THEORETICAL EFFICIENCY FOR TRIPLERS USING REAL VARISTER DIODES AT SUBMILLIMETER WAVELENGTHS

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Summary

The theoretical efficiency for frequency triplers from 300 to 900 GHz has been calculated for real GaAs Schottky diodes operating in the varister mode. The maximum efficiency is determined to be about 7%, only slightly smaller than that for ideal varisters. Guidelines for optimum bias conditions and embedding network impedances have been determined using the large signal analysis computer program of Siegel and Kerr (1).

Introduction

The choice of sources in the submillimeter wavelength regime is very restricted. Reliable fundamental sources with powers of tens of milliwatts exist for frequencies up to about 100 GHz in the form of Gunn oscillators, 200 GHz in the form of klystrons, and 400 GHz in the form of carcinotrons. Above 400 GHz gas lasers - both unwieldy and difficult to use - provide the only fundamental sources. Multiplication of lower frequency fundamental sources presents an attractive alternative in this wavelength range.

In this paper we seek to optimize the design and operation of the frequency multiplier most effective in submillimeter wavelength region: the GaAs Schottky barrier diode multiplier operating in the varister mode. Guidelines for optimizing varactor multipliers have long been established (2). We present a similar analysis for frequency multiplication arising from the nonlinear resistance of the forward biased Schottky barrier diode. It has been shown that, for an ideal varister (one with an infinitely high cutoff frequency), the conversion efficiency to the nth harmonic is the inverse of n^2 (3,4). Actual efficiency, however, is reduced due to losses in parasitic multiplier elements. Design guidelines seek to minimize this deviation from the ideal in physical multipliers.

To establish such design guidelines for a tripler, with input frequency at 300 GHz and output frequency at 900 GHz, we examine the dependence of multiplier performance on its operating point, embedding network, and diode parameters using a modified version of the large signal analysis subroutine of GISSMIX, the mixer analysis program by Siegel and Kerr (1). The diode parameters used are characteristic of state of the art GaAs Schottky barrier mixer diodes. Such a multiplier could employ a carcinotron as its pump source and be implemented with a combination of waveguide and quasi optical components.

Analytic Method

Our program implementation closely parallels that of Siegel and Kerr (1) for the analysis of mixers. However, because multipliers are optimized differently than mixers, we have altered the operating point variables in the GISSMIX program. Rather than adjusting a local oscillator power until a desired rectified current flows, frequency multipliers are usually set to a fixed pump power level while the dc bias voltage or current level is varied to obtain optimum efficiency. Therefore we take the pump power and not the DC bias current to be the independent variable for the multiplier. We have modified the program to reflect these needs. (Siegel, Kerr, and Hwang (5) have carried out similar modifications, however their implementation, in particular their method of calculating powers, differs slightly from ours). In addition, we have restructured the logic flow in the large signal analysis program to facilitate understanding and ease of modification.

We have verified the accuracy of the large signal analysis part of the GISSMIX program, modified as described above, by comparing its results to those of Penfield and Rafuse (2), who present a theoretical treatment of the ideal, abrupt-junction varactor, giving explicit solutions for doublers, triplers and higher harmonic generators. Ten test cases were chosen corresponding in most instances to the solutions that yield maximum efficiency at a given pump frequency. The diode, bias, and impedance values were input into the modified GISSMIX program and the conversion efficiency was calculated. A number of internal parameters, such as the Fourier components of the currents and voltages, were compared. The output efficiencies from the program and the Penfield and Rafuse formulation agreed within 5% in all but two cases. In one of the cases where agreement was not reached, the conversion efficiency was extremely low and the discrepancy resulted from round off errors in the Fourier transform. In the second case, the program failed to converge and was terminated after a certain number of trials.

0149-645X/85/0000-0315

The Varister Diode Tripler

We have used the modified GISSMIX program to determine the design parameters for a frequency tripler with input frequency at 300 GHz and output frequency at 900 GHz. The diode parameters used as input to the tripler runs are summarized in Table I. These parameters were chosen with two criteria: first that they represent the state of the art in high frequency mixer diodes, and second that the voltage dependence of the capacitance be suppressed so that the results could be assessed solely in terms of varister mode operation.

Table I. Varister Diode Parameters

R_{series}	10 ohms	
R_{skin}	0 ohms	
I_s	1.0×10^{-16}	amperes
C_o	1.0×10^{-15}	farads
Phi	1.0	
Gamma	0.0	
Eta	1.2	

The bias parameters were systematically varied over a given range. The pump power was set at two levels, 4 mW and 40 mW. The higher value was chosen since it is typical of the power obtained from a carcinotron at 300 GHz. The lower value was chosen because there may be substantial loss in coupling that power into the multiplier. The dc bias current was varied in the range 3 - 25 mA. This range was dictated by the optimum results. An operating temperature of 300 K was assumed.

The maximum tripler efficiency is determined to be about 7%, slightly smaller than the 11% expected for the ideal varister. A contour plot of the conversion efficiency as a function of pump power and $R_e(3fp)$ is shown in figure 1. For the range of these parameters tested, the maximum efficiency occurs at $R_e(3fp)$=50 Ohms and pump power=40 mW.

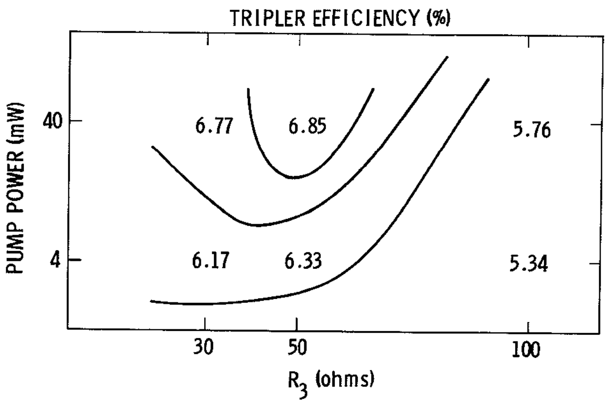

Fig. 1 Contour plot of the computed tripler efficiency for the varister diode as a function of the pump power and the real part of the third harmonic impedance.

The efficiency as a function of diode current, I_d, parameterized by pump power and the real part of the impedance at the third harmonic is given in figure 2. The efficiencies shown have been maximized with respect to the imaginary part of the impedance at the third harmonic. The current at which maximum efficiency occurs depends on the pump power but not on the mount impedance. For a pump power of 4 mW the current is about 5 mA, whereas for a pump power of 40 mW that current is about 15 mA. In practice currently available state of the art GaAs mixer diodes burn out if operated at more than about 10 mA drive current for extended periods of time. Therefore it may be impractical to pump such a diode with 40 mW of power.

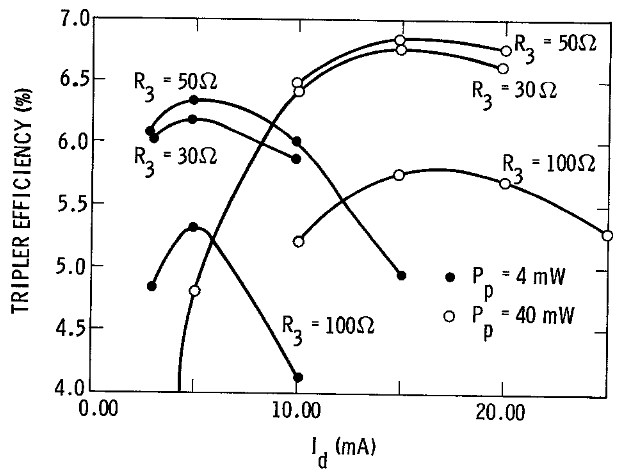

Fig. 2 The tripler efficiency as a function of dc drive current parameterized by the pump power and real part of the embedding network impedance at the third harmonic.

The optimum value of V_{diode}, the voltage at the diode (including the series resistance), also depends on pump power but not the embedding network impedance. For a pump power of 4 mW it is about 0.4 V while for 40 mW it is about -0.9 V. Note that even though the diode is operating solely in the varister mode (the voltage dependence of the capacitance is suppressed) it requires reverse bias for optimum operation if it is pumped with large enough powers. The strongly pumped diode draws positive current for reverse biases. This suggests that a practical determination of whether a multiplier is operating in the varactor mode is not a question of its reverse bias, but rather of whether it is drawing current.

Another design parameter for diodes is the reverse breakdown voltage, V_b. An output of the program is the instantaneous maximum value of the voltage swing in the diode. The reverse breakdown voltage must be greater than the largest instantaneous reverse voltage experienced by the diode. In general the required breakdown voltage is a function of both pump power and dc bias. It is larger for high pump powers since they determine the peak to peak voltage swing. Further the dc bias point determines the average value, so the breakdown voltage increases as the diode current decreases. For the diode parameters tested here, the required V_b is about -2 V when driven by 4 mW and about -9 V when driven by 40 mW. It is interesting to note that in some cases where both the efficiency and current are quite low, the required breakdown voltage can be quite large. For instance when I_d = 3 mA, P_p = 40 mW, and R_3 = 30 Ohms, the required V_b = -33 V. This phenomenom could explain some mysterious failures of diodes. We should point out that the breakdown voltages presented here are for optimum tuning only and do not indicate the maximum safe V_b for a given mount under all operating conditions.

As can be seen in figures 1 and 2 the efficiency is largest when the real part of the mount impedance at $3f_p$ is about 50 Ohms for a fixed bias condition. The efficiency at 30 Ohms is not significantly lower than that at 50 Ohms whereas that at 100 Ohms is reduced by about 20%. The sensitivity of tripler efficiency to the imaginary part of the impedance at the output frequency is much more dramatic as can be seen in figure 3. The optimum conversion efficiency was obtained when $X_e(3f_p)$ was about 90 Ohms independent of the real part of the impedance. This is considerably lower than the impedance required to tune out the zero bias capacitance at the third harmonic, about 177 Ohms. This suggests that some additional tuning (prehaps of the idler impedance) may further optimize the tripler conversion efficiency.

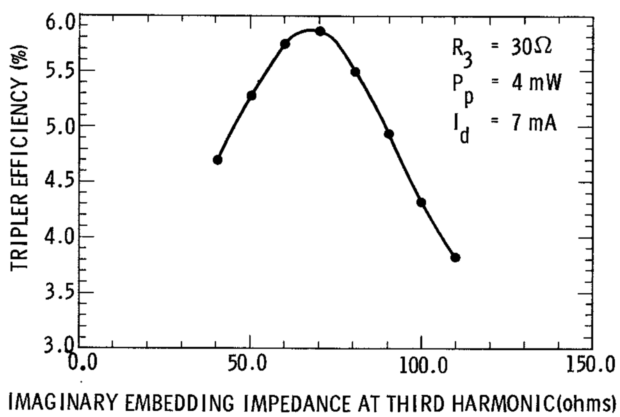

Fig. 3 The dependence of the tripler efficiency as a function of third harmonic imaginary impedance for a drive power of 4 mW, a dc bias current of 7 mA, and a third harmonic real impedance of 30 ohms.

At the idler frequency, $2f_p$, the real part of the impedance has been set to 0 while the imaginary part was set to 265 Ohms, the value required to tune out the 1 fF junction capacitance of the diode. We have not determined the sensitivity of the tripler efficiency to these impedances and suggest that the are not necessarily optimized.

The impedance at the pump frequency is determined by the program so that all the pump power is absorbed in the diode. The real and imaginary parts of the pump embedding impedance as a function of the real part of the mount impedance at $3f_p$ are shown in figure 4 for the optimum efficiciency points. The best value for this impedance is approximately 190 + j60 Ohms.

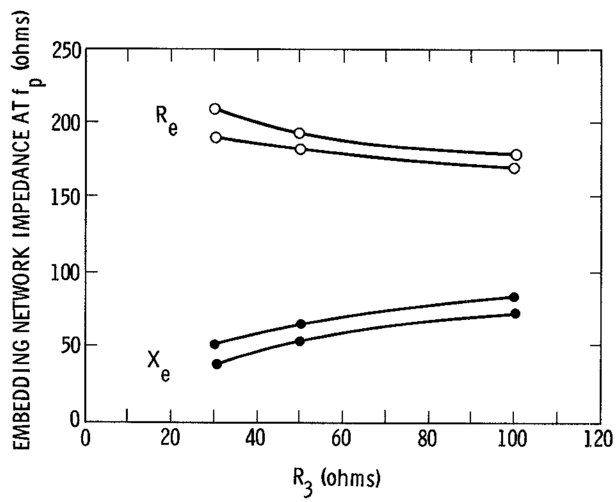

Fig. 4 The real and imaginary embedding network impedances at the pump frequency as a function of the real part of the embedding network impedance at the third harmonic parameterized by pump power for all the other parameters optimized. The upper curve in each set corresponds to a pump power of 40 mW while the lower curve is for 4 mW.

The third harmonic conversion efficiency is strongly correalated with the diode current at the third harmonic independent of embedding network impedances. This is illustrated in figure 5 where these two variables are plotted as a function of each other for all the runs for which the pump power is 40 mW and $R_e(3f_p)$ is 30 Ohms.

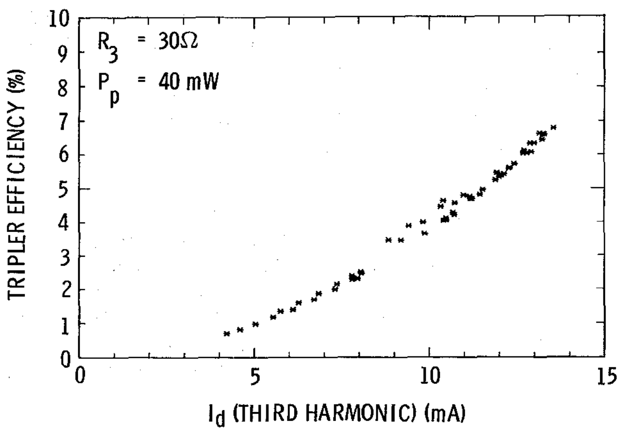

Fig. 5 The third harmonic conversion efficiency for the varister diode as a function of the magnitude of the current at the third harmonic for a 300 GHz pump power of 40 mW and the real part of the embedding network impedance = 30 Ohms.

Conclusion

We present a theoretical determination of the optimum embedding impedances for a submillimeter tripler employing a GaAs Schottky diode operating solely in the varister mode. The best theoretical third harmonic conversion efficiecy for this configuration is about 7% only slightly smaller that that for an ideal varister. The sensitivity of the conversion efficiency on bias parameters is also determined.

References

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