HIGHER ORDER FREQUENCY MULTIPLIERS — A SOLUTION FOR MM- AND SUBMM-WAVE LOCAL OSCILLATOR SIGNAL GENERATION

Timo Tolmunen, Antti Räisänen and Mikko Sironen

Helsinki University of Technology, Radio Laboratory
Otakaari 5 A, SF-02150 Espoo, Finland

ABSTRACT

A frequency quadrupler for 140 GHz and frequency doublers for 183 GHz and 230 GHz have been analyzed both theoretically and experimentally. A theoretical comparision of generation of 345 GHz signal using a doubler, tripler, quadrupler or two cascaded doublers, and generation of 460 GHz signal using a doubler, quadrupler or two cascaded doublers has also been carried out.

INTRODUCTION

The development of high efficiency frequency multipliers is especially important for the spaceborne mm-wave and submm-wave heterodyne receivers used for radio astronomy and remote sensing of the atmosphere. Recently we have designed, constructed and tested a frequency doubler and a frequency tripler for 80—120 GHz range with very high efficiencies (highest efficiency 45 % and 28 %, respectively) [1,2]. The optimization was based on extensive computer analyses and scaled model measurements.

In this paper we report our continuing effort on developing high efficiency multipliers, now for 100–500 GHz range. At the submm-waves higher order multipliers become very attractive in local oscillator signal generation due to their higher reliability in comparision to cascaded doublers. On the other hand, higher order varactor multipliers require reactive idler terminations which complicate the mount design and manufacturing.

To study the performance of multipliers of various orders and multiplier chains, extensive computer simulations [3] were made to analyze a doubler, a tripler, a quadrupler and two cascaded doublers for 345 GHz, and a doubler, a quadrupler and two cascaded doublers for 460 GHz. In order to get experimental background for those theoretical studies a quadrupler for 140–150 GHz and a doubler for 183 GHz were analyzed both theoretically and experimentally.

QUADRUPLER FOR 140-150 GHz

Extensive computer simulations were made to thoroughly analyze a frequency quadrupler for 140 GHz. Emphasis was placed on the study of optimum idlers at the 2nd and 3rd harmonics. While the highest efficiency obtained prior to this experimentally from quadruplers at mm-waves was only a few percent [4], our analyses [5] show that theoretically over 50 % efficiency is obtainable when a commercially available varactor is used.

A quadrupler is most efficient when it has an idler circuit both at the 2nd and 3rd harmonic frequencies. The simulations show that with matched terminations at the input and output frequencies and with optimum reactive terminations at both the idler frequencies it is possible to obtain in a lossless multiplier mount quadrupling efficiencies as high as 50–55 % in a reactive multiplication region by using commercially available Schottky-varactors (e.g. Farran Technology VD010, having C_0 = 19 fF, R_s = 10 Ω and γ = 0.45) at 140 GHz output frequency range. With high input power levels the varactor is driven into conduction and the multiplication becomes partly resistive. Due to this the efficiency decreases and is typically 15–30 %.

The results obtained from theoretical simulations were used in the design of an experimental quadrupler with fixed idler terminations for 140–150 GHz output frequency range. This quadrupler has been tested with different output configurations [5]. The highest efficiency obtained was 11.3 % at 148 GHz with an input power level of 10 mW. With input power of 40 mW an output power of 1.5–2.7 mW was available over a range of 5–15 GHz depending on the output configuration.

This quadrupler mount was tested also as a frequency quintupler [6] for 165–170 GHz by terminating the 4th harmonic with a high inductance. Thus, the conversion to the 4th harmonic was eliminated and a (1–2–3–5)-quintupler operation was obtained. The highest efficiency measured was 4.2 % at 168 GHz with an input power level of 10 mW. With input power of 40 mW an output power of 0.7–1.3 mW was available over the range from 165 to 170 GHz.

DOUBLERS FOR 183 AND 230 GHz

An effective doubler requires optimum matched termination at the 1st and 2nd harmonics and an open circuit for the higher harmonics. Theoretical calculations have been carried out for doublers from 92 to 184 GHz and from 115 to 230 GHz. The analyses show that in a lossless waveguide mount the efficiency can in both cases rise over 50 % in the region of purely reactive multiplication which in this case means that the diode absorbed power is $P_{abs} \approx 10$ mW and the reverse bias voltage is over 6 V. If the multiplication is partly resistive the theoretical efficiency is typically 20–30 % with $P_{abs} > 30$ mW and reverse bias voltage below 4 V. The diode parameters used in these analyses were: C_0 = 12.5 fF, R_s = 12 Ω, η = 1.15 and γ = 0.45 in the case of the doubler for 184 GHz, and C_0 = 10 fF, R_s = 14 Ω, η = 1.15 and γ = 0.45 in the case of the doubler for 230 GHz. Both parameter sets are typical for varactors commonly used in these output frequency ranges, for example VD011 and VD012 of Farran Technology.

Using these results and observations from the theoretical and experimental study of a frequency doubler for 100 GHz [1] crossed waveguide doublers for 183 GHz and 230 GHz were designed and constructed. Preliminary tests of a doubler for 183 GHz have been carried out. In this doubler a VD011-varactor ($C_0 \approx 12.5$ fF and $R_s \approx 12$ Ω) was used. According to the measurements the highest efficiency obtained was 22 % and typically 10...20 % in an output frequency range of 160–190 GHz with input power levels below 20 mW (Gunn). With high

CH2725-0/89/0000-1223$01.00 © 1989 IEEE

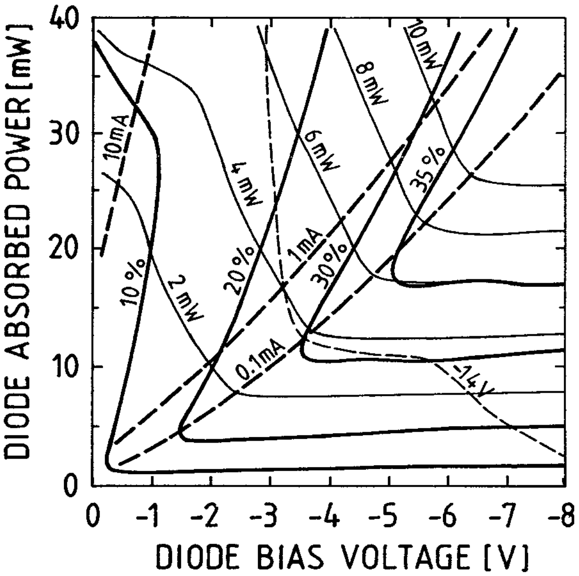

Figure 1. Intrinsic efficiency and output power of a frequency tripler for 345 GHz.

input power levels 30–100 mW (klystron) the output power of the experimental doubler was 5–10 mW in the range of 170–185 GHz.

MULTIPLIERS OF VARIOUS ORDERS FOR 345 GHz

As the basic choice for this multiplier a tripler was studied. A frequency tripler requires matched terminations at the input and output frequencies, optimum idler termination at the 2nd harmonic and an open circuit for the 4th and higher order harmonic frequencies. Computer simulations were carried out for a submm-wave tripler from 115 GHz to 345 GHz using the parameters of a varactor having $C_0 = 10$ fF.

The intrinsic efficiency and output power of this tripler is shown in Figure 1. The operation of the tripler is restricted by the diode breakdown voltage ($-V_{BR} \approx$ 14–16 V for VD012) and maximum rectified current for safe operation. This current is typically 10 mA for mm-wave Schottky varactors available today.

Reactive multiplication turns partly to resistive when rectified current starts to flow. This is clearly seen in Figure 1: the region of purely reactive multiplication is slightly below the dashed line marked by 0.1 mA. The highest efficiency is obtained in this reactive region. However, this cannot rise over 30 % if safe operation is required. To obtain the efficiencies shown in Figure 1 a lossless mount with optimum embedding impedances illustrated in Figure 2 are required.

For comparison a doubler, a quadrupler and two cascaded doublers giving the same output frequency of 345 GHz were studied. The highest efficiencies available form each multipliers with various input power levels are collected in Table I. In each case it is assumed that the reverse voltage swing across the diode junction do not exceed 16 V during a fundamental oscillator cycle. All 345 GHz signals are generated with a varactor having $C_0 = 10$ fF whereas the 172.5 GHz signal (abbreviated 172 GHz in the following text) required in the doubler chain is generated by a varactor having $C_0 = 12.5$ fF. Figure 3 illustrates the theoretical output power available from these multipliers as a function of the input power level.

The results show that the doubler from 172 GHz to 345 GHz gives the best efficiency and widest operational range (assuming that there are no restrictions due to the fundamental source at 172 GHz). This is natural because narrow band idler circuits

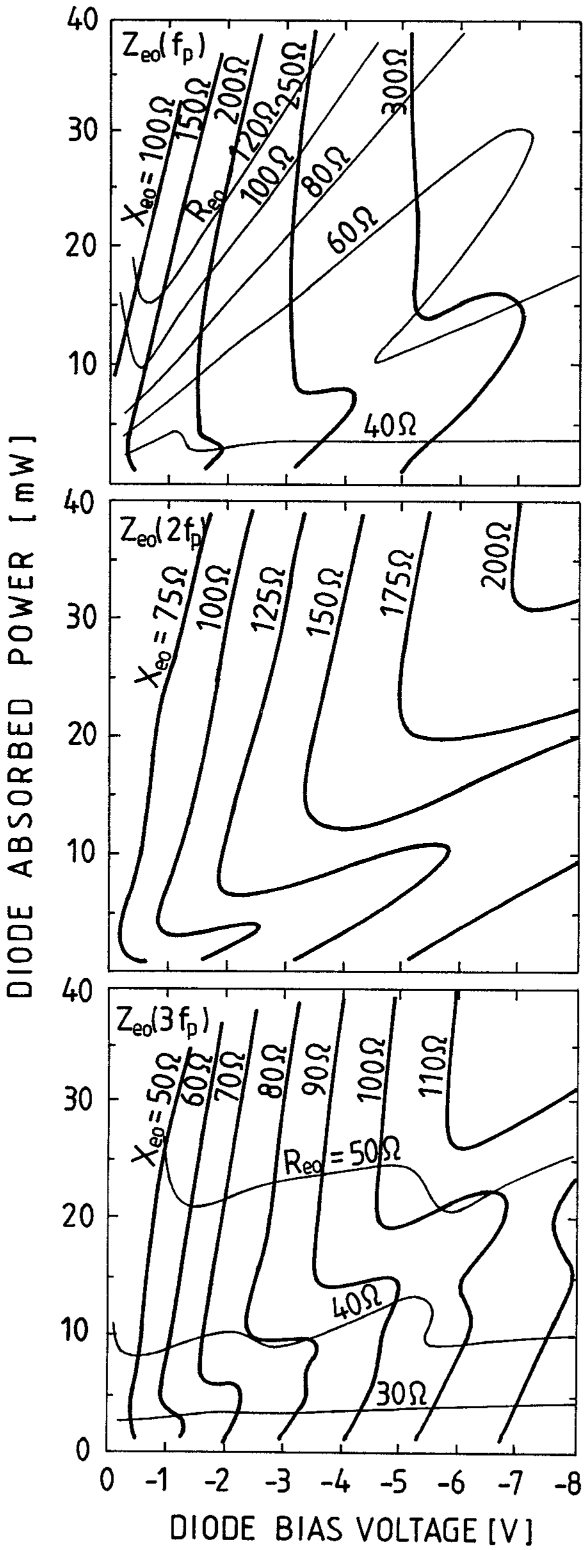

Figure 2. Optimum embedding impedances at the fundamental, idler and output frequencies of the tripler for 345 GHz. These impedances and a lossless waveguide mount are essential for the high efficiencies shown in Figure 1. At higher harmonics an optimum termination is an open circuit.

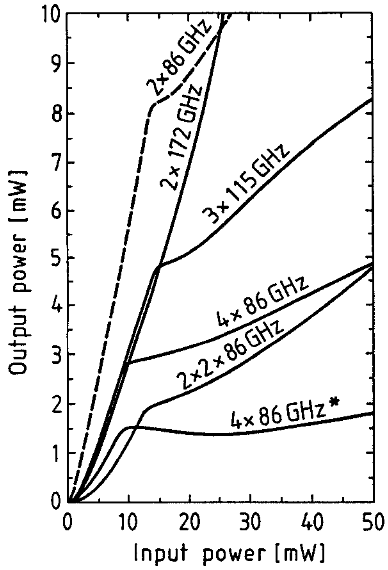

Figure 3. *A comparison of the highest theoretical output power available from multipliers of various orders at 345 GHz. The dashed line curve illustrates the output power of a doubler for 172 GHz required for the input power to the second stage of the cascaded doublers. The 4 × 86-curve denoted by an asterisk illustrates the output power available from the quadrupler where only the 2nd harmonic idler is used.*

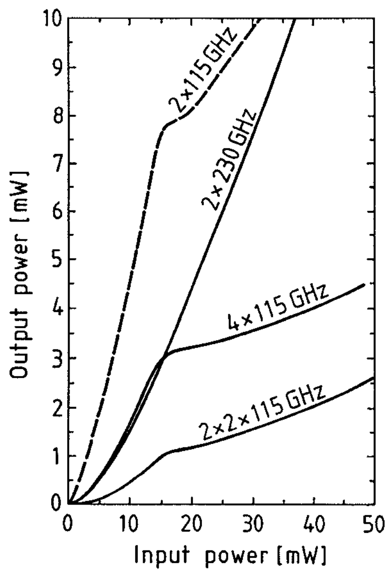

Figure 4. *A comparison of the highest theoretical output power available from a doubler, a quadrupler and two cascaded doublers at 460 GHz.*

are not needed in the doubler. In practice this doubler is not a good choice because there are no fundamental low noise solid state sources available at 172 GHz. This disadvantage can be overcome by using two cascaded doublers. In this case the 172 GHz signal is first created by a doubler from 86 GHz. The main disadvantage of this solution is the low output power at 345 GHz especially because in practice an isolator with several dBs of loss is needed between the doublers. In Table I and in Figure 3, however, it is assumed that the power available from the first doubler can be connected without external losses to the second doubler.

The remaining solution is a quadrupler from 86 GHz. It gives theoretically better efficiency than the two cascaded doublers, if the quadrupler has idlers both at the 2nd and 3rd harmonics. If only the 2nd harmonic idler is used the theoretical efficiency of the quadrupler is lower than that of the two cascaded doublers, but then again the quadrupler may be more attractive because of no need of an isolator at 172 GHz. On the other hand the quadrupler can provide only very limited operational frequency range.

To obtain the high efficiencies shown in Table I the mount should be lossless and the multipliers must be provided with the embedding impedances given in Table II.

GENERATION OF A 460 GHz-SIGNAL

Another comparison was made at 460 GHz output frequency range for a doubler, quadrupler and two cascaded doublers. The highest efficiency available from these configurations is shown in Table III and the output power in Figure 4. In each case the parameters of the varactor having $C_0 = 10$ fF is assumed.

Again the single doubler now from 230 GHz to 460 GHz gives the best efficiency and the highest output power if the input power level is higher than 15 mW. With input power below 15 mW the doubler and the quadrupler from 115 GHz to 460 GHz have almost an equal performance. If an all-solid-state signal is required the input power must be generated by another doubler from 115 GHz to 230 GHz. However, this doubler chain has a considerably lower efficiency than the quadrupler. The reason to this is in the optimum embedding impedances for these multipliers shown in Table IV. The doubler for 460 GHz has a very low input impedance ($Z_{in} = Z_{eo}^*$) at the fundamental frequency which is due to the "high" capacitance. Therefore, the diode series resistance is dominating and considerable losses are caused due to it at the fundamental frequency.

DISCUSSION

At 140 GHz range the highest efficiency obtained experimentally from the quadrupler was 6–7 dB below theoretical predictions. The main reason which in every case decreases the efficiency is resistive losses of the multiplier mount which in the quadrupler affect also at the idler frequencies. These losses are around 2–2.5 dB at 140 GHz. Another important reason is nonoptimal terminations at various harmonics. With fixed idler terminations and two tuning elements (one for the input and another for the output frequency) it is impossible to perfectly terminate all harmonics simultaneously. Therefore, the efficiency obtained experimentally is lower.

At 460 GHz range the losses of the mount are considerably higher than at 140 GHz. Assuming additional losses of 2–3 dB an output efficiency of 2–3 % may be available from a quadrupler with a similar simple structure as that used at 140 GHz. With a skillful manufacturing of the multiplier mount as presented in [7] it is possible to realize additional tuning elements. Varactor match at the fundamental frequency is usually difficult due to a small resistive and high reactive part of the varactor input impedance (see Tables II and IV). Therefore, an additional tuning element at the fundamental frequency may improve the operational bandwidth and the efficiency by providing a better match to the varactor over a large range of input power and diode bias levels. Naturally additional tuning elements at the idler frequencies are also useful.

At 345 GHz range similar assumptions predict efficiencies around 3–5 % for a quadrupler. At 345 GHz, however, it may be more reasonable to realize a frequency tripler because the state-of-the-art InP-Gunn-oscillators can provide an input power of 50 mW for the tripler at 115 GHz. The tripler requires only one idler and therefore the degradation of the efficiency caused by the losses of the mount and nonideal terminations are lower

TABLE I Comparison of the best theoretical efficiency of a doubler, tripler, quadrupler and two cascaded doublers for 345 GHz.

P_{in}	2×172	3×115	4×86	$2 \times 2 \times 86$
5 mW	21 %	22 %	22 %	7 %
10 mW	28 %	30 %	29 %	12 %
20 mW	34 %	26 %	16 %	11 %
40 mW	29 %	18 %	10 %	9 %

TABLE II Optimum embedding impedances required for the efficiencies shown in Table I.

DOUBLER 2×86 GHz

P_{in}, V_B	$Z_{eo}(f_p)$	$Z_{eo}(2f_p)$
5 mW, −3.0 V	$33 + j245\ \Omega$	$54 + j123\ \Omega$
10 mW, −5.2 V	$39 + j300\ \Omega$	$68 + j148\ \Omega$
20 mW, −4.7 V	$62 + j290\ \Omega$	$55 + j157\ \Omega$
40 mW, −4.3 V	$106 + j260\ \Omega$	$64 + j142\ \Omega$

DOUBLER 2×172 GHz

P_{in}, V_B	$Z_{eo}(f_p)$	$Z_{eo}(2f_p)$
5 mW, −1.4 V	$23 + j122\ \Omega$	$31 + j60\ \Omega$
10 mW, −2.8 V	$26 + j149\ \Omega$	$37 + j73\ \Omega$
20 mW, −6.4 V	$29 + j205\ \Omega$	$46 + j100\ \Omega$
40 mW, −4.9 V	$45 + j178\ \Omega$	$43 + j97\ \Omega$

TRIPLER 3×115 GHz

P_{in}, V_B	$Z_{eo}(f_p)$	$Z_{eo}(2f_p)$	$Z_{eo}(3f_p)$
5 mW, −2.2 V	$46 + j221\ \Omega$	$j113\ \Omega$	$33 + j69\ \Omega$
10 mW, −3.0 V	$54 + j267\ \Omega$	$j140\ \Omega$	$39 + j81\ \Omega$
20 mW, −3.9 V	$63 + j271\ \Omega$	$j157\ \Omega$	$49 + j93\ \Omega$
40 mW, −3.5 V	$131 + j250\ \Omega$	$j129\ \Omega$	$59 + j83\ \Omega$

QUADRUPLER 4×86 GHz

P_{in}, V_B	$Z_{eo}(f_p)$	$Z_{eo}(2f_p)$	$Z_{eo}(3f_p)$	$Z_{eo}(4f_p)$
5 mW, −3.6 V	$58 + j332\ \Omega$	$j161\ \Omega$	$j108\ \Omega$	$37 + j81\ \Omega$
10 mW, −3.6 V	$62 + j345\ \Omega$	$j235\ \Omega$	$j134\ \Omega$	$50 + j82\ \Omega$
20 mW, −2.9 V	$110 + j315\ \Omega$	$j220\ \Omega$	$j145\ \Omega$	$54 + j81\ \Omega$
40 mW, −2.4 V	$216 + j232\ \Omega$	$j180\ \Omega$	$j135\ \Omega$	$57 + j72\ \Omega$

in comparison to the quadrupler. The efficiency obtained from an experimental tripler at 100 GHz [2] was 2–3 dB below the theoretical predictions. Assuming a similar crossed waveguide structure also for 345 GHz with additional losses of 2–3 dB it may be possible to obtain tripling efficiencies of 5–12 %.

A doubler chain allows also a solid-state signal conversion to 345 GHz and 460 GHz. Theoretically the efficiency available from cascaded doublers is around 10 % at 345 GHz and 5 % at 460 GHz. Losses in both doubler stages reduce this efficiency remarkably. In the case of the experimental doubler for 183 GHz the efficiency was 3–4 dB below theoretical. Assuming similar losses also for the second stage the efficiency of cascaded doublers even without the isolator sinks below that available from a quadrupler for 345 GHz.

CONCLUSIONS

If tube oscillators are available at 170-230 GHz range the best choice in producing signals to either 345 GHz or 460 GHz is a doubler due to its relative simplicity which allows a wider operational range in comparision to higher order multipliers. However, if an all-solid-state source is required, a higher order multiplier may often be a more reasonable choice.

TABLE III Comparison of the best theoretical efficiency of a doubler, quadrupler and two cascaded doublers for 460 GHz.

P_{in}	2×230	4×115	$2 \times 2 \times 115$
5 mW	10 %	12 %	2.2 %
10 mW	16 %	17 %	4.8 %
20 mW	22 %	15 %	5.7 %
40 mW	28 %	10 %	5.1 %

TABLE IV Optimum embedding impedances required for the efficiencies shown in Table III.

DOUBLER 2×115 GHz

P_{in}, V_B	$Z_{eo}(f_p)$	$Z_{eo}(2f_p)$
5 mW, −2.4 V	$32 + j221\ \Omega$	$50 + j110\ \Omega$
10 mW, −4.6 V	$38 + j267\ \Omega$	$62 + j133\ \Omega$
20 mW, −4.9 V	$56 + j275\ \Omega$	$54 + j150\ \Omega$
40 mW, −4.5 V	$97 + j251\ \Omega$	$62 + j137\ \Omega$

DOUBLER 2×230 GHz

P_{in}, V_B	$Z_{eo}(f_p)$	$Z_{eo}(2f_p)$
5 mW, −0.8 V	$20 + j81\ \Omega$	$24 + j38\ \Omega$
10 mW, −1.8 V	$21 + j97\ \Omega$	$27 + j47\ \Omega$
20 mW, −3.2 V	$24 + j115\ \Omega$	$31 + j56\ \Omega$
40 mW, −6.2 V	$27 + j145\ \Omega$	$39 + j70\ \Omega$

QUADRUPLER 4×115 GHz

P_{in}, V_B	$Z_{eo}(f_p)$	$Z_{eo}(2f_p)$	$Z_{eo}(3f_p)$	$Z_{eo}(4f_p)$
5 mW, −2.4 V	$43 + j217\ \Omega$	$j105\ \Omega$	$j69\ \Omega$	$28 + j52\ \Omega$
10 mW, −3.6 V	$50 + j252\ \Omega$	$j140\ \Omega$	$j84\ \Omega$	$33 + j59\ \Omega$
20 mW, −3.1 V	$64 + j242\ \Omega$	$j166\ \Omega$	$j104\ \Omega$	$41 + j58\ \Omega$
40 mW, −2.9 V	$112 + j210\ \Omega$	$j150\ \Omega$	$j103\ \Omega$	$44 + j55\ \Omega$

The disadvantage of the higher order multipliers is the reactive idler terminations. However, experiments with a relatively simple crossed waveguide multiplier structures have shown that it is possible to obtain fairly high efficiencies over an operational bandwidth of 15 % in the case of a tripler and of 10 % in the case of a quadrupler. With additional tuning elements it may be possible to further improve the multiplier performance.

REFERENCES

[1] T.J. Tolmunen and A.V. Räisänen,"An efficient Schottky-varactor frequency multiplier at millimeter waves. Part I: Doubler," *Int. J. of Infrared and Millimeter Waves*, vol. 8, 1313–1336, (1987).

[2] As above. Part II: Tripler. 1337-1353.

[3] P.H. Siegel, A.R. Kerr, and W. Hwang,"Topics in the optimization of millimeter-wave mixers," NASA Technical Paper 2287, 512 p., 1984.

[4] N.R. Erickson, Millitech Corp., South Deerfield, Mass., private communication.

[5] T.J. Tolmunen and A.V. Räisänen,"An efficient Schottky-varactor frequency multiplier at millimeter waves. Part III: Quadrupler," To be published.

[6] T.J. Tolmunen and A.V. Räisänen,"An efficient Schottky-varactor frequency multiplier at millimeter waves. Part IV: Quintupler," To be published.

[7] R. Zimmermann, R. Zimmermann and P. Zimmermann,"490 GHz solid state source with varactor quintupler." 13th International Conference on Infrared and Millimeter Waves, R.J. Temkin (editor), SPIE vol. 1039, 77–78, (1988).