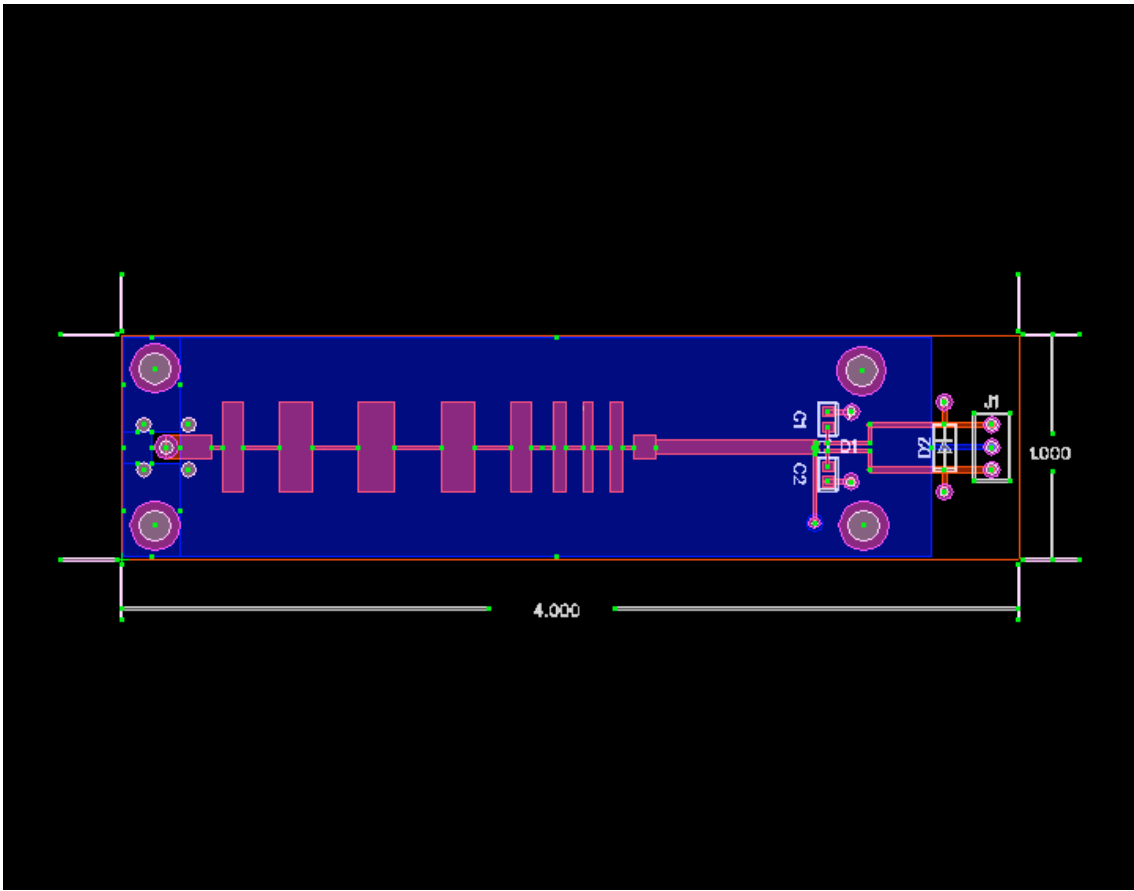


Figure 5  
2.45 GHz Rectifier Assembly Drawing

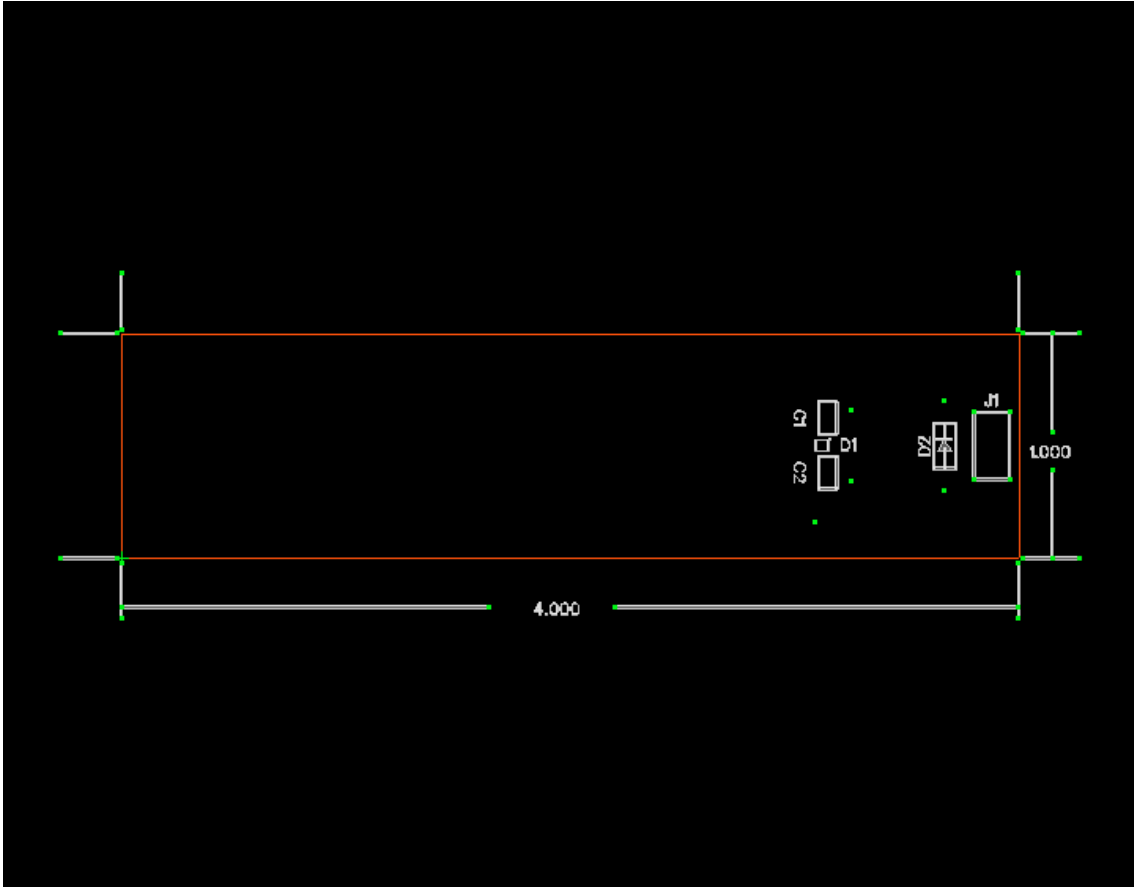


Figure 6  
2.45 GHz Rectifier Top Side Silkscreen

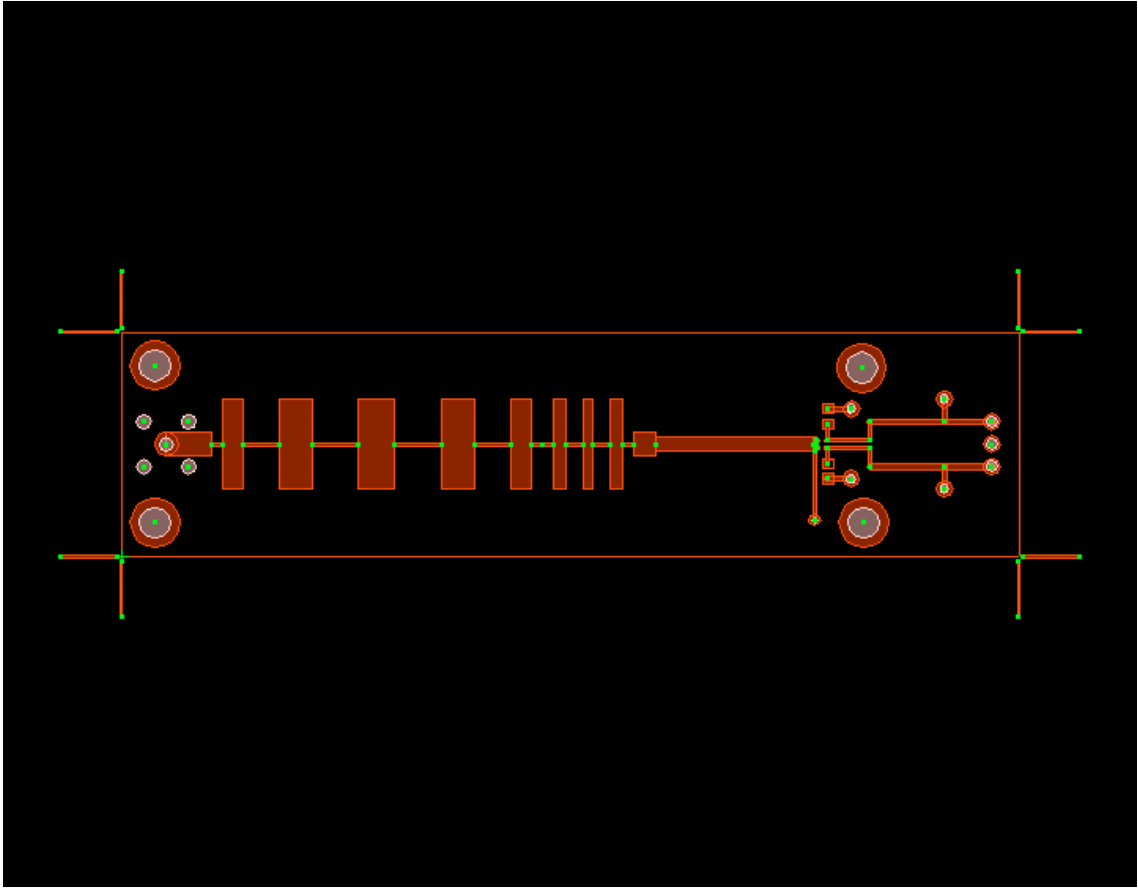


Figure 7  
2.45 GHz Rectifier Top Side Metal

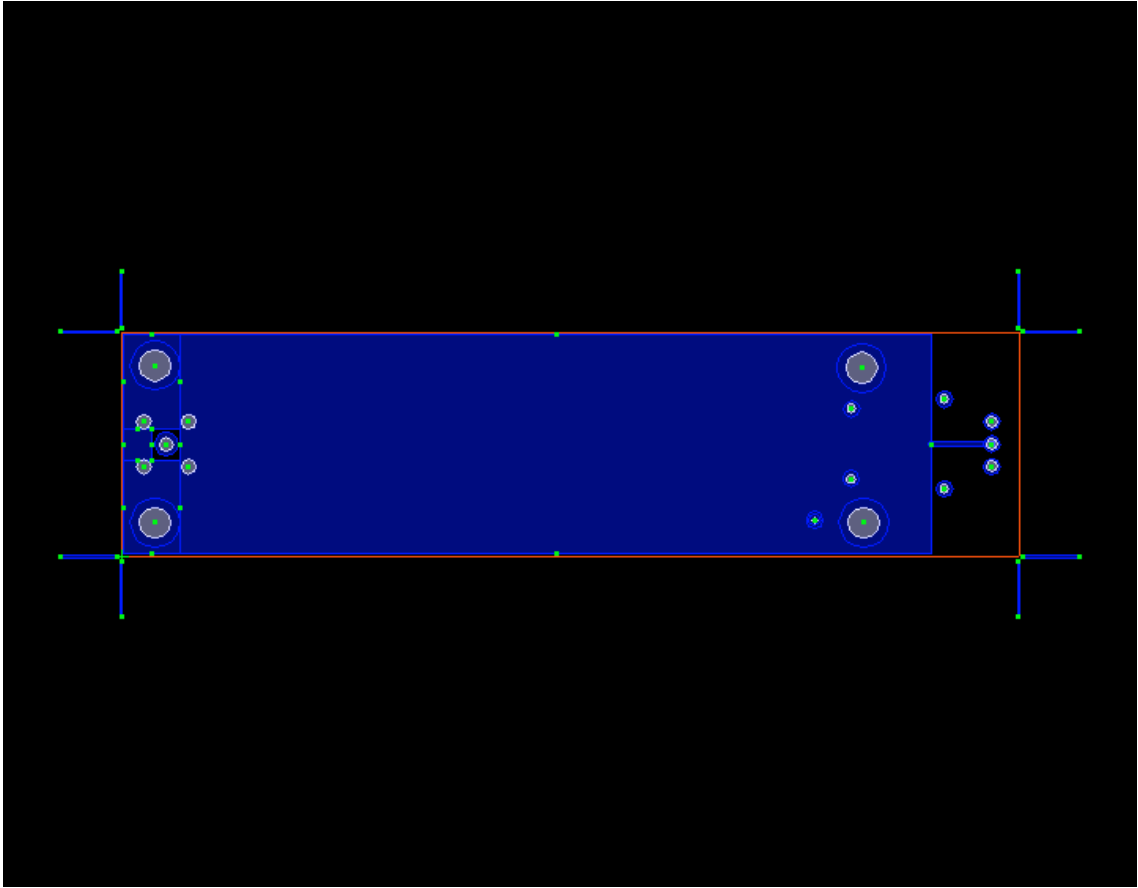


Figure 8  
2.45 GHz Rectifier Bottom Side Metal

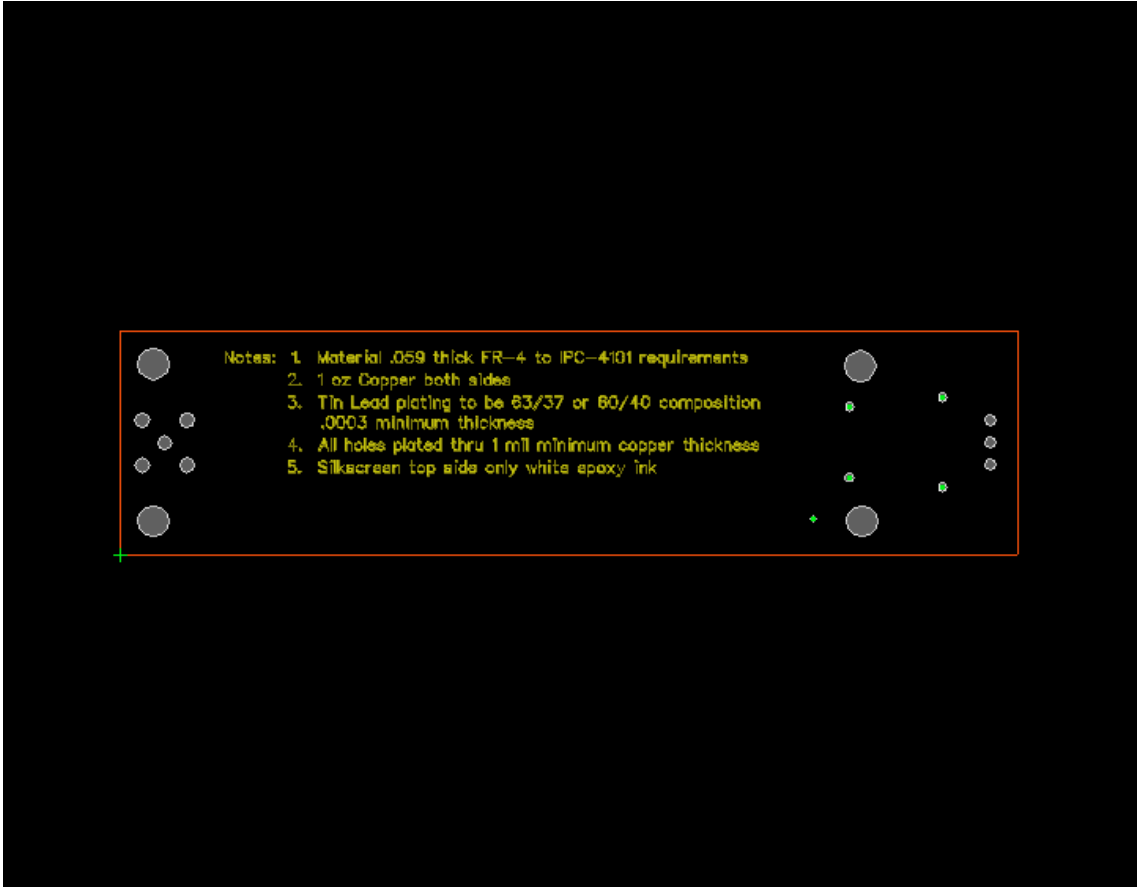
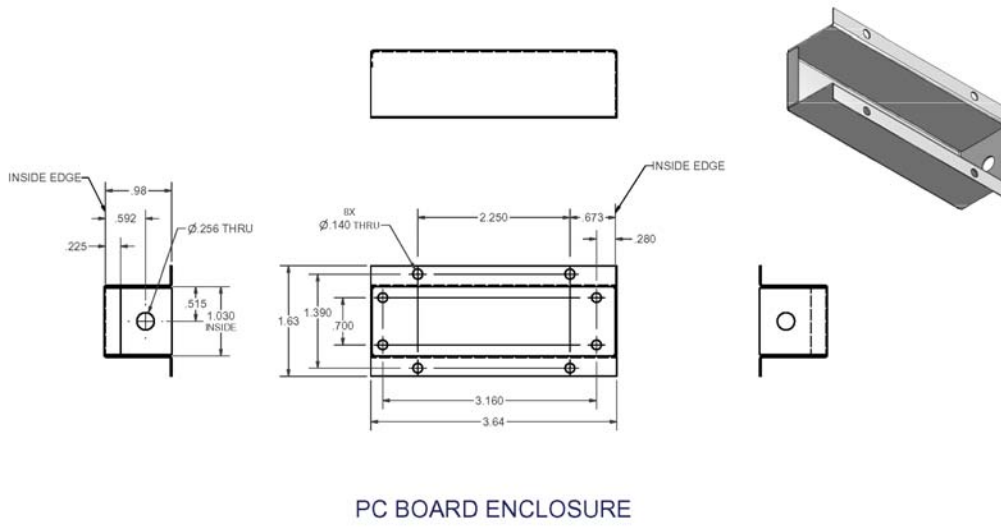
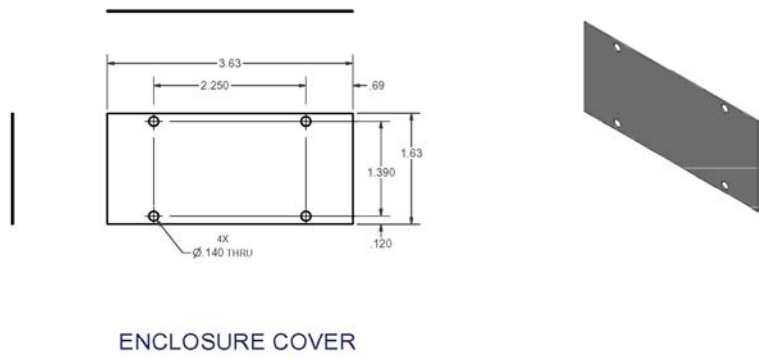


Figure 9  
2.45 GHz Rectifier Notes



NOTE:  
 1. MATERIAL TO BE .020 THICK CRS.  
 2. PLATE ALL OVER WITH HOT TIN.

Figure 10  
 2.45 GHz Rectifier Enclosure Upper Half



NOTE:  
 1. MATERIAL TO BE .020 THICK CRS.  
 2. PLATE ALL OVER WITH HOT TIN.

Figure 11  
 2.45 GHz Rectifier Enclosure Lower Half

## Parts List for 2.45 GHz Rectifier

Item No.	Qty	Description
1	1	2.45GHz circuit board
2	1	Pasternack PE4545 SMA female bulkhead right angle P.C. mount connector
3	1	Extra .250-36 nut for Item 2
4	1	Avago HMPS-2822-BLK dual anti parallel silicon schottky diode (MiniPak 1412 package)
5	2	100pF, 50 V, X7R 0603 pkg SMT Ceramic Capacitor
6	1	1N963B 12 V, 500mw zener diode
7	1	3 pin header .025 pins x .100 spacing Amp (Tyco) MTA .100 series 640456-3 or equivalent
8	1	Enclosure upper half
9	1	Enclosure lower half
10	4	Brass spacer .250 OD x .125 ID x .250 long
11	4	4-40 x 1/2 stainless steel pan head screw
12	4	4-40 stainless steel split lock washer
13	4	4-40 stainless steel small pattern nut

### Final Thoughts

Diode junction capacitance is not tightly controlled by device manufacturers. In the case of the Avago HMPS-2822 used in this design, the capacitance is specified as 0.7 pF typical, 1.0 pF maximum and no minimum is specified. In the author's experience, the minimum would be expected to be about 0.5 pF. In a circuit like Figure 4 where steps have been taken to tune out the junction capacitance, this variation will cause changes in circuit performance and critically tuned circuits with narrow bandwidth (high "Q") should be avoided as the performance will degrade to an unacceptable level. Figure 4 was evaluated with a junction capacitance of 0.5 pF and the resulting efficiency was 69.27% while with a junction capacitance of 1.0 pF the efficiency was 63.36%. These levels of degradation are within the normal range of variation for microwave circuits. The efficiency is harmed more by higher capacitance as might be expected from prior results and further emphasizes the importance of low junction capacitance in making a high efficiency rectifier.

When data is available to better define the power level that will be obtained from the receive antenna, it may be appropriate to re-optimize this circuit for that power level. In its present form, the circuit produces a small increase in efficiency as power is increased but it is also noticeable that the impedance matching is not optimum at higher power and a modest improvement in performance is likely by re-optimizing.