Cooled Schottky Varactor Frequency Multipliers at Submillimeter Wavelengths

Jyrki T. Louhi, Antti V. Räisänen, *Senior Member, IEEE,* and Neal R. Erickson

***Abstract*— The efficiency of a Schottky varactor frequency multiplier at submillimeter wavelengths can be increased by cooling the diode. The main reason for better efficiency is the increased mobility of the free carriers. Because of that the series resistance decreases and the efficiency can be expected to increase as much as a few dB at low input power levels. At high output frequencies and at high power levels the efficiency of the multiplication is decreased by the current saturation, because the junction capacitance cannot be pumped effectively. When the diode is cooled the maximum current of the diode increases and much more output power can be expected. There are also slight changes in the I -V characteristic and in the diode junction capacitance, but they have a negligible effect on the efficiency of the multiplier. The theoretical maximum output power at near 1 THz is calculated to increase by about 10 dB from 50 μW to 500 μW, when the multiplier chain is cooled to 77 K. However, cooling to 77 K is not necessary, because considerable improvement in the efficiency may be achieved by cooling to 150 K, readily available in space by passive cooling.**

I. Introduction

Schottky varactor frequency multipliers have been used for several years as standard components in millimeter wave receivers [1]. While this conventional Schottky varactor technique has also been used at submillimeter wavelengths, several novel diodes (SBV, BIN, QWD, HEMV, QBV) have been proposed as being more powerful in generating odd harmonics at very high frequencies [2], [3]. However, effective Schottky varactor frequency multipliers have already been constructed up to 650 GHz [4], while the experimental results of novel varactors are yet only promising [5]–[7]. Thus the conventional Schottky varactor technique seems to be useful in the near future at frequencies up to 1 THz, but at these high frequencies the diode and the mount of the frequency multiplier must be optimized very carefully.

It is well known that cooling of a Schottky diode mixer improves its sensitivity, i.e. reduces the mixer noise temperature. This is mainly due to the sharper *I–V* characteristic at cryogenic temperatures, and only weakly due to the smaller series resistance and lower metal losses in the mixer mount. In satellite applications the heterodyne receiver is readily cooled passively to temperatures of 110–150 K. Also, a space qualified 80 K cooler is available. This makes it very reasonable to consider the effect of cooling on the frequency multiplier performance.

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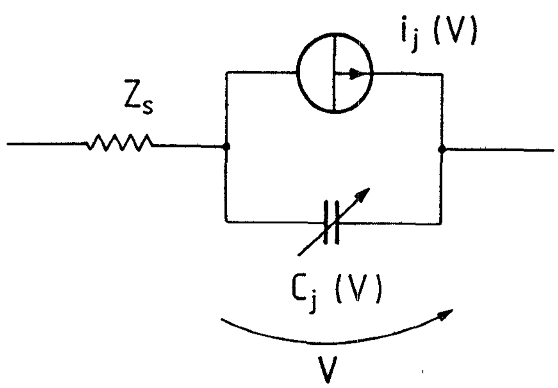


Fig. 1. A simple equivalent circuit of the Schottky diode.

II. Diode Model and Effect of Cooling

A simple equivalent circuit of the Schottky varactor contains three components: a nonlinear junction capacitance, nonlinear junction conductance and series impedance [8] (see Fig. 1). In the following we have considered the effect of cooling on the components of the equivalent circuit. As an example we have studied the equivalent circuit at temperatures of 300 K and 77 K, because the relevant parameters (contact potential, electron mobility, maximum velocity of electrons) are widely treated in the literature at these temperatures. A few examples of the diode behavior have been calculated also at temperatures between 77 K and 300 K.

2.1. Capacitance

The basic model for the junction capacitance of the Schottky diode is

$$C_j(V) = \frac{C_0}{\sqrt{1 - V/\phi_{\mathrm{bi}}}}, \tag{1}$$

where ϕ_{bi} is the built-in potential (about 1 V) and C_0 is diode capacitance at zero bias. For very small submillimeter wave diodes, the edge effect must be included in the diode model as [9]

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

$$w(V) = \sqrt{\frac{2 \cdot \epsilon_s}{q \cdot N_D} \cdot \left(\phi_{\mathrm{bi}} - V - \frac{k_0 \cdot T}{q}\right)}, \tag{3}$$

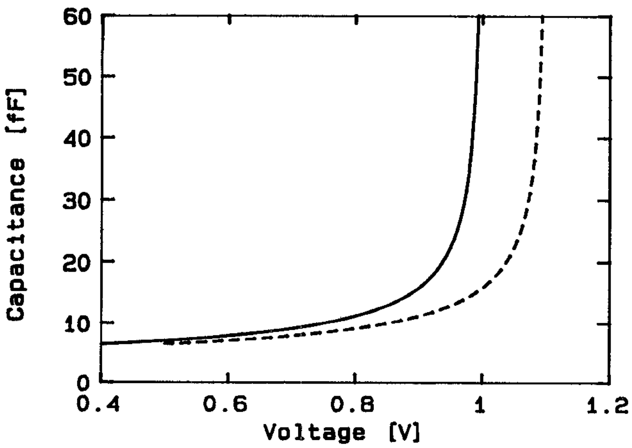


Fig. 2. The junction capacitance at the temperatures 300 K (solid line) and at 77 K (dashed line), when C_0 is 5 fF.

where A is the anode area, ϵ_s is the dielectric constant of the semiconductor, $w(V)$ is the length of the depletion region, r_a is the anode radius, q is the charge of an electron, N_D is the doping density in the semiconductor, k_0 is Boltzmann's constant and T is the temperature. In these models the junction capacitance is very high near the contact potential ϕ_{bi}. Physically this is impossible, and a better model for junction capacitance must be calculated by using the drift-diffusion model [10]. In any of the models, the primary mechanism for the efficiency of the multiplier, the degree of capacitance nonlinearity, is not temperature dependent. In the two simple models the only temperature dependent factor is ϕ_{bi}. When the diode is cooled from 300 K to 77 K, the contact potential ϕ_{bi} increases by about 0.1 V [11] (see Fig. 2). Because ϕ_{bi} varies only slightly when the diode is cooled, the same operation point can be reached if the negative bias potential V_{bias} is changed as much as the contact potential ϕ_{bi} increases by cooling, so that the same maximum and minimum values of the junction capacitance are reached during the voltage sweep. In all, the effect of cooling on the junction capacitance is so small that it has an almost negligible effect on the multiplier efficiency.

2.2. Series Impedance

When the nonlinearity of the epitaxial layer above the plasma resonance is not included, the series impedance of the submillimeter wave Schottky diode is modeled as [12]

$$Z_s(\omega) = Z_{\text{epi}}(\omega) + Z_{\text{sub}}(\omega) + Z_{\text{skin}}(\omega) + R_c \tag{4}$$

$$Z_{\text{epi}}(\omega) = \frac{\rho_{\text{epi}} \cdot t_{e(\text{eff})}}{A} \cdot \left[\frac{1}{1+j\omega/\omega_s} + j\frac{\omega}{\omega_d}\right]^{-1} \tag{5}$$

$$Z_{\text{sub}}(\omega) = \frac{\rho_{\text{sub}}}{4 \cdot r_a} \cdot \left[\frac{1}{1+j\omega/\omega_s} + j\frac{\omega}{\omega_d}\right]^{-1} \tag{6}$$

$$Z_{\text{skin}}(\omega) = \sqrt{2j} \cdot \frac{\rho_{\text{sub}}}{2\pi \cdot \delta_s} \cdot \ln\left(\frac{b}{r_a}\right)\left[\frac{1}{1+j\omega/\omega_s} + j\frac{\omega}{\omega_d}\right]^{-(1/2)}, \tag{7}$$

where R_c is the contact resistance (about 1 Ω), ρ is the resistivity, $t_{e(\text{eff})}$ is $t_e - w(V_{\text{bias}}), t_e$ is the thickness of the epitaxial layer, b is the radius of the chip and δ_s is the skin depth in the substrate given by

$$\delta_s = \sqrt{\frac{2 \cdot \rho_s}{\omega \cdot \mu_0}}, \tag{8}$$

where μ_0 is the permeability of GaAs. The scattering frequency ω_s and the dielectric relaxation frequency ω_d are

$$\omega_s = \frac{q}{m^* \cdot \mu_s} \tag{9}$$

$$\omega_d = \frac{1}{\rho_s \cdot \epsilon_s}, \tag{10}$$

where m^* is the effective carrier mass and μ_s is the carrier mobility. The resistivity is

$$\rho = \frac{1}{q \cdot n \cdot \mu_s}, \tag{11}$$

where n is the concentration of the free electrons in the conduction band.

In a semiconductor, the concentration of the free carriers n and the mobility of the carriers μ_s are the most important temperature dependent factors in equations given above. In GaAs the donor binding energy E_D is so small and the concentration of donors N_D is usually so high that the concentration of the free carriers n is equivalent to N_D at all temperatures where the diode should be used. The mobility of the free carriers can be calculated from the mobilities of the various scattering processes. In GaAs the most important scattering processes are ionized impurity scattering, acoustic-mode scattering and polar-optical scattering. At room temperature, the polar-optical scattering dominates. When GaAs is cooled, the mobility increases until the mobility of the polar-optical scattering and the mobility of the impurity scattering are equal. At that temperature, mobility μ_s has a maximum, and when the diode is cooled more the mobility decreases. When N_D is rather low ($1 \cdot 10^{16}$ cm $^{-3}$) the optimum temperature is low (~50 K) and the mobility greatly increases [13]. At very high doping concentration ($2 \cdot 10^{17}$ cm^{-3}) the optimum temperature is higher (~150 K) and the mobility increases only a little when the diode is cooled to 77 K.

When considering the effect of cooling on the series impedance of the Schottky diode, it is simplest to consider first its effect on the dc resistance and then the effect on the series impedance at high frequencies. When the diode is cooled to 77 K, the mobility of electrons increases and thus the resistivity of the epitaxial layer decreases, which also decreases the dc resistance of the diode. When the doping concentration of the epitaxial layer is low, the dc resistance decreases significantly. (For diode UVA 6P2 the measured decrease is about 43%, from a value of 10.5 Ω to 6 Ω; the calculated values agree very well, see Fig. 3.) When the doping rate is higher the decrease of the resistance is not as large. (For diode UVA 2T2

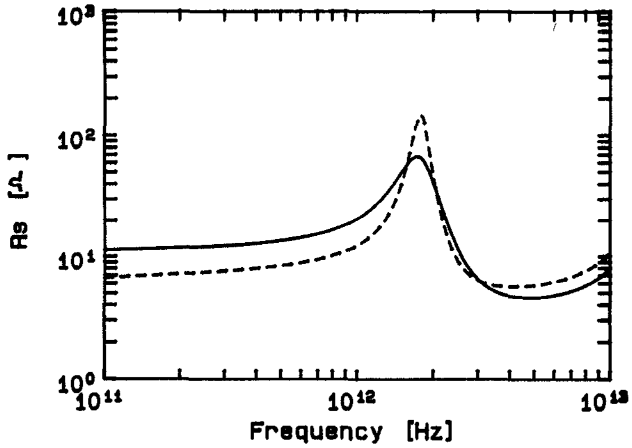


Fig. 3. The series resistance of diode UVA 6P2 at the temperatures 300 K (solid line) and 77 K (dashed line).

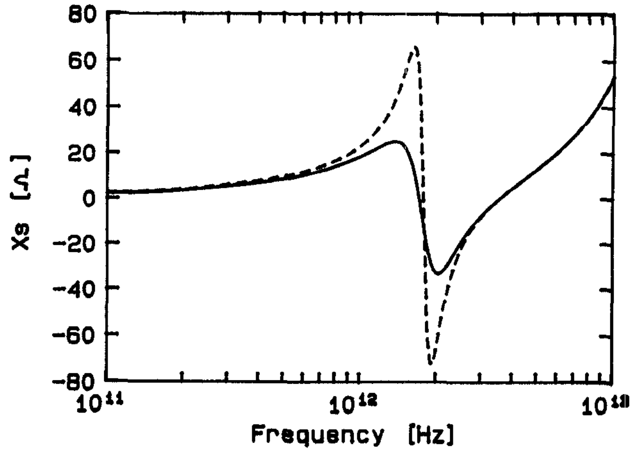


Fig. 4. The series reactance of diode UVA 6P2 at the temperatures 300 K (solid line) and 77 K (dashed line).

the calculated decrease is about 29%, from a value of 12 Ω to 8.5 Ω.) By cooling the diode only to 150 K, which is realistic in the satellite applications with passive cooling, most of the series impedance reduction is achieved. (For diode UVA 6P2 the calculated decrease of the series resistance is about 29%, when the diode is cooled to 150 K.)

When considering the effect of the decreased series resistance on the efficiency of the multiplication, it must be noticed that the resistance of the epitaxial layer Z_{epi} is a function of the thickness of the layer. In an efficient reactive multiplication, the voltage across the depletion region spends a substantial part of the pump cycle in the low voltage region, where the contribution of Z_{epi} in Z_s is large, but a small part of the pump cycle in the high reverse voltage region, where the contribution of Z_{epi} in Z_s is small. When the diode is now cooled, the decrease of the series resistance is smaller than the decrease of the dc resistance, but still the decrease of resistance has a very strong positive effect on the efficiency of multiplication. The effect of the decreased series resistance on the efficiency of the multiplication can be determined exactly by calculating the voltage and current waveforms of the pumped varactor [14]. With these waveforms known the amount of the power lost in series resistance can be calculated by integrating over a pump cycle the series resistance times the current squared.

At high frequencies the series impedance of the Schottky diode is no longer purely resistive, because of the plasma resonance and the skin effect. When the diode is cooled, the plasma resonance frequency

$$\omega_p = \sqrt{\omega_s \cdot \omega_d} = \sqrt{\frac{n \cdot q^2}{m^* \cdot \epsilon_s}} \tag{12}$$

does not change, because it is independent of the electron mobility μ_s. Because ω_s and ω_d are temperature dependent, the Q-factor of the resonance is also temperature dependent, and when the diode is cooled to 77 K the Q-factor increases (see Fig. 4). Because the mobility in the substrate changes very little when the diode is cooled, the impedance of the substrate Z_{sub} and the impedance of the skin effect do not change significantly.

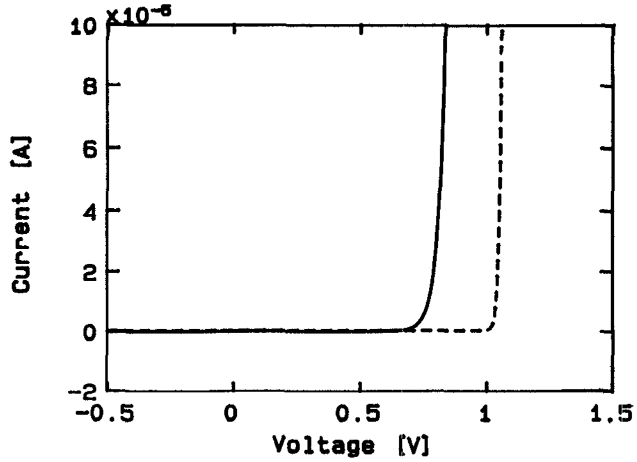


Fig. 5. The current-voltage characteristic at the temperatures of 300 K (solid line) and 77 K (dashed line).

2.3 I–V Characteristic

For a Schottky diode the I–V characteristic is assumed to be [11]

$$I_j(V) = A \cdot R^{**} \cdot \theta^2 \cdot e^{q \cdot (V - \phi_{\text{bi}})/k_0 \cdot \theta} \tag{13}$$

$$\theta = \theta_f \cdot \coth\left(\frac{\theta_f}{T}\right) \tag{14}$$

$$\theta_f = \frac{q \cdot \hbar}{k_0} \cdot \sqrt{\frac{N_D}{4 \cdot \epsilon_s \cdot m^*}}, \tag{15}$$

where R^{**} is modified Richardson's constant, $\hbar$ is $h/2\pi$ and h is Planck's constant.

There are two important factors of the I–V characteristic for the efficiency of the frequency multiplication: the turn-up point of the I–V curve, and the steepness of the I–V curve beyond that. When the Schottky diode is cooled, the possible voltage range where the multiplication is mainly reactive increases, and thus the maximum efficiency can also increase (see Fig. 5). For a cooled diode the shape of the I–V characteristic is also sharper, and therefore the resistive multiplication is slightly more effective.

2.4 Current Saturation

The above classical model of the Schottky varactor is not quite satisfactory, because there is evidence of a saturation phenomenon in a high power doubler experiment [15]. Kollberg *et al.* have studied this [16] and explain the observed saturation by current saturation, which takes place because the electron current through the undepleted epilayer cannot at any time exceed the maximum current of the diode. They also suggest an empirical model for taking the saturation into account in calculations by a rapidly increasing series resistance. Although the suggested model seems to have no physical background, we have used it in our simulations, because so far no better model has been published.

At a low electric field the electron drift velocity v_d is directly related to the electric field $\mathcal{E}$ as

$$v_d = \mu_s \cdot \mathcal{E}, \tag{16}$$

where μ_s is the electron mobility. When the electric field increases the drift velocity also increases until the velocity reaches a maximum value $v_{\max}$ (= $2.2 \cdot 10^5$ m/s at about 3.2 kV/cm in an intrinsic case). In that situation the electron conduction current

$$i_e = A \cdot n \cdot q \cdot \mu_s \cdot \mathcal{E} \tag{17}$$

must be replaced by the maximum current [16]

$$i_{\max} = A \cdot n \cdot q \cdot v_{\max}, \tag{18}$$

where A is the anode area and n is the concentration of free electrons. This current saturation causes a very significant decrease in the efficiency of the multiplier at high power levels and also when the output frequency is high, because the junction capacitance cannot be pumped with an optimum current. The current saturation seems to be the most important factor for a submillimeter wave frequency multiplier, when the maximum output power is considered. When the diode is cooled, the maximum drift velocity increases [13] and because of that the maximum electron current also increases. Therefore, when the diode is cooled the effect of the current saturation is less significant. This increases the efficiency especially at high power levels, at high frequencies, and in the case of a high multiplication factor.

The current saturation may be modelled by strongly current dependent series resistance $R_s(i)$ above the maximum current. Kollberg *et al.* have presented the following empirical model [16]:

$$R_s(i) = R_s(dc) \cdot (1 + a \cdot i^6), \tag{19}$$

where a is a parameter depending on the maximum current of the diode $i_{\max}$. The meaning of $R_s(i)$ is to modify the current waveform approximately as required by causing a very strong increase in the series resistance when the current of the diode is higher than the maximum current $i_{\max}$. The parameter a has been fitted empirically to the measured results only in one case and must be estimated for other diodes and frequencies. In our calculations we have used the same values for parameter a as Kollberg *et al.* [16] at 300 K. We have assumed the maximum velocity to increase about 65%, when the diode is cooled to 77 K [13]. We have simply scaled the new values for parameter a by $(1/1.65)^6$ to be used at 77 K. (For diode UVA 6P2 we have used values of $a = 3.2 \cdot 10^7$ at 300 K and $a = 1.6 \cdot 10^6$ at 77 K.) The values for parameter a at temperatures between 77 and 300 K can be scaled the same way, but then the increase of the maximum velocity is not as high as in the case of cooling to 77 K. We have assumed $v_{\max}$ to increase about 20% and 40%, when the diode is cooled to the temperatures of 225 K and 150 K, respectively (doping concentration of less than or about $10^{17}\,\mathrm{cm}^{-3}$ is assumed). We have observed that when the $R_s(i)$ model has been added to the model of the Schottky varactor, the voltage sweep tends to be not as large as before. In other words, the voltage sweep tends to avoid the breakdown voltage, if the current saturation is taken into account. (Without the current saturation in the model, we have to avoid the reverse breakdown voltage by using a smaller negative bias voltage.)

Recently J. East has suggested a new model to calculate the effect of the current saturation, where the voltage waveforms are calculated directly from the physical properties of the GaAs material [17].

TABLE I
PARAMETERS USED FOR VARACTORS

Varactor	Temperature	C_0	A	t_e	N_D	μ	i_{max}
UVA 6P2	300	21.0	33	1.0	$3.5 \cdot 10^{16}$	0.61	44
	77	21.0	33	1.0	$3.5 \cdot 10^{16}$	1.40	72
UVA 2T2	300	6.5	6	0.5	$1.0 \cdot 10^{17}$	0.55	23
	77	6.5	6	0.5	$1.0 \cdot 10^{17}$	0.90	38
	K	fF	μm^2	μm	cm^{-3}	m^2/Vs	mA

III. MULTIPLIER CHAINS AT NEAR 1 THz

When constructing multiplier chains for near 1 THz, a reasonable choice is first to double the output frequency of a powerful W-band Gunn oscillator and then to follow by a tripler and a doubler or by a doubler and a tripler. The latter choice depends not only on the varactor diodes but also on the technology to build fine mechanical multiplier mounts. We have first considered the effect of cooling on a two diode balanced doubler for 160 GHz, because we have experimental results for this case [15]. After that we have analysed the second stages of the multiplier chains and finally we have calculated the maximum theoretical output power of the last stage multipliers at 960 GHz. The effect of cooling has been considered in all cases at temperatures of 300 K and 77 K, while some results are also given at temperatures of 150 K and 225 K.

At millimeter wavelengths Schottky varactors are often driven into conduction, which is only nearly optimal. In this case, the usefulness of classical theories [18] is poor and harmonic balance analysis should be used. One form of the harmonic balance analysis is the multiple reflection technique [19], where the multiplier circuit is divided into linear and nonlinear subcircuits, which are then analyzed in the frequency and time domain. In our analyses we have used two real varactors, whose parameters are shown in Table I. Varactor UVA 6P2 has been used as a doubler for 160 GHz, and UVA 2T2 has been used for the second and last stage multipliers.

TABLE II
THEORETICAL AND EXPERIMENTAL OUTPUT POWER VERSUS TEMPERATURE AND INPUT POWER AT 160 GHz (TWO DIODES)

		Input power				
	Temperature	10	33	50	100	mW
Theoretical	300 K	4.8	17.4	24.1	32.6	mW
	225 K	5.2	20.5	29.4	40.5	mW
	150 K	5.8	22.2	33.0	45.5	mW
	77 K	6.2	22.7	34.3	46.9	mW
Experimental	300 K	1.6	9.0	13.9	22.0	mW
	223 K	1.9	10.4	16.3	26.7	mW
	77 K	2.2	12.8	18.7	30.7	mW

3.1 First Stage, Doubler for 160 GHz

The two diode construction with diode UVA 6P2 has been first analyzed at 300 K and at 77 K. The efficiency has been calculated with optimum embedding impedances (see Table II). These results have been plotted in Fig. 6 (solid lines) together with experimental results, where the estimated losses of 0.5 dB in the input and of 0.8 dB in the output have been taken into account. Here the efficiency has a poor correlation with the measurements (O and X) because of the VSWR, which is mainly caused by the fact that the embedding impedances of the experimental multiplier are optimized for high input power. When the doubler is then analyzed by using the optimum embedding impedances for high input power at all input power levels, the correlation is much better, especially when the estimated losses have been taken into account.

In order to understand better the agreement between the theory and experiment, it is worth separating the effects of the decreased series impedance and the increased current handling capability due to the cooling. First, if the current saturation is omitted in the theoretical analysis, the effect of cooling is as follows. At low input power levels when the multiplication is purely reactive, the decreased series impedance causes a clear increase in the efficiency due to smaller losses in the series impedance. According to our simulations, the increase of the efficiency in the above case at low input power levels is about 1.5 dB. However, when the input power per diode is large (i.e. >20 mW per diode), the multiplication efficiency tends to decrease with the increased input power due to the resistive multiplication. This is because the voltage swing reaches the conduction region during every cycle. The smaller the series impedance, the lower the input power needed to reach this conduction, and thus, resistive multiplication. Therefore, the gain due to the smaller series impedance is smaller at high input power levels than at low power levels. According to the simulations, the efficiency increase due to the smaller series impedance in the multiplier described above is only 0.5 dB at 50 mW input power per diode.

When the current saturation is taken into account, but not the series resistance, the positive effect of cooling is seen only at high power levels. This is because the junction capacitance can be pumped at 77 K more effectively than at 300 K. At small power levels the saturation, of course, does not play an important role. According to our simulations, the higher current handling capability of the cooled diode 6P2 improves the efficiency by 1 dB at 50 mW input power per diode.

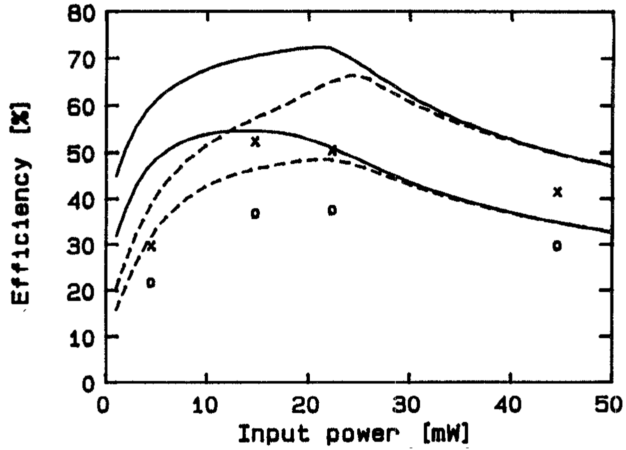


Fig. 6. The efficiency of the 160 GHz doubler at 300 K and at 77 K (above), when using optimum impedances (solid line) and impedances optimum for high power (dashed line). Measurement results, after reduction of 0.5 dB input losses and 0.8 dB output losses, at 300 K (o) and at 77 K (x) have also been plotted.

These two effects of cooling together, the decreased series impedance and the increased current handling capability, explain the experimentally verified 1.5 dB increase in the multiplication efficiency at all power levels and therefore give strong evidence for the current saturation in the diode at high input power levels. Due to the higher efficiency at high input power levels, the maximum output power is also increased by the same amount (from 22 mW to 31 mW), which helps in pumping the following stage in the multiplier chain producing submillimeter wave frequencies.

The doubler for 160 GHz has also been analyzed at temperatures of 225 K and 150 K. These results are shown in Table II and in Fig. 7. When the diodes are cooled to 225 K, the theoretical output power has been calculated to be 40.5 mW, which can be well compared with the experimental result of 26.7 mW, when the mount losses are taken into account. According to our results, the maximum output power at the temperature of 150 K is almost the same as at 77 K. That can be easily explained, because at both temperatures the maximum current of the diode $i_{\max}$ is higher than the electron current needed to pump the junction capacitance effectively. The extra 0.1 dB increase of the efficiency by cooling from 150 K to 77 K is simply due to the smaller series resistance. Therefore, this extra cooling is not useful in the case of a doubler for 160 GHz.

3.2 Second Stages

The second stage multipliers have also been analysed by using the harmonic balance technique, but now we have used a UVA 2T2 varactor to generate harmonics at submillimeter wavelengths. Because the doping concentration of the epitaxial layer is now rather high, the decrease of the diode series resistance is not as large as the decrease for varactor UVA 6P2, when the diodes are cooled. Therefore the multiplication efficiency does not increase as much as in the above case due to the change in the series resistance. But at higher power levels, the effect of current saturation is much more important and a remarkable increase in the maximum output power may be expected by cooling the multiplier.

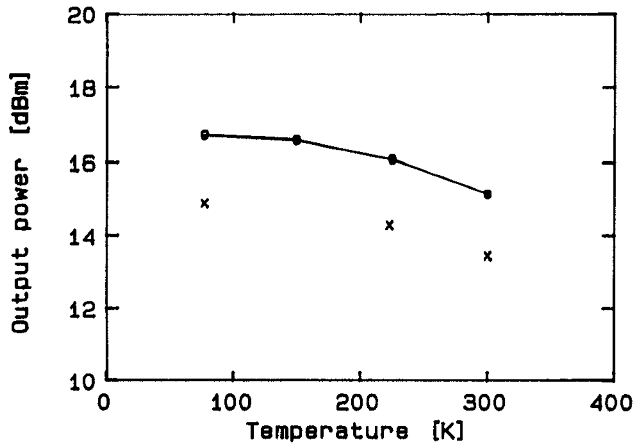


Fig. 7. The theoretical maximum output power at 160 GHz versus temperature (two diodes). Experimental results have also been plotted (x).

The results of our analyses show that the current saturation is not very severe in a doubler for 320 GHz and so the efficiency of multiplication increases only a little when the diode is cooled to 77 K. According to our results the efficiency is insensitive to input power over the range of 20–30 mW and so the output power increases, when the input power increases. Because the input power at 160 GHz increases and the series resistance decreases, the maximum theoretical output power increases from 5.8 mW to 8.5 mW, when the multipliers are cooled from 300 K to 77 K (see Table III).

When considering the tripler for 480 GHz, the current saturation must be included in the diode model, because the maximum current needed to pump the junction capacitance effectively is much larger than the maximum current of the diode at 300 K. So the output power at 480 GHz saturates at the power level of about 2 mW at 300 K, which can be well compared with a previous experimental research result of 0.7 mW, if the losses have also been taken into account [15]. But when the diode is cooled to 77 K, the maximum current of the diode increases. Therefore, the current saturation is less severe and so the output power increases significantly, if the input power of the tripler increases, so that the efficiency of the multiplication is almost constant at these input power levels. According to our results the maximum output power is as high as 5 mW at 77 K and when the losses are taken into account, the maximum output power may actually be about 2 mW at 480 GHz.

3.3 Last Stages, Multipliers at Near 1 THz

When considering the results of the last stage doubler and tripler at 960 GHz, it is simplest to consider the results of the complete multiplier chains at the same time, and then we can make comparison between the alternative multiplier chains. While the current saturation may be significant in the doubler for 160 GHz and in the second stage multiplier, it is now the most important factor for the terahertz multiplier. According to our simulations the maximum output power at 960 GHz seems to be about 50 μW at 300 K and 500 μW at 77 K for both alternative multiplier chains (see Table IV). And so the efficiency increases by about 10 dB when all diodes of the multiplier chain are cooled to the temperature of 77 K. These results remain to be verified by experiments, but cooling seems to be the way to generate more than 100 μW power by an all solid-state local oscillator at 960 GHz.

TABLE III
THEORETICAL OUTPUT POWER FOR SECOND STAGE MULTIPLIERS

		Input power			
Multiplier	Temperature	20	25	30	mW
2X160 GHz	300 K	5.6	6.3	7.1	mW
	77 K	6.8	7.7	8.5	mW
3X160 GHz	300 K	1.6	1.7	1.8	mW
	77 K	3.5	4.2	4.8	mW

TABLE IV
THEORETICAL OUTPUT POWER FOR MULTIPLIER CHAINS AT 960 GHz, D RIVEN BY A DOUBLER AT 160 GHz

		Input power			
Multiplier	Temperature	20	25	30	mW
2X -> 3X	300 K	52	55	58	μW
	77 K	470	500	530	μW
3X -> 2X	300 K	45	53	60	μW
	77 K	300	350	470	μW

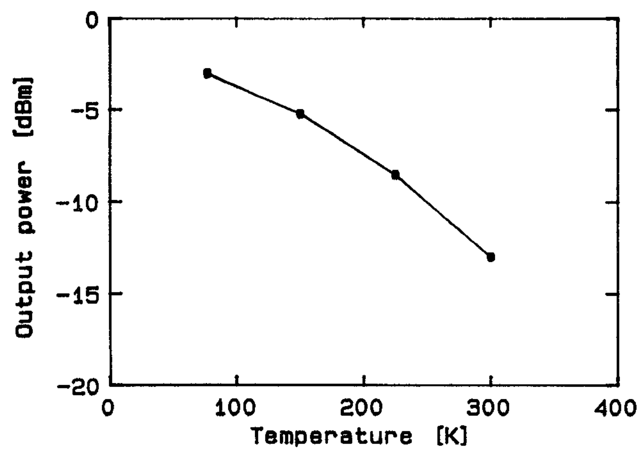


Fig. 8. The theoretical output power at 960 GHz versus temperature.

The choice for the second and last stage multipliers is open, if the figure of merit is only the maximum output power at 960 GHz, because both chains seem to be capable of generating almost the same power. But the choice to use first a doubler and then a tripler may actually be better, because in that construction the output power is less sensitive to the input power level of the last stage, in other words small losses at 320 GHz will not decrease the output power very significantly. The output power of the alternative chain, a tripler followed by a doubler, is very sensitive to the input power level of the last stage, and so possible extra losses at 480 GHz will decrease the maximum output power at 960 GHz very much.

Because the chain utilizing first a doubler for 320 GHz and then a tripler for 960 GHz is more attractive, we have studied it also at the temperatures of 225 K and 150 K. According to our simulations, the maximum output power at near 1 THz tends to increase even below 150 K (see Fig. 8). That can be understood, because the current saturation is so high for the last stage multiplier that even at the temperature of 77 K the electron current needed to pump the junction capacitance is higher than the maximum current of the diode. In other words, any extra current handling capability of the diode, which is gained by cooling down to 77 K, will increase the maximum output power. While the maximum output power of 500 μW is reached at the temperature of 77 K, the passive cooling in satellite applications to the temperature of 150 K is still quite useful providing about 300 μW output power. The extra increase of the maximum output power by 2 dB by cooling from 150 K down to 77 K must be traded against the more complicated cooling mechanism necessary in the satellite.

IV. Conclusions

Cooling of a Schottky varactor multiplier increases its efficiency by as much as several dB's. Because of the smaller series impedance the efficiency of frequency multiplication increases by 1–2 dB at small input power levels. At large input power levels the efficiency of a multiplier chain increases by 2–10 dB due to the higher current handling capability of the diodes. The theoretical maximum all-solid-state local oscillator power at 960 GHz seems to be about 500 μW, when the multiplier chain is cooled to 77 K. Resistive losses in the mounts of the second and third multiplier altogether may be estimated at 3–10 dB, which will be slightly reduced by cooling. Therefore, in practice an output power of about 100 μW can be expected.

According to our results a doubler should be used when the input power is high, in other words at low frequencies, while the triplers should be used only as the last stage multipliers, when the input power is low. If the maximum output power is needed, the multiplier chain must be cooled, at least the last stage. In satellite applications, passive cooling down to the temperature of 150 K may be enough.

References

[1] A. V. Räisänen, "Frequency multipliers for millimeter and submillimeter wavelengths," (Invited papers), *Proc. IEEE, Special Issue on Terahertz Technology,* vol. 80, no. 11, pp. 1842–1852, Nov. 1992.

[2] T. J. Tolmunen and M. A. Frerking, "Theoretical performance of novel multipliers at millimeter and submillimeter wavelengths," *Int. J. Infrared and Millimeter Waves,* vol. 12, no. 10, p. 1111–1133, 1991.

[3] E. Kollberg, "New solid state devices and circuits for millimeter wave applications," *Proc. 21st European Microwave Conf.,* Stuttgart, 1991, pp. 36–54.

[4] R. Zimmermann, R. Zimmermann, and P. Zimmermann, "All solid-state radiometers for environmental studies to 700 GHz," *Proc. 3rd Int. Symp. on Space Terahertz Technology,* Ann Arbor, MI, 1992, pp. 706–723.

[5] E. Kollberg, and A. Rydberg, "Quantum-barrier-varactor diodes for high-efficiency millimeter-wave multipliers," *Electron. Lett.,* vol. 25, no. 25, pp. 1696–1697, 1989

[6] A. Rydberg, H. Grönkvist, and E. Kollberg, "Millimeter and submillimeter-wave multipliers using quantum barrier varactors," *IEEE Electron Device Lett.,* vol. 11, no. 9, pp. 373–375, 1990.

[7] D. Choudhury, M. Frerking, and P. Batelaan, "A 200 GHz tripler using single barrier varactor," *Proc. 3rd Int. Symp. on Space Terahertz Technology,* Ann Arbor, MI, 1992, pp. 164–180.

[8] A. V. Räisänen, and M. Sironen, "Capability of Schottky-diode multipliers as local oscillators at 1 THz," *Microwave and Optical Technology Lett.,* vol. 4, no. 1, pp. 29–33, 1991.

[9] J. A. Copeland, "Diode edge effect on doping-profile measurements," *IEEE Trans. Electron Devices,* vol. ED-17, no. 5, pp. 401–407, 1970.

[10] H. Hjelmgren, E. Kollberg, and L. Lundgren, "Numerical simulations of the capacitance of forward-biased Schottky-diodes," *Solid-State Electron.,* vol. 34, no. 6, pp. 587–590, 1991.

[11] E. L. Kollberg, H. Zirath, and A. Jelenski, "Temperature-variable characteristics and noise in metal-semiconductor junctions," *IEEE Trans. Microwave Theory Tech.,* vol. MTT-34, no. 9, pp. 913–922, 1986.

[12] T. W. Crowe, "GaAs Schottky barrier mixer diodes for the frequency range 1–10 THz," *Int. J. Infrared and Millimeter Waves,* vol. 10, no. 7, pp. 765–777, 1989.

[13] J. G. Ruch and W. Fawcett, "Temperature dependence of the transport properties of Gallium Arsenide determined by a Monte Carlo method," *J. Applied Phys.,* vol. 41, no. 9, pp. 3843–3849, 1970.

[14] J. T. Louhi and A. V. Räisänen, "Cooled cascaded frequency multipliers at 1 THz," *Proc. 22nd European Microwave Conf.,* Espoo, Finland, 1992 pp. 597–602.

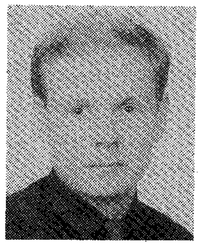
[15] N. R. Erickson, "High efficiency submillimeter frequency multipliers," *IEEE MTT-S Int. Microwave Symp. Dig.,* vol. III, Dallas, 1990, pp. 1301–1304.

[16] E. L. Kollberg, T. J. Tolmunen, M. A. Frerking, and J. R. East, "Current saturation in submillimeter wave varactors," *IEEE Trans. Microwave Theory Tech.,* vol. 40, no. 5, 1992, pp. 831–838.

[17] J. East, private communication, (Mar. 1992).

[18] P. Penfield and R. P. Rafuse, *Varactor Applications.* Cambridge, MA: MIT Press, 1962.

[19] P. H. Siegel, A. R. Kerr, and W. Hwang, "Topics in the optimization of millimeter - wave mixers," NASA Tech. Paper 2287, 1984.



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Neal R. Erickson, photograph and biography not available at the time of publication.