# V-8. Microwave Applications of the Step Recovery Diode

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There has been increasing interest in the past few years in methods for obtaining microwave power derived for vhf sources by means of single-stage multipliers of higher harmonic order. While such a method is less efficient than a cascade of varactor doublers and triplers, the reduced complexity and increased versatility will often mitigate the additional vhf drive power required. A single-stage high-harmonic-order multiplier usually consists of an input matching network and output cavity or bandpass filter. The input and output of single-stage multipliers are usually terminated with linear loads, whereas varactor chains are often difficult to align due to the nonlinear interaction between stages. An additional advantage of the single-stage multiplier is the possibility of employing *prime* harmonic numbers.

The mechanism of this type of higher-order harmonic multiplication is usually attributed to a combination of the voltage-dependent depletion layer capacitance and the charge storage effect in silicon *PN* junctions. This paper describes microwave applications for silicon *PN* junction "step-recovery" diodes in which charge storage is controlled to produce the desired characteristics for a particular application.

Several theoretical investigations[1,2] have been made into the properties of an ideal step-recovery diode, and others[3,4,5,6] have analyzed certain practical circuits.

The *C-V* curve of an ideal step-recovery diode is given by a capacitance which is infinite for $V > 0$ and zero for $V < 0$. The ideal element will store

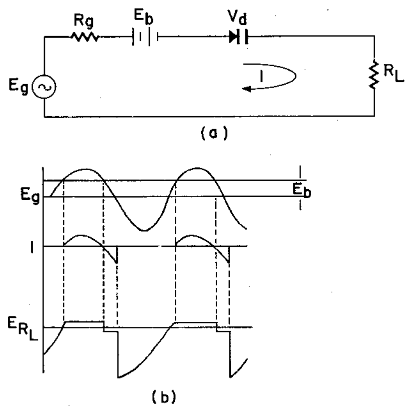


Fig. 1.(a) Untuned nonlinear capacitor circuit. (b) Voltage and current responses of the nonlinear capacitor.

charge on forward conduction and recover charge during reverse bias at a rate proportional to the bias (Fig. 1 (a)).

Charge recovery with finite reverse bias is accompanied by a step function of voltage and current as the charge becomes exhausted (Fig. 1 (b)). Leenov and Uhlir have shown that the higher harmonic content of these waveforms diminishes as $1/n^2$ (20 db per decade) for the untuned circuit of Fig. 1 (a). When tuning is provided, complete power conversion between two frequencies is theoretically possible, but is limited in practice by diode losses and recombination during forward conduction. Krakauer,[3] Hedderly,[4] and Leeson and Weinreb[6] have analyzed optimum circuit conditions and diode parameters. Step-recovery diodes with specified lifetimes and transition times are now available commercially. The lifetime is a relative measure of the time constant associated with recombination at the junction and should be greater than $1/f_o$, where $f_o$ is the source frequency. The transition time, $tr$, is defined as the time from 10% to 90% of the peak value of the voltage or current step. For efficient conversion, $tr$ should be less than $1/f_n$, where $f_n$ is the highest desired harmonic.

*Narrow Band Harmonic Generators.* Figure 2 is an equivalent circuit for the type of narrow-band step-recovery diode harmonic multipliers developed at Melabs. The role of the intermediate harmonics between the fundamental source frequency, $f_o$, and the desired output harmonic, $nf_o = f_n$, is not completely understood for $n$ large. Extensive experimental work has indicated, however, that consistently good results are obtained when the intermediate harmonics are confined to the loop formed by the diode, $C_n$, and the cavity coupling. When the input low-pass filter cut-off frequency is between the fundamental and the second harmonic, this condition is approximately satisfied. The harmonics above $f_n$ are terminated in a reactance which depends on the cavity coupling and loaded $Q$. Since relatively little power is contained in these harmonics, their effect, though not understood, should be small. The input low-pass filter is designed to operate between identical terminations equal to the real part of the diode impedance at the operating power level. The function of the input matching network is to transform the input low-pass filter impedance, $Z_1$, to the complex conjugate of the source impedance, $Z_g$. The network $L_1$, $C_1$, $L_2$, $C_2$, is an approximate lumped element equivalent for a double-stub slide-screw tuner and has been successfully used with all the diodes tested to reduce the input reflection to a negligible value.

The circuit of Fig. 2 will accommodate a range of diodes and frequencies and can be used for preliminary investigations. The final form of a harmonic

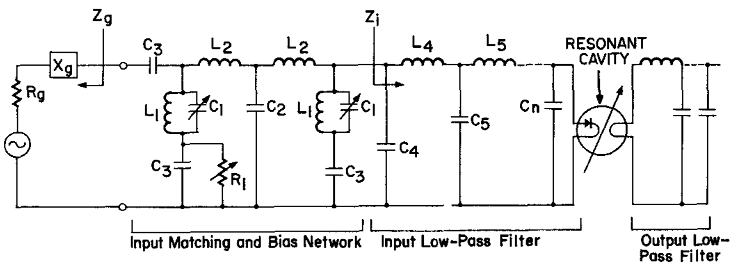


Fig. 2. Equivalent circuit of the narrow-band harmonic multiplier.

multiplier can usually be greatly reduced in complexity.

Table I is a summary of data obtained with the various diodes listed operating in circuits similar to that of Fig. 2. The input power required to obtain conversion efficiencies of the order of 1 db per harmonic is between 250 mw and 2 watts per diodes tested. Heating and saturation limit the harmonic output at high input drive levels, and at very low levels the transition characteristic becomes excessively rounded.[7]

TABLE I.

Single-Stage, Step-Recovery Diode Multipliers (Narrow-Band)

Input Power $p_i$ at frequency $f_i$ → × $n$ → Output Power $P_o$ at frequency $f_o$

| $f_i$ (Mc/s) | $p_i$ (dbm) | $n$ | $f_o$ (Gc/s) | $P_o$ (dbm) | Diode | Conversion Efficiency db/$n$ |
|---|---|---|---|---|---|---|
| 10 | +24 | 9 | .090 | +12.5 | BA 0104 | 1.28 |
| 100 | +24 | 84 | 8.4 | −30 | BA 0106 | .65 |
| 100 | +25 | 10 | 1.0 | +10 | SG 5000 | 1.50 |
| 105 | +22 | 40 | 4.2 | −27 | FD 600 | 1.20 |
| 200 | +27 | 31 | 6.2 | −7 | BA 0106 | 1.10 |
| 200 | +34 | 31 | 6.2 | +7 | BA 0106 | 1.32 |
| 200 | +33 | 18 | 3.6 | +18.75 | BA 0106 | .78 |
| 300 | +30 | 21 | 6.3 | 0 | BA 0106 | 1.42 |
| 450 | +30.7 | 18 | 8.1 | +4.2 | BA 0106 | 1.47 |
| 500 | +26 | 17 | 8.5 | +3.0 | BA 0111 | 1.41 |
| 500 | +30 | 20 | 10.0 | +6.0 | BA 0111 | 1.20 |
| 900 | +29 | 9 | 8.1 | +3.2 | BA 0106 | 2.65 |

*Broadband "Comb Spectrum" Generators.* A "comb-spectrum" will be defined here as energy confined to discrete frequencies spaced at equal frequency intervals. A microwave signal with this type of spectrum is found useful in a number of applications, including microwave receiver calibration and frequency measurements. The circuit in Fig. 2 will produce this spectrum if the output circuit is made to be broadband. The simple quarter-wave stub shown in Fig. 3 is usually adequate for most broad-band applications in *TEM* lines.

The data obtained over the range 1–12 Gc is given in Fig. 4 and seems to follow the 20 db/decade slope, but is 6 to 10 db below the conversion loss for an ideal untuned step-recovery diode.

*Operation in the Reverse-Breakdown Region.* Another interesting property of the thin, diffused silicon *PN* junctions used in step-recovery diodes is the minute, isolated microplasmas associated with the reverse avalanche breakdown which has been studied by several authors. Diodes have been operated in this region as harmonic generators, and have provided conversion efficiencies which compare to those obtained in the step-recovery mode. As the driving source frequency is lowered to audio frequencies, the response, as measured through a broadband microwave filter, is short ($< 25\ \mu$sec) pulses of apparently incoherent microwave energy with the audio repetition rate. As the bandwidth of the microwave filter is reduced, the output response is indistinguishable from pulsed, filtered white noise.

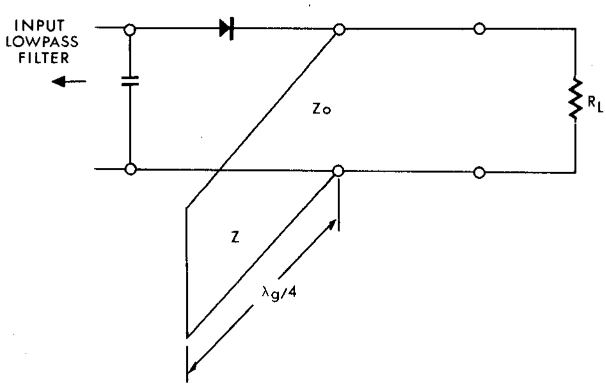


Fig. 3 Modification of the circuit of Figure 2 for use as a broadband "comb spectrum" generator.

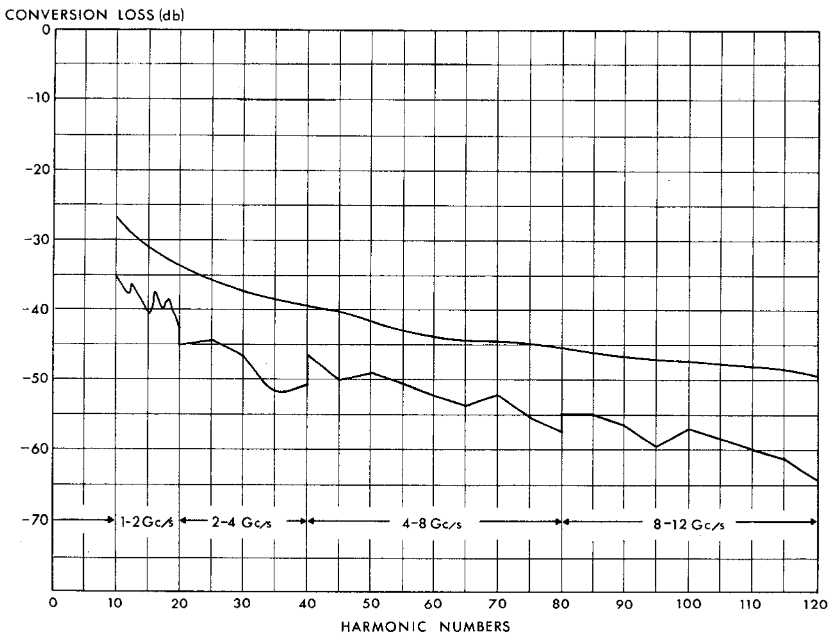


Fig. 4 Date on broadband "comb spectrum" generators.

The experiments conducted here using vhf sources and the circuit of Fig. 2 required tuning adjustments to compensate for the change in junction capacitance and resistance level. The levels of harmonic power obtained compared to those achieved in the step-recovery mode. In the tests conducted at audio frequencies, a single bypass capacitor served as the only isolation between the microwave and audio circuits. The energy content per unit bandwidth remained fairly constant up to approximately 6 Gc, and then began to diminish as the filter center frequency was increased to 10 Gc, where the output was approximately 10 db below that obtained at 6 Gc. Pulses of amplitude +10 dbm were measured through a 4 Mc bandwidth filter with a 10 kc/s source frequency.

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