CAPABILITY OF SCHOTTKY DIODE MULTIPLIERS AS LOCAL OSCILLATORS AT 1 THz

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ABSTRACT

There is a strong need of all-solid-state local oscillators at mm- and submm-waves especially in spaceborne applications such as remote sensing of the atmosphere and radio astronomy. Up to 150 GHz this need can be satisfied with fundamental (second harmonic) sources such as Gunn oscillators. Up to about 600 GHz Schottky varactor multipliers with sufficient output power have been built. In the 1 THz region the efficiency and output power of the varactor/varistor multipliers becomes very low.

In the Radio Laboratory of the Helsinki University of Technology sponsored by the European Space Agency and Farran Technology Ltd. extensive studies on the theoretical performance of Schottky varactors and varistors as multipliers of a frequency around 100 GHz to submm region (300-1200 GHz) have been carried out. The performance of a commercially available diodes as well as experimental diodes have been analyzed in various direct and cascaded configurations of low and high order multipliers using harmonic balance analysis. Also optimum diode structures for multiplier applications have been searched. Because of high circuit losses ($\geq$ 10 dB) in a multiplier chain producing 1 THz, the output power seems to stay at or below 100 μW even in the best multiplier configurations when the available input power at 100 GHz is 50 mW.

INTRODUCTION

Currently, there is a lot of interest in developing high-efficiency multipliers for 1 THz range and above. One of the corner stone missions of the European Space Agency (ESA) is the Far Infrared and Submillimeter Space Telescope (FIRST) [1]. Therefore, the ESA has recently awarded a stydy contract "Development of Critical Detection Technologies for Spaceborne Submillimeter Heterodyne Receivers" in which several companies, universities and research institutes are involved in Ireland, Sweden, the Netherlands, Great Britain, France, Italy, West Germany and Finland.

At the Helsinki University of Technology, generation of 1 THz signals using Schottky-varactors/varistors has been studied by computer simulations. The study is based on the use of harmonic balance analysis, where the harmonic balance is solved by using multiple reflection technique [2-4]. A major problem is the modelling of the Schottky diode used as a multiplier.

The validity of the existing simple modelling of the diode (see Figure 1 and equations (1)–(7)) in the harmonic balance analysis has been tested with several multipliers of various orders at frequency range of 100-200 GHz at the Helsinki University of Technology [5-9]. The multipliers utilize Farran Technology VD010, VD011 and VD012 varactors. Nonlinear analysis and scaled modeling have been utilized in design. In the case of a doubler for 80-100 GHz the peak efficiency abtained is as high as 45%. A tripler for 100-115 GHz has produced a peak efficiency 28%, a quadrupler for 140-155 GHz an efficiency 11% and a quintupler for 165-170 GHz an efficiency of 4.3%. A doubler for 160-193 GHz gives maximum efficiency of 23%. All of these results are in reasonable agreement with the theory when waveguide losses and other nonidealities are taken into account.

At submillimeter frequencies the diode modelling is more complicated [10] and no good comparisons between the theory and experiment exist.

An efficient way of producing signals in the range of 1 THz is first to double the 100 GHz signal, which can be obtained from a Gunn oscillator at a power level of 50 mW, and then to quadruple the 200 GHz signal to 800 GHz, or to quintuple it to 1000 GHz, or to sextuple it to 1200 GHz.

Theoretically varactor VD012 gives an efficiency of about 25% for a doubler from 100 to 200 GHz. Experimentally 15% efficiency or maximum power of 7 mW can be obtained. Therefore, the input power to higher order multipliers at 200 GHz is assumed to be 7mW.

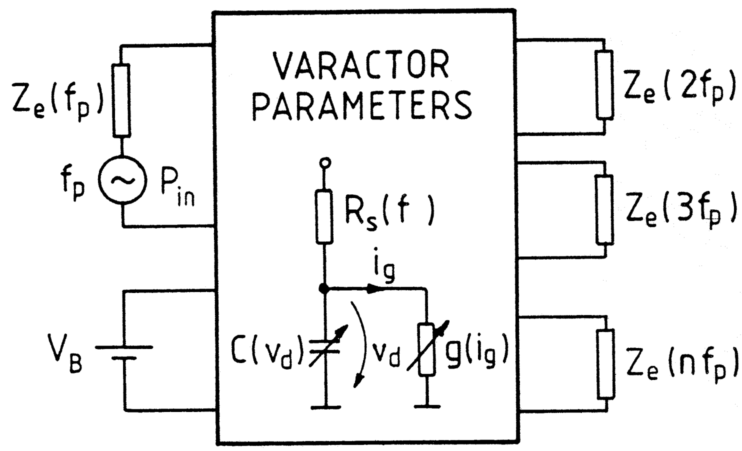

Figure 1. *Equivalent circuit of a Schottky-varactor frequency multiplier.*

DIODE MODEL

Varactor capacitance is assumed to be

$$C_j(V) = \frac{C_0}{(1 - v/\phi_{bi})^{\gamma_0(1+kV)}} , \tag{1}$$

where $C_0 = C_j(0)$, ϕ_{bi} is the built-in potential and γ_0 and k are dependent on the doping profile. Usually the varactor capacitance is less nonlinear with high reverse bias. This is taken into consideration by choosing a positive value for parameter k. Typical values are $\gamma_0 = 0.45 - 0.5$ and $k = 0 - 0.01$. Varistors are assumed to have a constant capacitance below approximately 0.25 V and ϕ_{bi} is artificially chosen to be 1.3 V to emphasize resistive multiplication.

For both varactors and varistors the I-V characteristic is assumed to be

$$I_d(V) = I_0\big(\exp(\frac{qV}{\eta kT}) - 1\big) , \tag{2}$$

where I_0 is saturation current, q is elementary charge, k is Boltzmann's constant, T is absolute temperature and η is ideality factor.

The series impedance is modelled as the following [12]:

$$Z_s(\omega) = Z_{epi}(\omega) + Z_{sub}(\omega) \tag{3}$$

$$Z_{epi}(\omega) = \frac{\rho t_e}{A}\left[\frac{1}{1+\jmath\omega/\omega_s} + \jmath\frac{\omega}{\omega_d}\right]^{-1} \tag{4}$$

$$Z_{sub}(\omega) = \frac{\rho}{2\pi\delta}\ln\left(\frac{b}{r_a}\right)\frac{\sqrt{2\jmath}}{\sqrt{\frac{1}{1+\jmath\omega/\omega_s} + \jmath\frac{\omega}{\omega_d}}} + \frac{\rho}{4r_a}\frac{1}{\frac{1}{1+\jmath\omega/\omega_s} + \jmath\frac{\omega}{\omega_d}}\ , \tag{5}$$

where t_e is thickness of epilayer, ρ is resistivity, A is anode area, r_a is anode radius and b effective radius of the chip. ω_s and ω_{ds} are the scattering and dielectric relaxation frequency defined as

$$\omega_s = \frac{q}{m^*\mu} \tag{6}$$

$$\omega_d = \frac{1}{\epsilon_s\rho}, \tag{7}$$

where m^* is effective carrier mass, μ is carrier mobility and ϵ_s is dielectric constant of the chip.

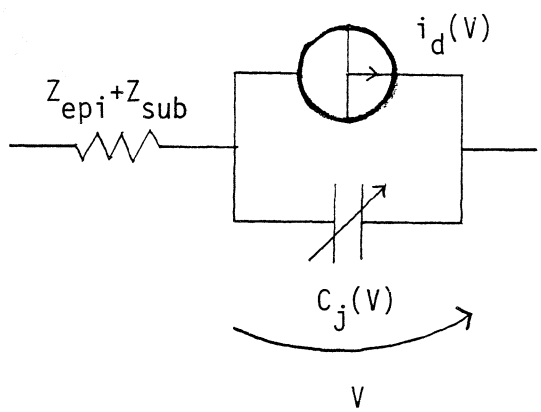

Figure 2. *Simple Schottky barrier diode model.*

MULTIPLICATION OF 200 GHz TO 1 THz RANGE

4 x 200 GHz

Theoretical calculations were carried out for seven different realizable diodes presented in Table 1, where r_a, N_D and t_e correspond anode radius, epilayer doping concentration and epilayer thickness, respectively. Varactor VD012 is commercially available, while all other diodes are experimental diodes by Farran Technology Ltd. The input power was assumed to be 7 mW in each case.

Table 1. Diode characteristics.

type	diode	C_{jo} [fF]	R_s [Ω]	V_B [V]	r_a [μm]	N_D [cm^{-3}]	t_e [μm]
varactor	VD012	12.5	11.0	14.0	1.8	$6.5 \cdot 10^{16}$	0.8
	A	9.5	7.2	9.0	1.5	$2 \cdot 10^{17}$	0.25
	B	3.4	30.0	17.0	1.1	$9 \cdot 10^{16}$	0.49
	C	5.1	11.5	9.0	1.0	$2 \cdot 10^{17}$	0.25
	D	3.3	12.0	6.9	0.8	$3 \cdot 10^{17}$	0.18
varistor	054	2.8	12.0	8.0	0.65	$6.5 \cdot 10^{16}$	0.11
	074	4.2	12.0	8.0	0.85	$6 \cdot 10^{16}$	0.11

Table 2. Optimum performance and parameters of quadruplers 4 x 200 GHz.

Diode	η [%]	P_{out} [mW]	$V_{b\ opt}$ [V]	R_1 [Ω]	X_1 [Ω]	X_2 [Ω]	X_3 [Ω]	R_4 [Ω]	X_4 [Ω]
VD012	0.2	0.014							
A	9.0	0.63	-2.0	24	126	66	38	17	23
B	6.2	0.43	-4.0	91	427	211	124	67	82
C	15	1.1	-1.7	53	224	144	85	35	45
D	12	0.84	-0.8	159	283	181	123	50	64
057	2.2	0.15	-1.8	116	268	47	21	30	39
074	0.94	0.066	-1.4	60	166	19	4	26	23

In Table 2 also the optimized termination impedances are given. With a varistor the best performance is obtained if the intermediate harmonics are nearly short or open circuited. The efficiency decreases if these harmonics are terminated with an inductance which resonates with the varistor capacitance at that particular frequency. Although a similar procedure normally improves the efficiency in the case of reactive multiplication, a weak nonlinearity of the $C - V$-curve of the varistor causes an opposite effect. The reactive multiplication is ineffective and the permitted current flow at the intermediate harmonics only increases losses in the varactor series resistance decreasing conversion efficiency to the 4th harmonic.

5 x 200 GHz

Theoretical calculations were made for varactors VD012 and C assuming 7 mW of input power. With varactor VD012 a quintupler with all idlers was analyzed. With varactor C two cases were analyzed. Firstly (I) a quintupler with all idlers and secondly (II) a quintupler with 2. and 3. optimum idlers and open circuited 4. harmonic. The optimized theoretical efficiencies are 0.03%, 10.3% and 3.4% for VD012, CI and CII, respectively.

6 x 200 GHz

Again similar theoretical calculations were carried out for varactors VD012 and C. For VD012 varactor the calculation was made with all idlers. In the case of varactor C three different cases were analyzed: (I) all idlers, (II) 2. and 3. optimum idler and 4. and 5. harmonic open circuited, and (III) 2. and 4. optimum idler and 3. and 5. harmonic open circuited. The optimized theoretical efficiencies are 0.0003%, 6.9%, 0.87% and 2.1% for VD012, CI, CII and CIII, respectively.

DIODE OPTIMIZATION

Varactor optimization was carried out for 4x, 5x and 6x200 GHz using the diode model above, but for the junction capacitance the following expression [11]:

$$C_j(V) = \frac{A\epsilon_s}{w(V)}\left(1 + \frac{3}{2}\frac{w(V)}{r_a}\right) \tag{8}$$

$$w(V) = \sqrt{\frac{2\epsilon_s}{qN_D}\left(\phi_{bi} - V - \frac{kT}{q}\right)}, \tag{9}$$

$w(V)$ stands for the width of the depletion region. The epilayer thickness was determined according to equation (9) by using the break-down voltage for V, which means that at break-down voltage the epilayer is completely depleted.

The overall optimum diode for all high-order multipliers described above has an epilayer thickness of about 0.3 μm, anode radius of 1.2 μm and epilayer doping density of $1.6 \cdot 10^{17}\text{cm}^{-3}$. The optimum diode parameters are quite similar to those of varactor C, and the optimum diode gives only slightly better performance.

COMPARISON OF VARIOUS MULTIPLIERS PRODUCING 800 GHz

Comparison of the performance of four differrent multiplier configurations producing 800 GHz signal was made by computer simulations. In these configurations 100 GHz signal is multiplied: 8x, 2x2x2x, 4x2x and 2x4x.

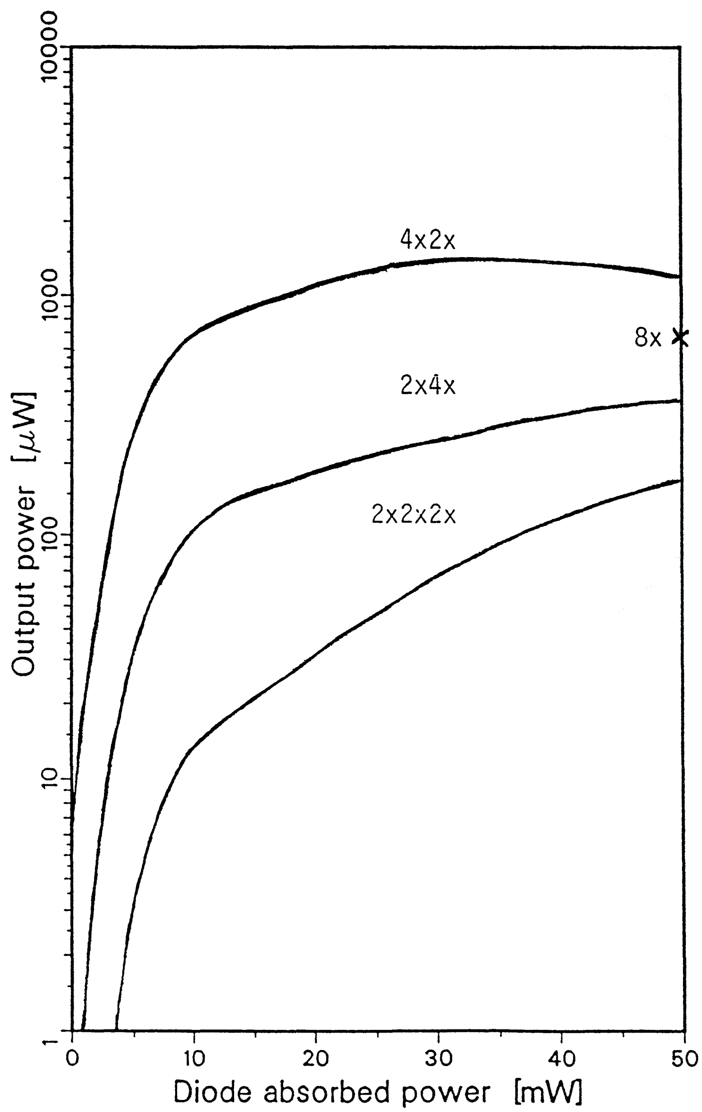

Figure 3. *Comparison of theoretical performance of various multipliers producing 800 GHz.*

Theoretical efficiencies were calculated for varactors VD012, B and C (as an octupler). The input power was assumed to be 50 mW. In the case of diode B this high input power causes the rectified current to rise up to 15 mA, which may burn the diode.

The calculation show that diode C is not able to handle 50 mW input power, but will break-down. Therefore, varactor VD012 is the best choice giving 1.3% efficiency with 50 mW input power.

Figire 3 shows the performance of three other configurations, where VD012 is used for multipliers 2x100 GHz, 4x100 GHz and 2x200 GHz, and the optimized diode (as described above) is used for 4x200 GHz and 2x400 GHz. At 50 mW input power 4x2x100 GHz cascaded multiplier gives by far the best result. The octupler is also clearly more efficient than the other two configurations. These performances are purely theoretical, because no metal losses are assumed and all ideal idler terminations are assumed in the higher-order multipliers. However when nonidealities are reasonably taken into account, the cascaded multiplier 4x2x100 GHz is still by far the best and can produce about 100μW at 800 GHz.

In fact the Schottky barrier diode is more complicated than assumed above. Reactive elements of the diode series impedance due to dielectric relaxation and carrier scattering in epilayer have also voltage dependence. Also the series recistance in epilayer is voltage modulated. These nonlinearities can be presented in following fashion [10] :

$$R_e(V) = \rho \frac{t_e - w(V)}{A} \tag{10}$$

$$L_i(V) = R_e(V) \frac{1}{\omega_s + v_d/t_e} \tag{11}$$

$$C_e(V) = \frac{\epsilon_s A}{t_e - w(V)}, \tag{12}$$

where v_d is (maximum) drift velocity. Figure 4 shows this diode model.

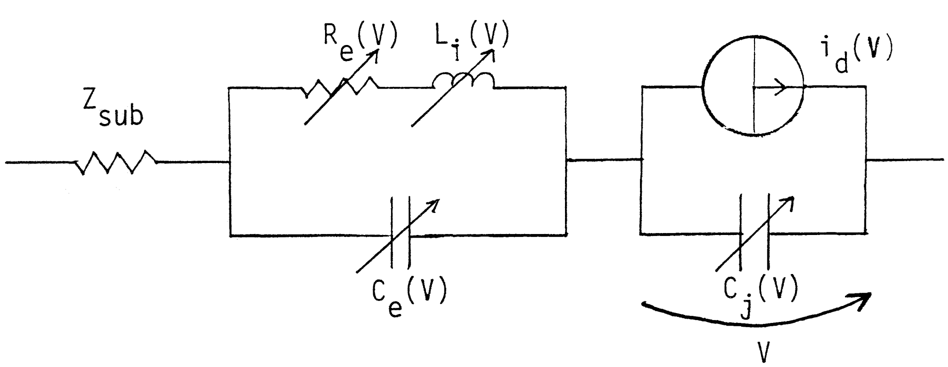

Figure 4. *Schottky barrier diode model including nonlinearities of the undepleted part of the epilayer.*

Taking these extra nonlinearities into account improves the theoretical efficiency of the multipliers considerably at low input power levels, but only slightly at high input power levels. The efficiency improvement increases as a function of frequency.

CONCLUSIONS

A quadrupler, quintupler and sextupler utilizing an optimized realizable varactor pumped with 7 mW power at 200 GHz can produce theoretical efficiencies of 17.8%, 11.8% and 7.8%, respectively. This optimum varactor is quite similar to a varactor already realized, varactor C, which gives theoretical efficiencies of 15%, 10.3% and 6.9%, respectively. In practice, the nonidealities in idler circuits and metal losses are expected to drop the efficiencies by 10 dB or more.

An octupler 8 x 100 GHz utilizing a commercially available varactor can give theoretically an efficiency of 1.3% when pumped with 50 mW power. In this case the nonidealities in idler circuits and mount losses are expected to be so high, that in practice only 10 μW power would be obtained. The output power at 800 GHz from a doubler-quadrupler-combination is expected to be about 100 μW.

Varistors are clearly much less effective than varactors. However, in practice designing a high-order varistor multiplier is much easier than that of a varactor multiplier. A few microwatts can be obtained also from varistor multipliers at 1 THz and that is enough for SIS mixers.

Results presented here are only preliminary. Clearly a lot of work must be done for the proper modelling of Schottky diodes at 1 THz.

ACKNOWLEDGEMENTS

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