MULTIPLIERS FOR THz HETERODYNE SYSTEMS

B.L.A. Rydberg, B.N. Lyons and U.S. Lidholm
Farran Technology Ltd.
Ballincollig, Cork, Ireland

Abstract:

The development of a 750 GHz tripler having a measured output power and efficiency of more than 120 µW and 0.8 % respectively at a frequency of 803 GHz is described. The output powers and efficiencies are the highest reported for this frequency. The development of a 250 GHz tripler to be used as a pump source for the 750 GHz tripler is also described.

Introduction:

Due to the development of mixers, for example SIS-mixers, at frequencies around 1 THz, the demand for solid state local oscillators has been steadily increasing. In 1988 Farran Technology was commissioned by the European Space Agency to investigate and develop solid state sources based on Schottky diode multipliers to be used as local oscillators in such receivers. One of the targets has been to develop a 750 GHz solid state source with a predicted output power of 50 µW based on two triplers pumped by an 83 GHz InP-TED oscillator. We here report on the progress and results in developing such a source.

Theoretical study and mount design:

Using a large signal multiplier analysis program based on the principle of harmonic balance developed by Siegel et al. [1], different Schottky varactor diodes were investigated for the two multipliers. The output power for four different devices ranging from $C_j(0)=1.6$ to 3.4 fF was calculated for the 750 GHz tripler, see Fig.1. The input power in the investigation was varied between 1-6 mW since this was assumed to be a reasonable estimate of what it is possible to achieve from a 250 GHz tripler. The description of the devices used in the simulation was simplified in that a fixed layer thickness and doping of 0.49 μm and $9{\cdot}10^{16}$ cm^{-3} respectively was used for the low doped epitaxial region. The breakdown voltage V_b varied between 4 - 7 V for the devices, see Fig.1. The series resistance was set to 20 ohm, which is assumed to be a reasonable value for diodes having a capacitance $C_j(0)$ of 1.6 - 3.4 fF.

The marked region in Fig.1 shows the operating condition when the maximum voltage V_{max} that is the bias voltage plus the peak rf-voltage is approximately equal to the breakdown voltage. Thus diodes with a capacitance between 2.2 - 2.8 fF should be the most suitable ones. The device capacitance was chosen to be 2.8 fF. The calculated output power for such a device is about 500 μW, allowing 10 dB matching and circuit losses, yields the required output power of $\geqslant 50$ μW. Experimental results have shown that twice the pump power needed for V_{max} to reach V_b can be used [2]. Therefore it should be possible to use a pump power of approximately 5 mW thereby increasing the output power by a factor of two.

A cross sectional view of the 750 GHz tripler is shown in Fig.2. The function of the idler resonator, see Fig.2, used in the multiplier is based on the principle developed by Erickson [3]. The step in the outer diameter of the coaxial resonator is incorporated in order to achieve a better short circuit at the end of the idler [4]. The input waveguide is a reduced height WR-3 waveguide. The wide dimension of the output waveguide is 0.258 mm, thus being cutoff at 581 GHz. A conical horn was used for the output port due to the ease with which it could be machined. By proper selection of the length and horn opening it is possible to have a nearly identical beam pattern in the E and H planes [5]. The waveguide is matched to the horn using a 5λ long taper with a square cross section at the horn throat, having the same cutoff frequency as the circular horn throat. Thus the impedance discontinuity between the horn and the waveguide becomes very small.

A scaled model of the mount (scaling factor = 83.31) was designed in order to investigate and optimize the embedding impedances seen at the input, idler and output frequencies by the diode. Using the scaled model it was found that most resonances in the embedding impedance were due to higher order mode excitation in the rf-filter, see Fig.3. These resonances were particularly strong close to the cutoff frequency for the particular mode. Due to mechanical limitations it was not possible to shift the coaxial TE_{11}-mode cutoff frequencies for the rf-filter above the highest operating frequency except for the last rf-filter section. The TE_{11}-mode cutoff frequencies for the other filter sections were instead shifted to the frequency region between the input and the idler frequency, thereby minimizing the influence of the resonances related to the cutoff frequency. The rf-filter is extended by a $\lambda/2$ coaxial section in order to make the middle block easier to machine, see Fig.2.

A theoretical model was developed for the mount, where the coupling between the rf-filter and the input waveguide was calculated using the theory by Williamson [7]. For the output port a simplified theoretical model was used based on the assumption that the embedding impedance seen by the diode is the sum of the impedances from (i) the output waveguide in parallel with the backshort, (ii) the rf-filter and (iii) the idler. Though this simplified model is not sufficient to fully describe the output port it was used in the absence of a more accurate one. The bias filter was assumed to present a short circuit at the input frequency.

Using the theoretical and the scaled models of the mount the embedding impedances seen by the device at the input, idler and output frequencies were calculated and measured respectively, see Fig.4. The bias filter was short circuited in the measurements.

It can be seen in Fig.4 that there is a difference in reactance between the measurements and the calculated values. The discrepancy in reactances is believed to be related to the simplifications in the theoretical model used in the calculations. The increased capacitance due to the measurement cable - waveguide junction compared to the actual device was found to add a capacitance of only about 43 fF to the actual values. Thus this capacitance does not account for the noted discrepancy.

In Figure 4 is also plotted the complex conjugate of the diode impedance, Z_d^x, or the reactance, X_d^x, at the input, idler and output frequencies. Comparison between Z_d^x or X_d^x and the measured embedding impedance shows that a match to the device could be achieved particularly at the high frequency end of the output frequency range 675 - 825 GHz wanted for the tripler.

Simulations using the theoretical model of the mount gave a maximum efficiency for the tripler of 11 % at 750 GHz, compared to the theoretical value of 12.2 % found in the diode simulations for 2.5 mW in input power.

The 250 GHz tripler which very recently has been assembled has a similar design to the 750 GHz tripler. However the low pass filter structure for the bias filter is replaced with a radial-line resonator filter [8]. The step in the outer diameter of the idler resonator, see Fig.2, was not used in this design due to better mechanical control. The 250 GHz tripler is designed for a 17 fF, varactor diode from Farran Technology, nr. VD10A. Simulations using this device have shown that output powers of about 22 mW can be generated for input powers of 64 mW. However due to mount losses, impedance mismatch etc., this power is reduced by a factor of 2 - 4 [2]. Thus it is reasonable to expect about 5 mW of output power for a well optimized mount, since output powers of 1 - 3 mW are commonly achieved for this type of mount [9].

Measurements:

In the initial test phase a carcinotron was used as the pump source for the 750 GHz tripler.

The mount was developed for a 2.8 fF varactor diode. However due to lack of a suitable diode with this capacitance a 5.4 fF varactor diode having a series resistance of 11 ohm was tested in the mount, see Fig.5. The use of a higher capacitance device means in principle that more pump power is needed in order to achieve the same output power as for a 2.8 fF device, assuming the same series resistance for the diodes. However this is compensated for by the much smaller series resistance for the 5.4 fF, 11 ohm as compared to 20 ohm assumed for the 2.8 fF device.

Computer simulations of the tripler using the theoretical model showed that it is possible to match the 5.4 fF diode, by reducing the whisker length to 50 μm compared to 60 μm for the 2.8 fF device, though with a loss in maximum efficiency. Thus it was found using computer simulations that a maximum efficiency of 12.8 % for the mount compared to a maximum of 16.3 % using optimum embedding impedances could be achieved at 750 GHz, at 6 mW input power. This can be compared to an efficiency of 18.4 % for the 2.8 fF diode at optimum embedding impedances using the same input power. The small difference, that is 16.3 - 18.4 % is mainly due to the difference in cutoff frequency for the devices.

The measured results for the 750 GHz tripler using the 5.4 fF diode are shown in Fig.5. The output power and efficiency are as can be seen in Fig.5, very sensitive to the input power. The higher input power means that a larger backbias voltage or in this case a smaller forward bias voltage can be used thereby making the diodes work more in varactor mode, see Fig.6. Thus the output power and efficiency using this operating point are greater, compare Fig.5 and 6. It can be seen, comparing Fig.6 with Fig.5, that the operating points vary according to the pump power available from the carcinotron and seem to be less dependent on the pump frequency Thus the passband for the rf-filter seems to have little variation in attenuation over the investigated frequency range, which was also anticipated.

The work on optimizing the 250 GHz tripler is about to commence. Initial output powers of 1 mW at 250 GHz has been achieved.

Future work:

The 250 GHz tripler will be optimized as a pump source for the 750 GHz tripler.

The 5.4 fF varactor will be replaced by a 2.8 fF device which we have now fabricated, having a series resistance of 16 ohm.

Single barrier varactors (SBV) will be tested in the mount. Due to the symmetrical I-V and C-V characteristic of the SBV-diodes only odd harmonic are generated in these devices [10]. Thus they are particularly suitable for use in example triplers since no idler resonator is needed, thereby reducing the losses at the idler frequency to zero [11].

Conclusions:

The design and development of a solid state source for 750 GHz consisting of two triplers has been described. State of the art output powers of more than 120 μW has been achieved at 803 GHz using a carcinotron as the initial test source for the 750 GHz tripler.

Acknowledgements:

We would like to thank Dr. D. Vizard for helpfull discussions and Mr. J. Pike for assistance in selecting the diodes and diode manufacture. Messrs. K. Barrett and M. Fehilly are thanked for skilful manufacturing and assembly of the multipliers as well as technical ideas. Miss M. Tubridy is also thanked for help with optimization of the mount using Touchstone.

The European Space Agency (ESA) is acknowledged for financial support (ESA contract no. 7898/88/NL/PB).

References:

1. P.H. Siegel, A.R. Kerr and W. Hwang, Topics in the optimization of millimeter-wave mixers," NASA tech. paper 2287, 1984.

2. N.R. Erickson, "Very high efficiency frequency tripler for 100-300 GHz," Proc. of the 10th Int. Conf. on Infrared and Millimeter Waves, pp. 54-55, 1985.

3. N.R. Erickson, "A high efficiency frequency tripler for 230 GHz," Proc. of the 12'th European Microwave Conf., pp. 241-246, 1982.

4. N.R. Erickson, "High efficiency submillimeter frequency multipliers," Proc. of IEEE-MTT Conf. 1990, pp. 1301-1304, 1990.

5. R.C. Johnson and H. Janik, Antenna engineering handbook, second edition, McGraw-Hill, pp. 15-13 - 15-17, 1984.

6. T.J. Tolmunen and A.V. Raisanen, "An efficient Schottky-varactor frequency multiplier at millimeter waves, Part II: Tripler," Int. Journal of Infrared and Millimeter Waves, vol. 8, pp. 1337-1353, 1987.

7. A.G. Williamson, "Analysis and modelling of "two-gap" coaxial-line rectangular waveguide junctions," IEEE Trans. on Microwave Theory and Tech., vol. MTT-31, pp. 295-302, 1983.

8. A. Rydberg, "Calculation of microwave radial-line filters," Microwave and Optical Technology Lett., vol.1, pp. 4-7, 1988.

9. A. Rydberg, "Oscillator and multiplier development for millimeterwave radioastronomy," Proceedings of the workshop on solid state sources at millimeter and submillimeter wavelengths, Ulm, BRD, October 1987.

10. E. Kollberg and A. Rydberg, "Quantum-barrier-varactor diodes for high-efficiency millimeter-wave multipliers," Electron. Lett., vol. 25, pp. 1696-1698, 1989.

11. A. Rydberg, H. Gronqvist and E. Kollberg, "Millimeter- and submillimeter-wave multipliers using Quantum-Barrier-Varactor (QBV) diodes," IEEE Electron Device Lett., vol. 11, pp. 373-375, 1990.

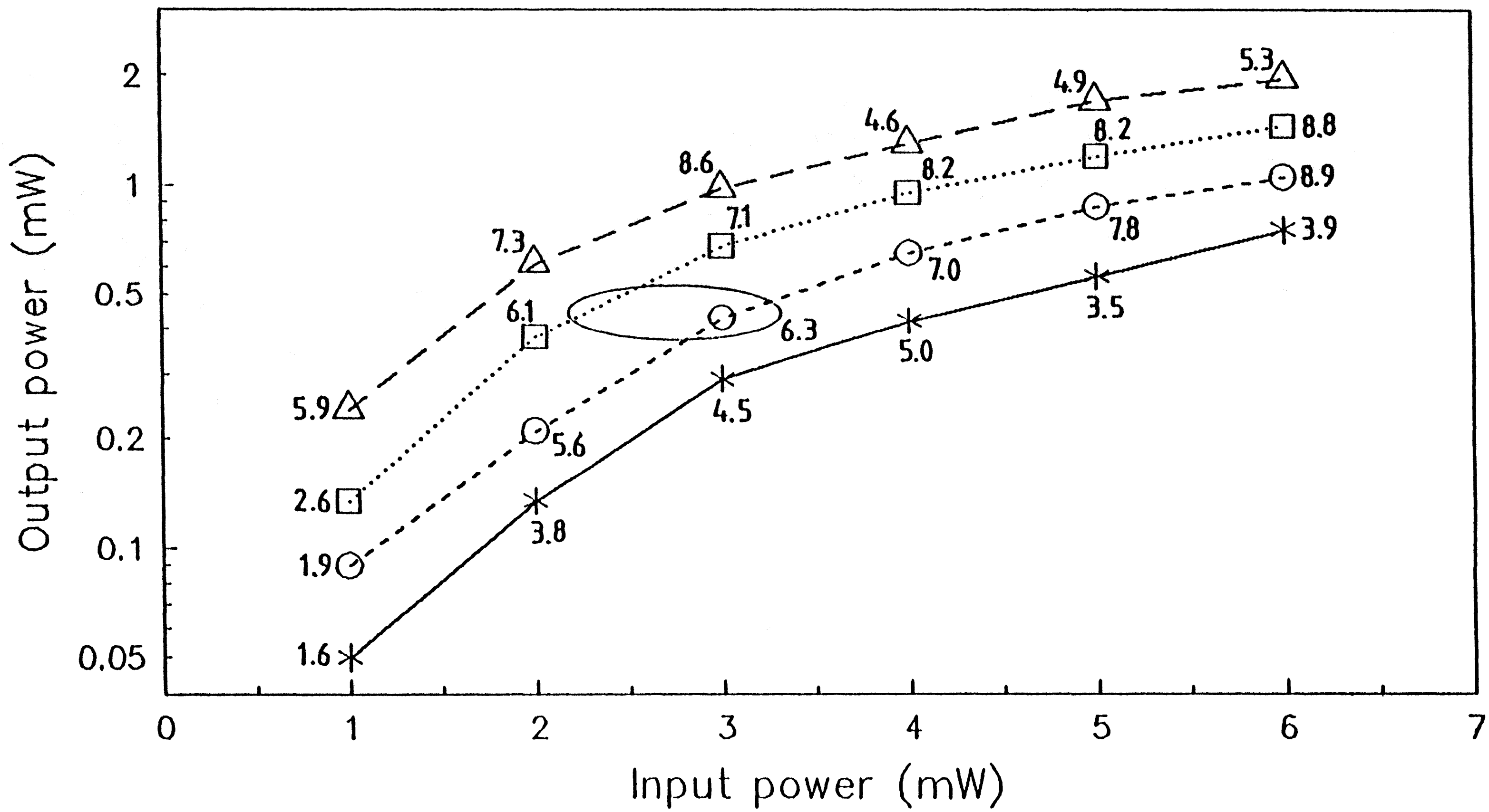

Fig.1 Calculated output power as a function of input power for Schottky varactor diodes having a capacitance $C_j(0)$ of between 1.6 - 3.4 fF. The bias voltage is optimized for best efficiency. The numbers along the curves are the maximum voltages V_{max} across the device at the particular operating point.

(Δ): $C_j(0)$ is 1.6fF, V_b = 4 V.

(□): $C_j(0)$ is 2.2fF, V_b = 6 V.

(O): $C_j(0)$ is 2.8fF, V_b = 6.5 V.

(x): $C_j(0)$ is 3.4fF, V_b = 7 V.

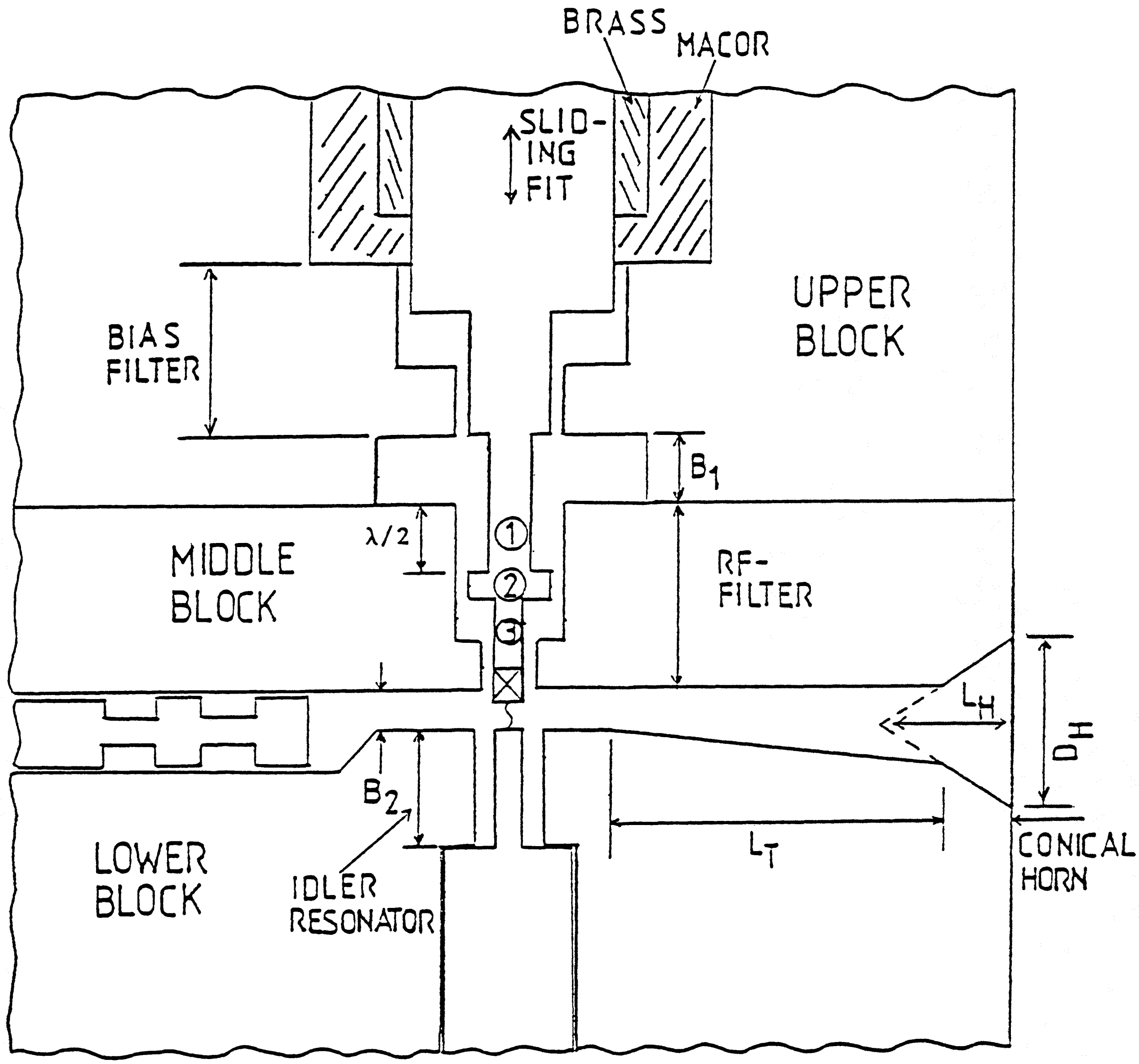

Fig.2 Cross-sectional view of the 750 GHz tripler. (Not to scale). B1=0.091 mm, B2=0.041 mm, $L_H=2\lambda$, $D_H=2.54\lambda$, $L_T=5\lambda$.

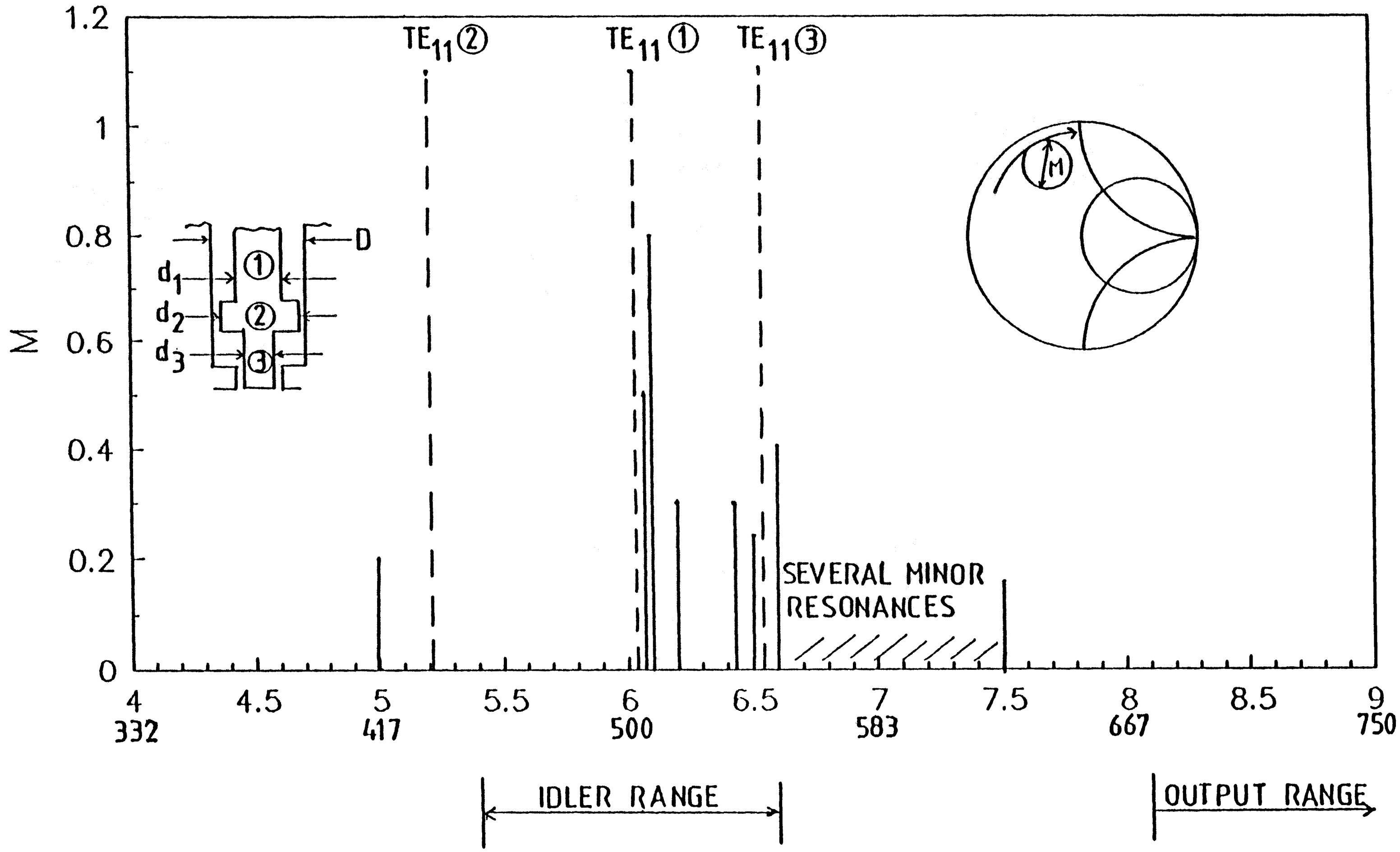

Fig.3 Measured resonances and calculated coaxial TE_{11}-mode cutoff frequencies for the rf-filter as a function of frequency. The measured resonances are plotted as the diameter of the resonance loop "M", see sketch in Fig.3. The maximum value of "M" is 1. The frequency is plotted both as the real and the scaled model frequencies for the multiplier. D=0.25 mm, d_1=0.13 mm, d_2=0.19 mm, d_3=0.1 mm.

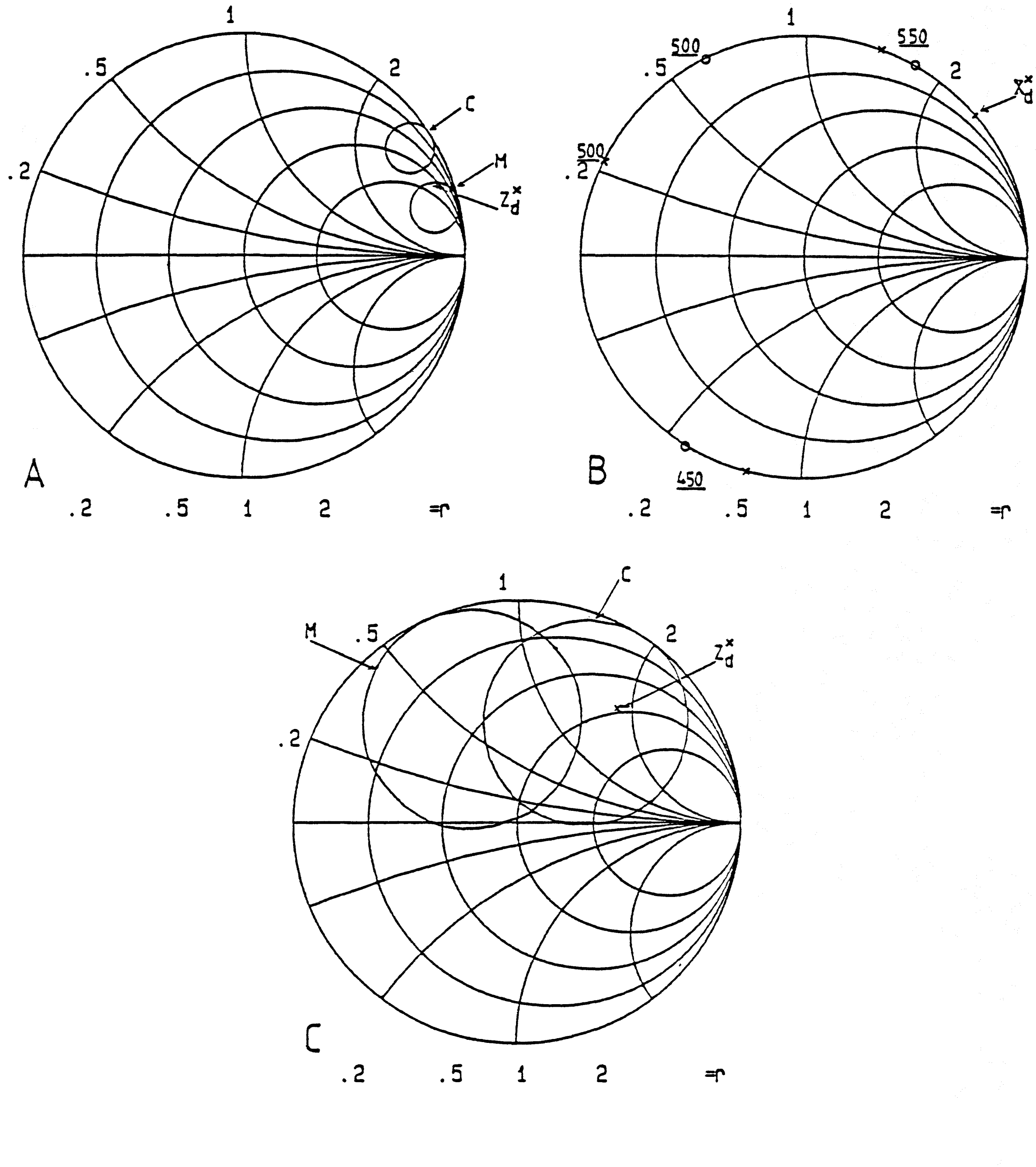

Fig.4 Measured and calculated embedding impedances seen by the diode at the input, idler and output frequencies. Z_d^x and X_d^x are the complex conjugate of the diode impedance and reactance respectively at 250, 500 or 750 GHz. M is measured and C is calculated in the figures, except for the idler where "o" = calculated and "x" is measured.

A: input frequency, 250 GHz.

B: idler frequencies, 450, 500 and 550 GHz.

C: output frequency, 750 GHz.

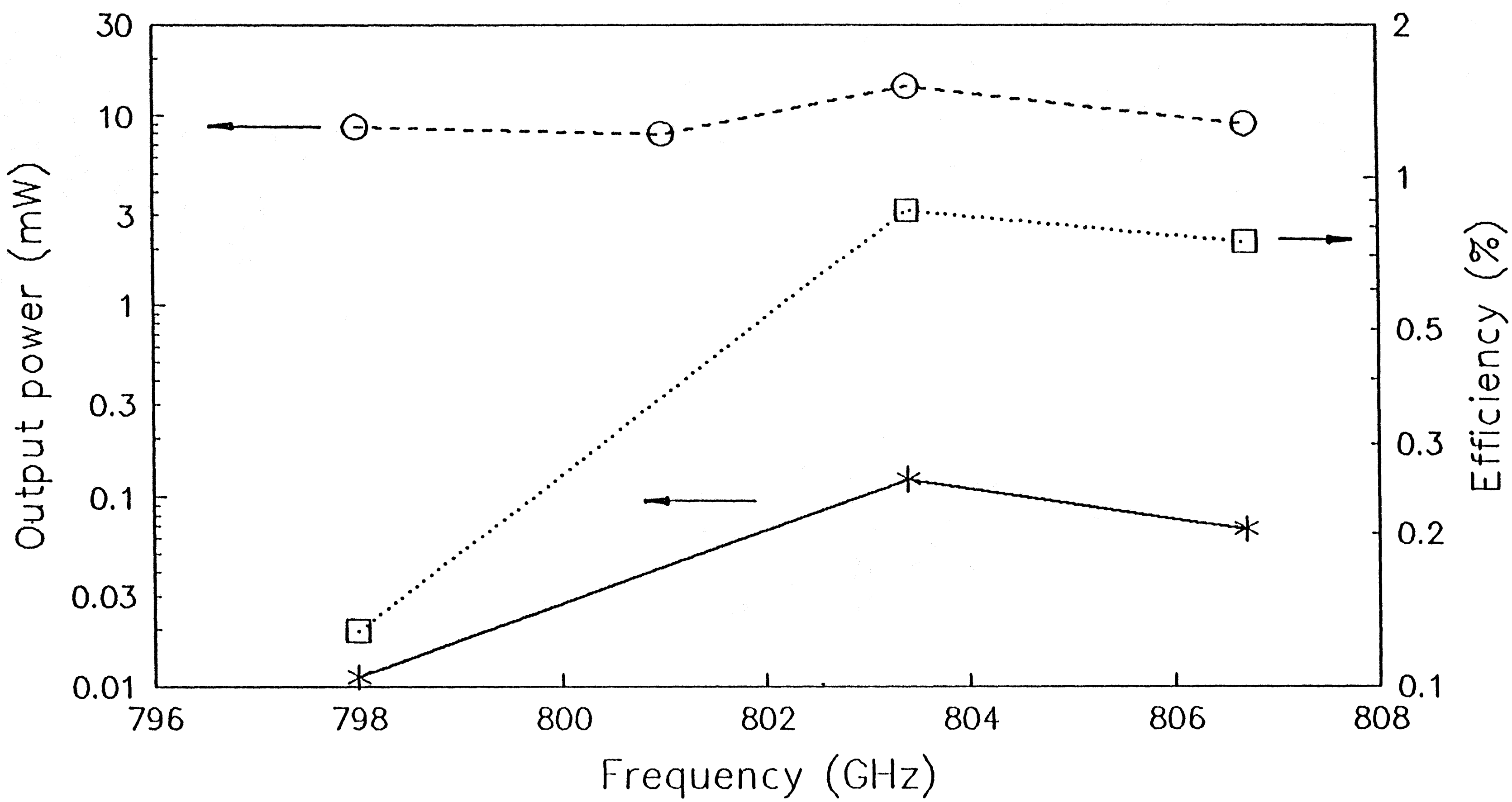

Fig.5 Output power and efficiency for the 750 GHz tripler as a function of the output frequency. The output power for the pump source (carcinotron) is also shown.

(x): output power from the tripler.

(□): efficiency for the tripler.

(o): output power from the carcinotron.

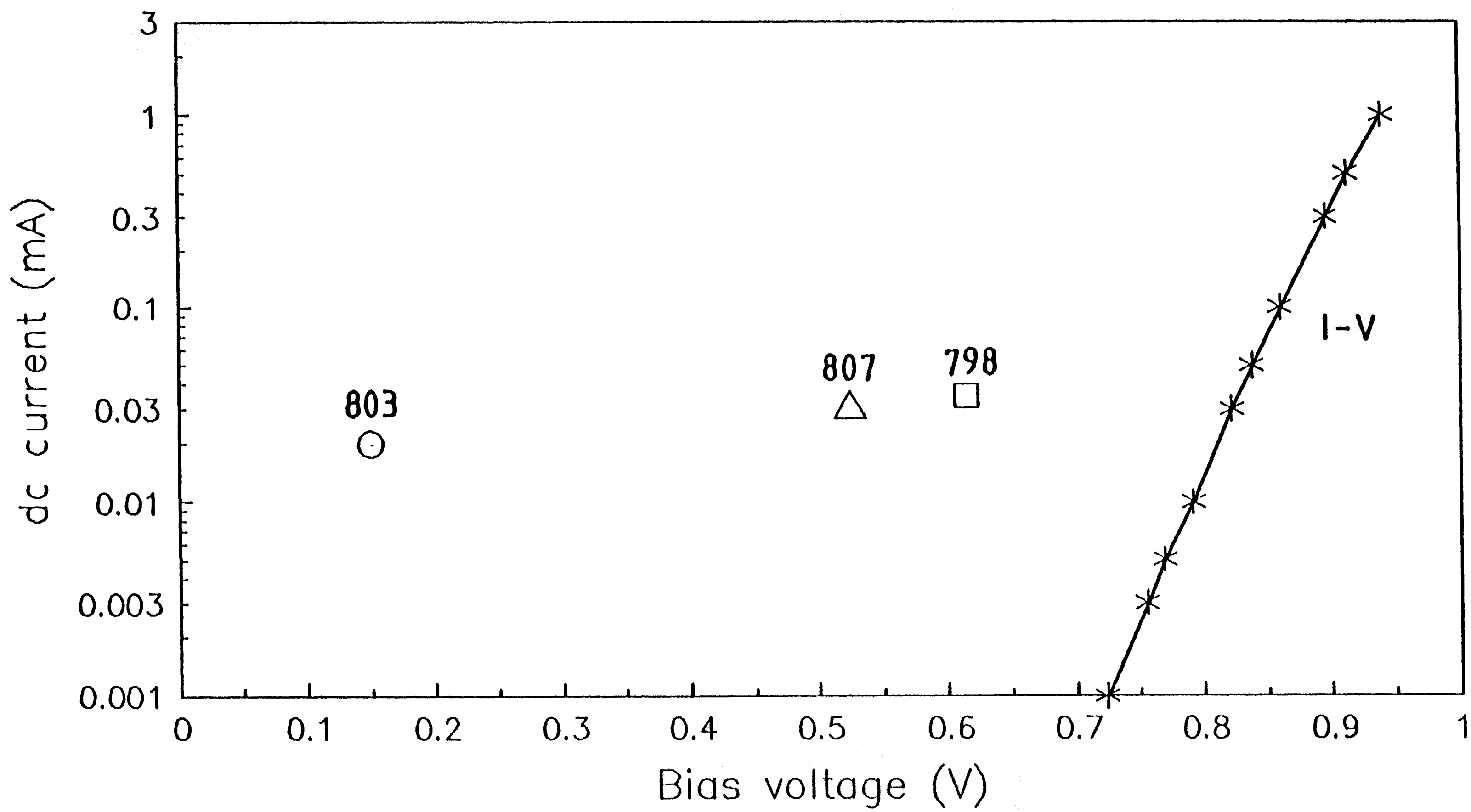

Fig.6 I-V curve and operating points for the 5.4 fF diode. The numbers at the operating points refer to the operating frequency in GHz for the particular operating point.