SHUNT-MOUNTED HARMONICALLY-TUNED POWER RECTIFIER FOR DISTRIBUTED POWER CONVERTERS

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ABSTRACT

A RF power rectifier has been designed, constructed in surface-mount technology and evaluated for use in distributed power converters for advanced electronic packaging applications. With commercially available components, a 40 watt rectifier with a 100 MHz input from a 50 ohm source impedance provides 2.9 V output with 38% conversion efficiency. Detailed simulation and characterization indicates that 50 watt and 10 watt converters are capable of 70% and 80% conversion efficiency respectively, with low loss RF implementations.

Efficient distributed power converters allow improved efficiency of prime power in electronics systems, by allowing power distribution at relatively high DC voltages (~50 V) and converting the power efficiently close to point-of-use. Such prime power distribution network becomes increasingly important as the voltage levels of advanced ICs decrease and electronic power distribution requires thin-film conductors near point-of-use, such as prevalent in multichip module technology.

DC-DC converters for these applications must be efficient and be space conservative in order to enable such a power system design. These factors combine to force operation at higher switching frequencies than typically employed in switching converters. In this work, a 100 MHz switching converter was designed to take a 50 V DC signal and provide lower voltages required in advanced ICs (such as 5 V, 3.3 V, 2.5 V etc.). This paper presents the RF power rectifier part of the converter, which takes a 100 MHz sinusoidal input (output of the inverter) with any equivalent source impedance and provides a DC output of between 2.5 V and 5 V depending upon the application. For testing and characterization purposes, a source impedance of 50 ohms was used. In an actual DC-DC converter, the low output impedance of many inverter circuits will alleviate the impedance transformation required and allow improved conversion effciency.

CIRCUIT TOPOLOGY

The basic shunt-mounted harmonically-tuned rectifier is based upon the earlier work of R.J. Gutmann and J.M. Borrego [1,2] and is shown in Fig. 1a. The circuit consists of an input filter which allows power transmission at the input frequency and provides a high impedance at all odd harmonics. The output filter provides a short circuit at the even harmonics and blocks the fundamental and odd harmonics from reaching the DC load. With an ideal diode (zero turn-on voltage, no resistance and no leakage current) and lossless reactive components, 100% conversion efficiency can be obtained. A circuit that meets these requirements is shown in Fig. 1b. Fortunately, a simpler circuit meets these requirements almost as well as shown in Fig. 1c, with the L-section input providing a necessary 50 ohm to 1 ohm transformation at 100 MHz (for the overall DC-DC converter, different impedance matching is provided as required by the inverter circuit requirements).

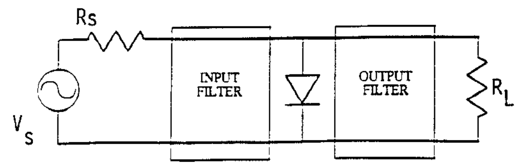

Figure 1a Basic Rectifier Circuit

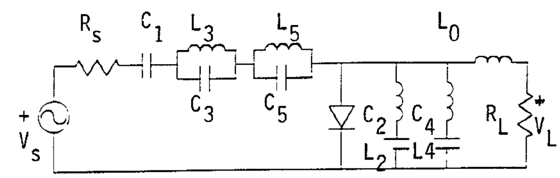

Figure 1b Ideal Shunt-Mounted Harmonically-Tuned Rectifier Circuit

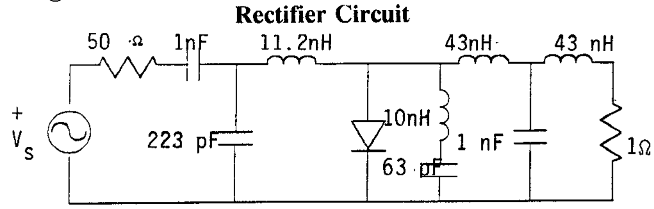

Figure 1c Modified Rectifier Circuit

The revised circuit includes only a second harmonic tank circuit. The diode junction area required to carry the peak current in the 50 W version of the rectifier provides an adequate low impedance during the non-conducting part of the RF cycle at higher even harmonics. In fact, with the Schottky diode used in our work (IR 40CPQ) there is very little difference in performance with and without the second harmonic tank. However, with lower power converters or with a diode selected more nearly matched to the 25 W circuit design, the second harmonic tank is desirable.

CIRCUIT SIMULATION

In order to fully design and evaluate the circuit topology, appreciable circuit simulations were done using mwSPICE and Libra. The simulations allowed us to fully evaluate the effect of the Schottky diode, reactive elements and circuit mounting parasitics on both nominal design parameters and reductions in conversion efficiency. In particular, the importance of the voltage-dependent Schottky diode junction capacitance, inductor Q, and parasitic inductances and resistances could be quantified. This was useful when evaluating our circuit implementation (such as the effect of diode lead inductance and ground lead resistance) and extrapolating to other switching frequencies, power module ratings and circuit packaging embodiments.

The key aspect in the feasibility of this technology is power conversion efficiency. Using mwSPICE simulations, the effect of the actual Schottky diode (IR 40CPQ), SMT inductors (Coilcraft Spring Air Core), SMT capacitors (AVX Ceramic NPO) and trimmer capacitors (Johnson) could be isolated. The results are presented in Table 1 for the 25 W converter design driven from a 50 ohm source impedance (focus of this paper) and a 50 W converter design driven from a 3 ohm source impedance. Inductor Q is a limiting factor on conversion efficiency. The improvement in efficiency with the latter design is due to the reduced impedance transformation required in the latter case and the better match of the diode to current handling requirements of the circuit.

	25 W 50 ohm source	50 W 3 ohm source
Physical Diode Model	89	88
$Q_{cap} = 500$; $Q_{ind} = 100$	66	73
$Q_{cap} = 100$; $Q_{ind} = 100$	60	70

Table 1 Efficiency with Increasing Dissipation Introduced

CIRCUIT IMPLEMENTATION

The circuit was implemented using 20 mil thick Duroid printed circuit board with commercially available surface mount technology (SMT) inductors and capacitors. A tuning cap is added both in the second harmonic tank circuit and the input L-section transformer/filter to tune the circuit for optimum conversion efficiency. It was found that tuning under small signal conditions (using a network analyzer with various diode bias) or large signal conditions (probing the voltage across the diode) were possible. The Schottky diode was bonded with a ribbon connection to minimize series inductance. Photographs of the circuit board layout and the low lead inductance bonded Schottky are shown in Fig. 2.

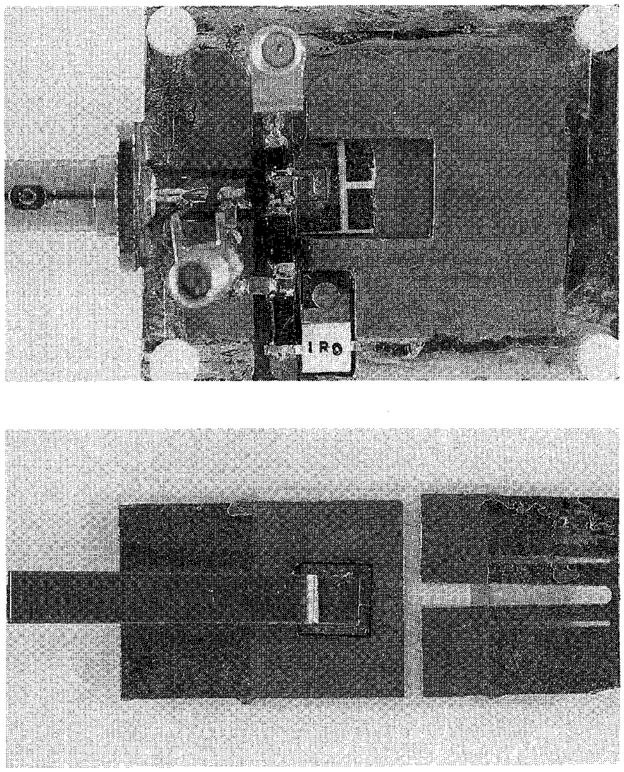

Figure 2 Photographs of Board Layout and Diode Mount

In order to evaluate this rectifier circuit topology as well as the effectiveness of the SMT implementation, the Schottky diode, SMT inductors and SMT capacitors were evaluated in detail using an automatic network analyzer and a commercial SMT mount. In addition, small signal measurements were taken on the rectifier circuit in order to insure that the circuit elements had been properly characterized and the mounting and circuit board parasitics could be properly taken into account (at least under small signal conditions). In addition, tuning the input and output to account for mounting parasitics and variations in component values was possible under small signal operation.

TEST RESULTS

The best efficiency obtained to date with the SMT implementation is 38% conversion efficiency with 2.9 V output and 40 W input. The DC output power versus RF input power is shown in Fig. 3, where the DC load resistance is 1.0 ohms. It should be noted that the rectifier is not perfectly matched and the efficiency quoted is available efficiency (ie. DC power out divided by net RF power in). We expect that improved soldering will increase the conversion efficiency of the SMT breadboard to approximately 45%, with the diode and input ground connections particularly critical. Our simulations indicate that 55% should be possible with the components actually utilized (compared to 63% for Q_{cap} = 300 indicated in Table 1 with proper component values). Simulated results with increased ground resistance (18 milliohms) that provides a match to the measured data at one operation point agrees well both with large signal data at different drive levels and under small signal RF characterization using the automatic network analyzer. Thus, we attribute our reduced efficiency to ground connection resistance, possibly the diode mount itself.

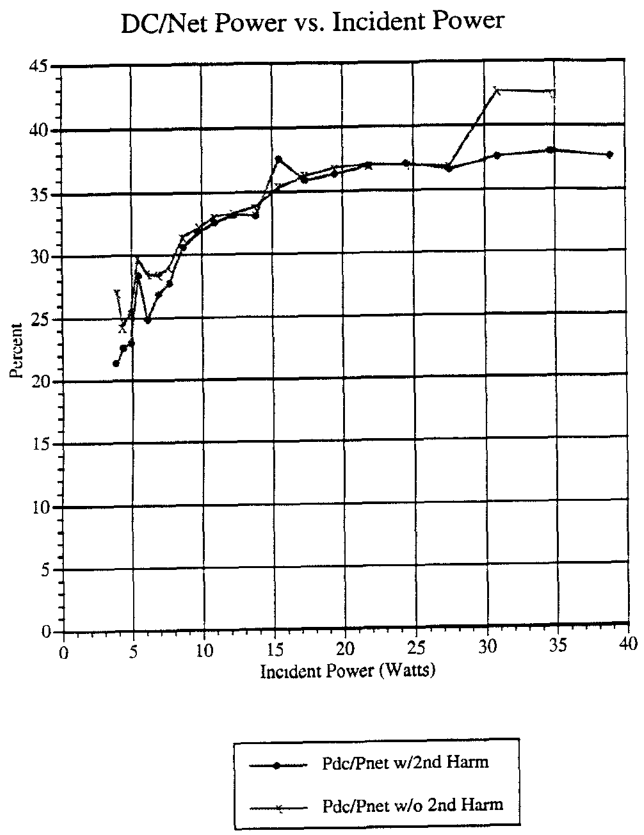

Figure 3 Output/Net Power versus Incident Power

CIRCUIT POTENTIAL

We believe that the efficiency potential of the circuit can be increased significantly by going to either an integrated packaging technique to minimize parasitic reactances and improving contact resistances and/or by going to lower power modules, thereby increasing the circuit impedance levels. A transfer of this technology to General Electric for implementation in their High Density Interconnect (HDI) packaging technology is underway with 47% being achieved in the initial implementation (compared to 38% in the SMT implementation). Simulation results indicate appreciably higher conversion efficiency with lower power modules (10 W instead of the 25 W and 50 W modules described here).

Besides the impedance level of the circuit, it is critical to match the Schottky diode current-handling ability and junction capacitance to the circuit. The effect is shown in Table 2 where 72% conversion efficiency is indicated for a 10 W circuit with a properly scaled current-handling capability, while the diode with over 50 W capability gives a lower 28% conversion efficiency. With improved mounting technology and circuit board layout as well as properly selected components for the circuit specifications, an 80% conversion efficiency is expected from the 10 W design (compared to 70% for 50 W designs in high performance circuit implementations).

	40 CPQ Diode	15 CPQ Diode
Diode Characteristics		
Cjo	5700 pF	360 pF
Rs	5.9 mΩ	20 mΩ
Is	11 μA	1 μA
Simulated Circuit Efficiencies		
Refl/Incident Power	21%	4%
Available Efficiency	23%	69%
Net Efficiency	28%	72%

Table 2 Simulated Power Conversion Efficiencies for 10 W SMT Implementation

SUMMARY AND CONCLUSION

A SMT breadboard implementation indicates that a shunt-mounted harmonically-tuned rectifier circuit is capable of 55-80% conversion efficiency with 100 MHz drive frequency, depending upon the Schottky diode, power module size and physical embodiment of the circuit. While additional conversion efficiency will be needed for practical distributed DC-DC converters, this performance sets a benchmark for the technology at such a switching frequency, particularly with the 2.9 V output voltage. While rectifier circuits have achieved efficiency near 90% at 2.45 GHz, the 1 W circuits have a much higher output impedance, with less circuit dissipation. [3] Power Schottkys with lower turn-on-voltage and inductors with high Q are necessary to improve efficiency.

ACKNOWLEDGEMENTS

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