EXPERIMENTS WITH SINGLE BARRIER VARACTOR TRIPLER AND QUINTUPLER AT MILLIMETER WAVELENGTHS

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Abstract

InGaAs/InAlAs single-barrier varactor diodes were tested as frequency triplers and quintuplers. Two different diodes, one made at MIT Lincoln Laboratory and the other made at the Chalmers University of Technology were tested in crossed-waveguide tripler and quadrupler/quintupler mounts.

In the tripler mount only the Lincoln diode was tested. The highest observed flange-to-flange tripling efficiency was 6.5 % with 2 mW of input power at an output frequency of 116 GHz. The highest measured output power was 200 μW. The experimental results of the tripler are in a close agreement with theoretical simulations which predict 11 % peak efficiency with 2-3 mW of pump power. Beyond the peak the efficiency decreases quickly due to the leakage current.

In the quintupler mount both diodes were tested. The highest measured quintupling efficiency of the Lincoln diode was 0.93 % at 171.5 GHz with input power of 14 mW. The Chalmers diode was able to provide 0.65 % peak efficiency at 172.5 GHz with input power level of 22 mW. The highest observed output power was 137 μW and 150 μW for the Lincoln and Chalmers diode, respectively. The highest efficiency exceeds slightly and the highest output power exceeds by a factor of five the best results reported previously for single-barrier varactor quintuplers.

I INTRODUCTION

At millimeter wavelengths above 100 GHz frequency multipliers have been used extensively in generation of coherent LO power. Most commonly these multipliers are based on the back-biased GaAs Schottky-varactors due to their mature technology. However, recently interest has also grown in novel varactor diodes having symmetric capacitance versus voltage (C-V) characteristic about zero bias. The greatest benefit of the symmetry is the odd-harmonic power generation. This generally simplifies the design of triplers and especially quintuplers or other higher-order harmonic multipliers, because of the reduction in the number of idler circuits.

The devices having symmetric C-V characteristics include diodes such as back-to-back BNN (bbBNN), resonant tunneling diode (RTD) and single-barrier varactor (SBV). Due to its highly nonlinear C-V curve, the single-barrier varactor has been considered as one of the most attractive alternative for conventional Schottky-varactors in higher-order frequency multiplication [1].

In simpliest form, the single-barrier varactor consists of two n-type semiconductor cladding layers separated by an electron barrier layer. The doping profile in the cladding layers is perfectly symmetric about the center of the barrier so that the C-V characteristics is symmetric about zero bias. With cladding layers made of GaAs and the barrier of AlGaAs, single-barrier varactors have been demonstrated as triplers with output between 200 and 300 GHz, yielding a maximum flange-to-flange efficiency of 5 % at 222 GHz [2] and 2 % at 192 GHz [3]. The device in Ref. 2 was also tested as a quintupler at 310 GHz, yielding a maximum efficiency of 0.2 %.

Recently, with InGaAs cladding layers and an InAlAs barrier, single-barrier varactors have been tested as a quintupler with output at 150–190 GHz [4], yielding maximum efficiency of 0.78 % at an output frequency of 172 GHz. The combination of InGaAs/InAlAs materials yields a larger barrier height with less excess conduction current compared to the GaAs/AlGaAs diodes.

In the present work two different InGaAs/InAlAs single-barrier varactors, one made at MIT Lincoln Laboratory and the other made at the Chalmers University of Technology, were examined. These diodes were tested as triplers for 115 GHz and as quintuplers for 170 GHz. In the experiments multiplier blocks originally designed for Schottky-varactors were used [5,6]

II MULTIPLIER DEVICES

Both the Lincoln and Chalmers diodes consisted of an $In_{0.53}Al_{0.47}As$ barrier embedded between n-type $In_{0.53}Ga_{0.47}As$ cladding layers. The epitaxial layers.

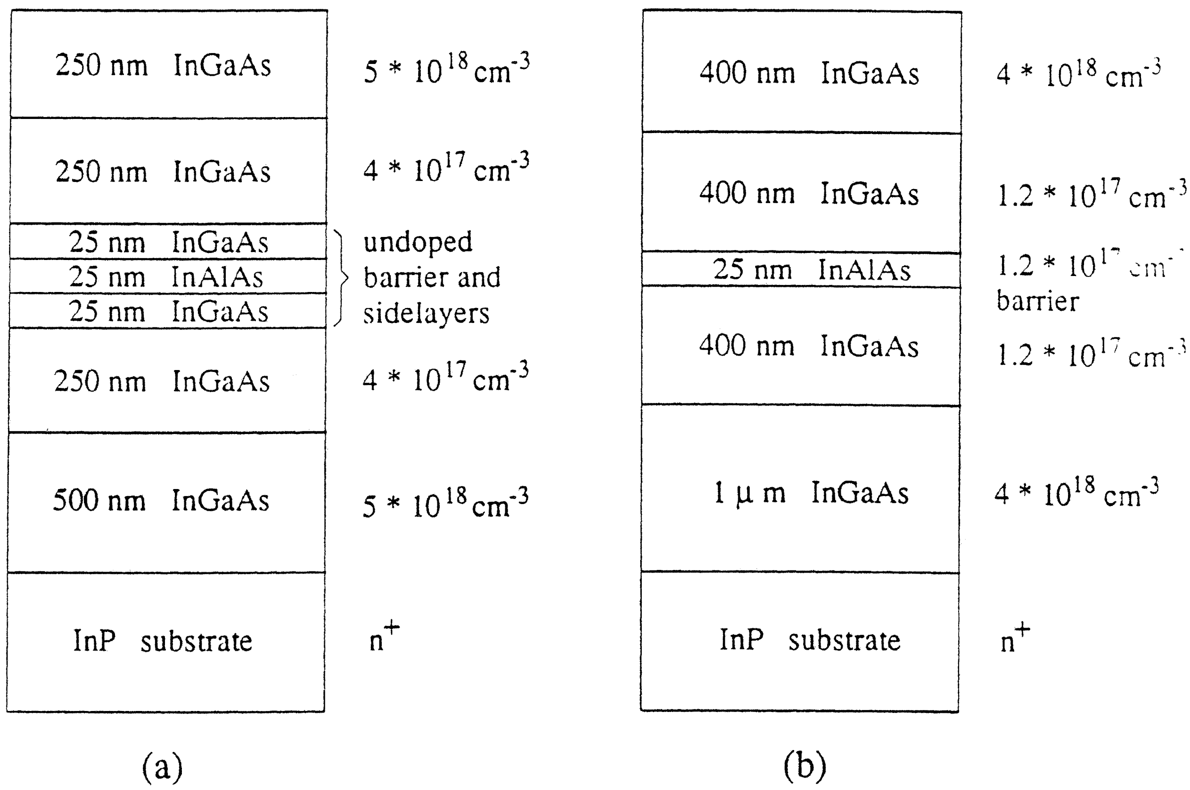

Figure 1. Epitaxial layer structure of the a) Lincoln diode and b) Chalmers diode.

depicted in Fig. 1, were grown by molecular beam epitaxy on an InP substrate.

In order to assist the whisker contacting of mesa diodes, the regions between mesas in the Lincoln diode were filled with Si_3N_4. The same procedure was carried out on the Chalmers diode with photoresist instead of Si_3N_4. The Lincoln and Chalmers diodes have areas of about 16 μm^2 and 30 μm^2, respectively. Figure 2a shows the theoretical and measured C-V characteristics of the Chalmers diode, Figure 2b shows the theoretical curve of the Lincoln diode and Figure 3 shows the measured I-V characteristics of the sample diodes used in these experiments. Note that only the positive half of the antisymmetric I-V curve is presented.

Figure 3 indicates clearly that the leakage current is remarkable especially in the case of the larger-area Chalmers diode. Therefore, the multiplication can be purely reactive only with relatively low input power levels. With higher pump power the multiplication is dominated by the resistive multiplication which results in considerably lower performance.

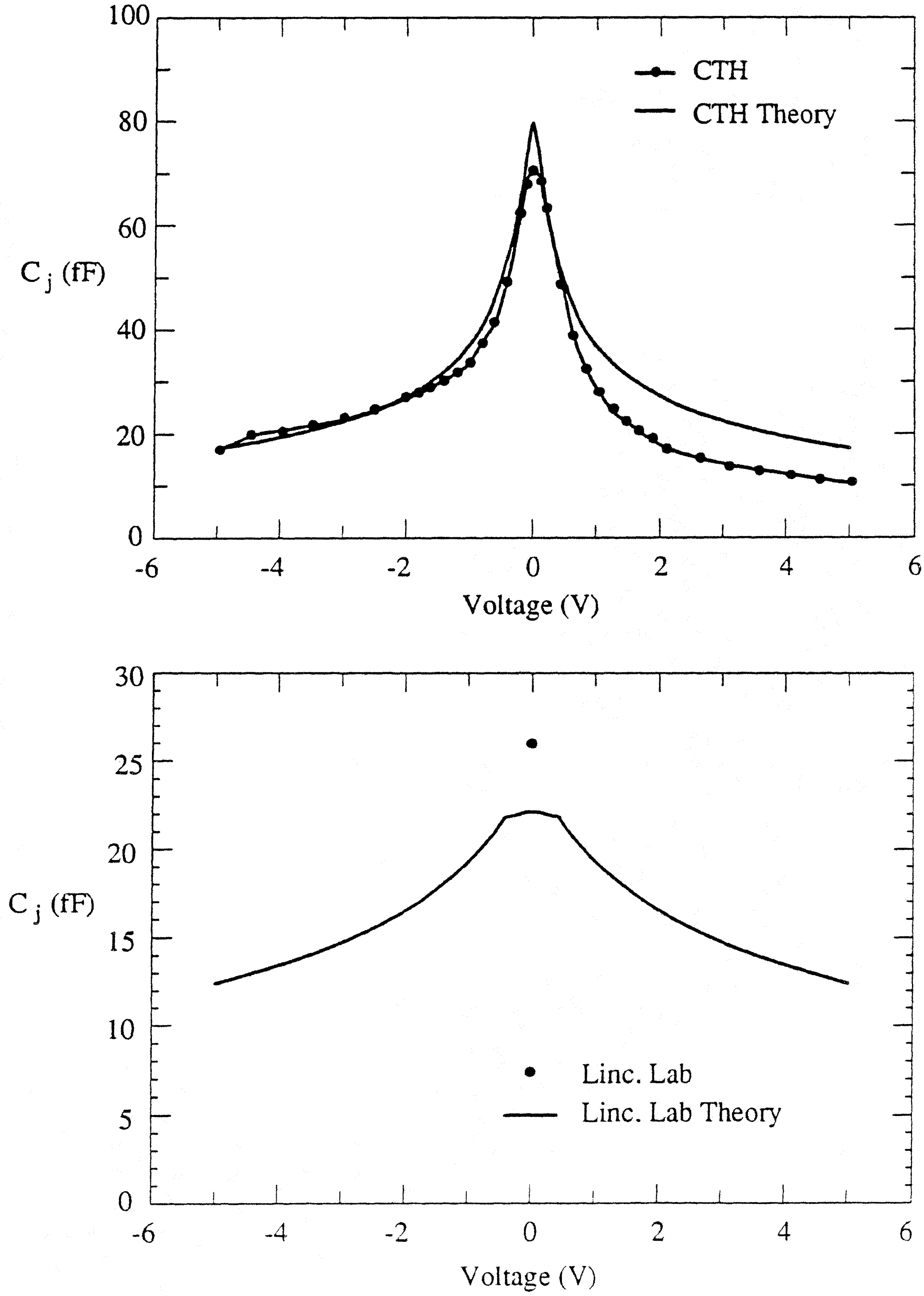

Figure 2. C-V characteristics of the a) Chalmers diode and b) Lincoln diode. Solid line is theoretical and dotted line is measured.

III TEST MOUNTS

The single-barrier varactors were tested in a crossed-waveguide tripler and quadrupler/quintupler structure in which the input and output waveguides are separated by a low-pass filter. The mounts were originally optimized for conventional 5-μm-diameter Schottky-varactors [5,6]. In both mounts input power is coupled in through a half-height WR-22 waveguide and is impedance matched to the coaxial filter using a non-contacting sliding backshort. The diode is soldered to the far end of the filter pin and is located in an output waveguide having non-standard dimensions (1.80×0.45 mm^2) at the diode location. In the quintupler mount this non-standard waveguide also forms an idler cavity which is tuned by a non-contacting sliding backshort. The idler cavity and the output waveguide (WR-4) are coupled through a transition in the waveguide width. In the tripler mount the reduced-height non-standard dimensions are simply tapered in order to form a full-height output waveguide. In both mounts the diode is dc biased through a whisker contact across the output waveguide (or the idler cavity) and through the coaxial filter. More detailed descriptions of both crossed-waveguide mounts including the schematics are given in Refs. 5 and 6.

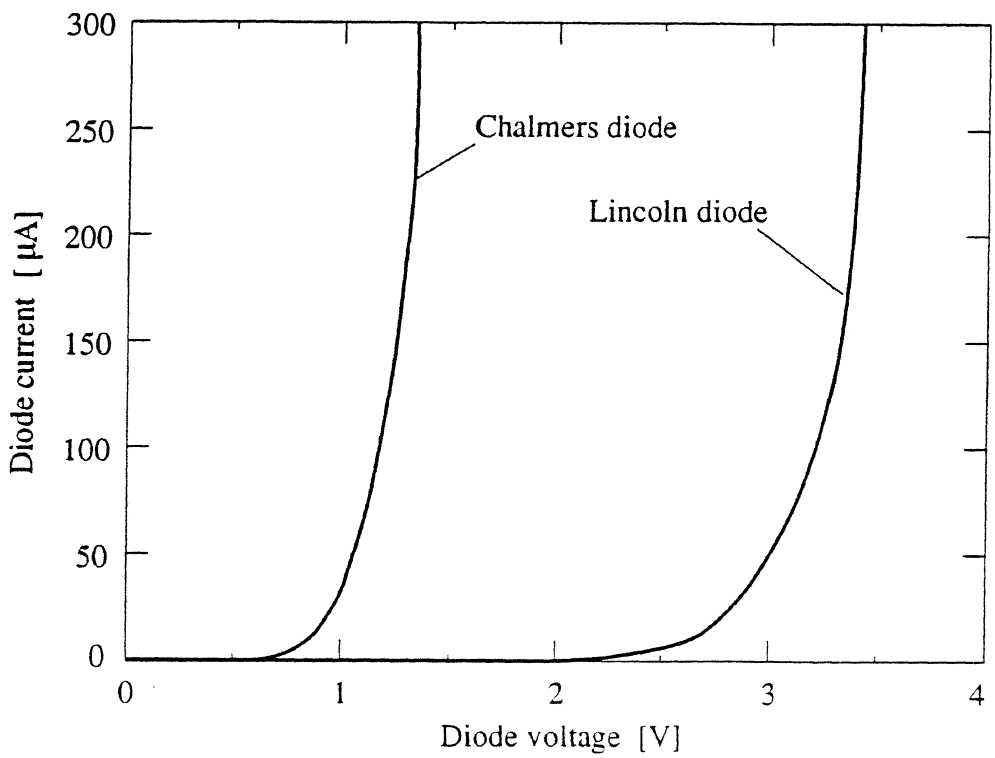

Figure 3. Measured I-V curve of the Chalmers and Lincoln diodes.

IV EXPERIMENTAL RESULTS

In the tripler mount only the Lincoln diode was tested. In the experiments 12.7-μm-diameter whiskers having lengths of 200–400 μm were used. In order to assist the input matching the whisker was soldered at the end of the center pin of a 1.4-mm-long coaxial resonator. The resonator was approximately $\lambda/6$-long at the fundamental frequency. Therefore, it increased the embedding inductance. At the third harmonic the resonator was $\lambda/2$-long and did not have any effect on the embedding impedance.

Figure 4 shows the measured flange-to-flange tripling efficiency versus output frequency at pump power levels of 2.0 and 6.0 mW. The best conversion efficiency was 6.5 % with a pump power of 2 mW at an output frequency of 115.8 GHz. The results shown in Figure 4 were obtained with the whisker length of 250 μm. It was also observed that the output power was saturated to around 200 μW at input power levels of 5–8 mW. With higher input power levels the output power decreased slightly. This phenomenon was caused by the resistive multiplication process due to the leakage current which become dominating at these input power levels.

In the quintupler mount both devices were tested. In these experiments 12.7-μm-

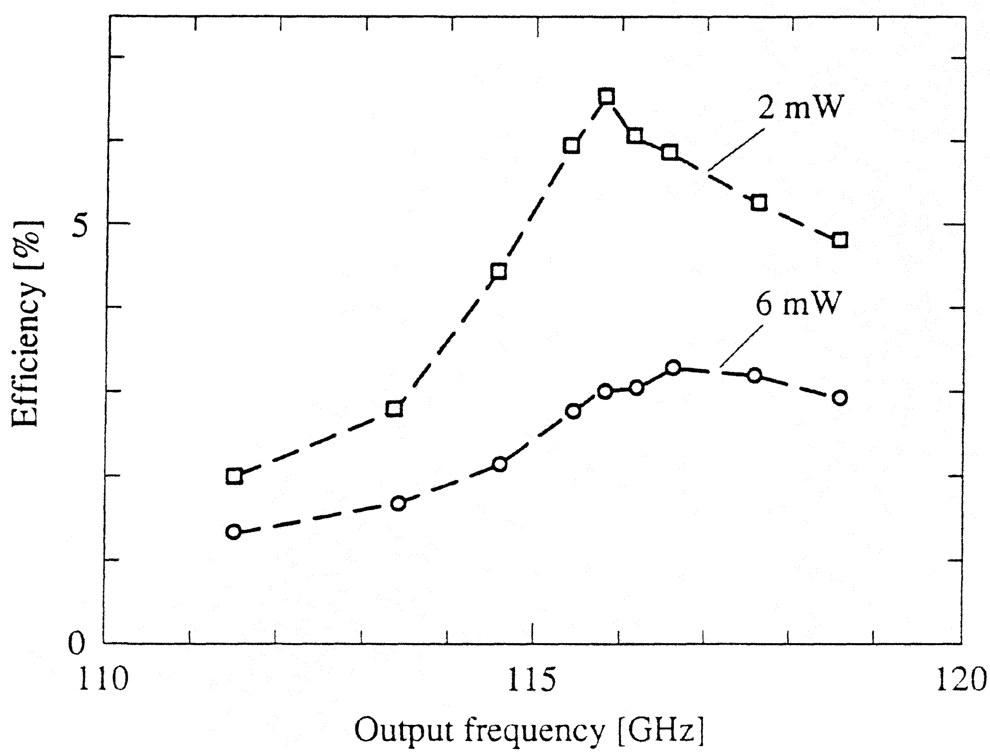

Figure 4. Measured flange-to-flange tripling efficiency versus frequency for the Lincoln diode.

diameter whiskers having lengths of 200–500 μm were used. Also the coaxial-resonator was used in order to assist input matching. In this case, however, the length of the resonator was chosen to be around $\lambda/5$ at the fundamental. This kind of resonator increased highly the fundamental and slightly the idler embedding inductance, but had no effect at the output frequency.

The highest measured quintupling efficiency of the Lincoln diode was 0.93 % at 171.5 GHz with pump power level of 14 mW. In the case of the Chalmers diode the highest efficiency was 0.65 % at 172.5 GHz with input power level of 22 mW. In both cases the whisker length of around 200 μm yielded the best performance. In Figure 5 the quintupling efficiency of both devices is illustrated versus input power level at frequencies where the efficiency peaks. The highest measured output power was 137 μW and 150 μW for the Lincoln and Chalmers diode, respectively.

V DISCUSSION

The performance of the tripler and quintupler was analyzed theoretically at the output frequencies where the peak efficiency was obtained. In the simulations

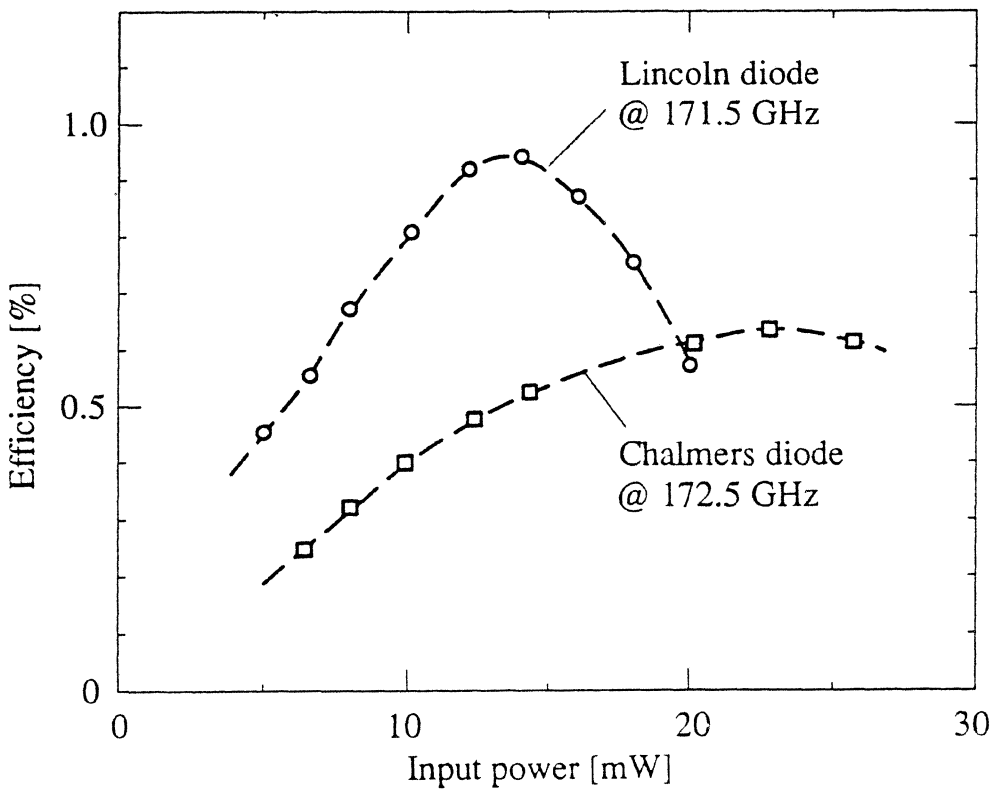

Figure 5. Quintupling efficiency versus input power at frequencies where the peak efficiency was obtained.

measured *I-V* and *C-V* curves (Figs. 2 and 3) of the sample diodes were used. In the case of the Lincoln diode, however, the *C-V* curve was theoretical.

In Figure 6 the theoretical performance of the Lincoln diode as a frequency tripler is presented together with experimental results as a function of input power. The theoretical results indicate that with perfect impedance matching and in the absence of waveguide losses, the tripling efficiency of the Lincoln diode would be about 11 % with 3 mW of pump power. Beyond the peak the efficiency decreases quickly due to the increasing leakage current. The difference between theoretical and experimental curves is around 2.5 dB. Based on earlier experiments with Schottky-varactors the embedding impedances provided by the tripler mount at various frequencies are rather well understood [5]. Therefore, it is belived that the impedance matching at the fundamental and output frequencies was nearly optimum. However, the total ohmic losses of the waveguide mount are estimated to reduce conversion efficiency by around 1.5 dB below the theoretical. Taking losses into account the agreement between theory and experiments is rather good.

It is interesting to compare single-barrier varactor tripler results to those obtained with a conventional Schottky-varactor in the same mount. A VD010 varactor by Farran Technology was able to provide 28 % peak efficiency at 107 GHz with pump power of 5 mW [5]. Also in this case the best results were approximately 2.5–3.0 dB

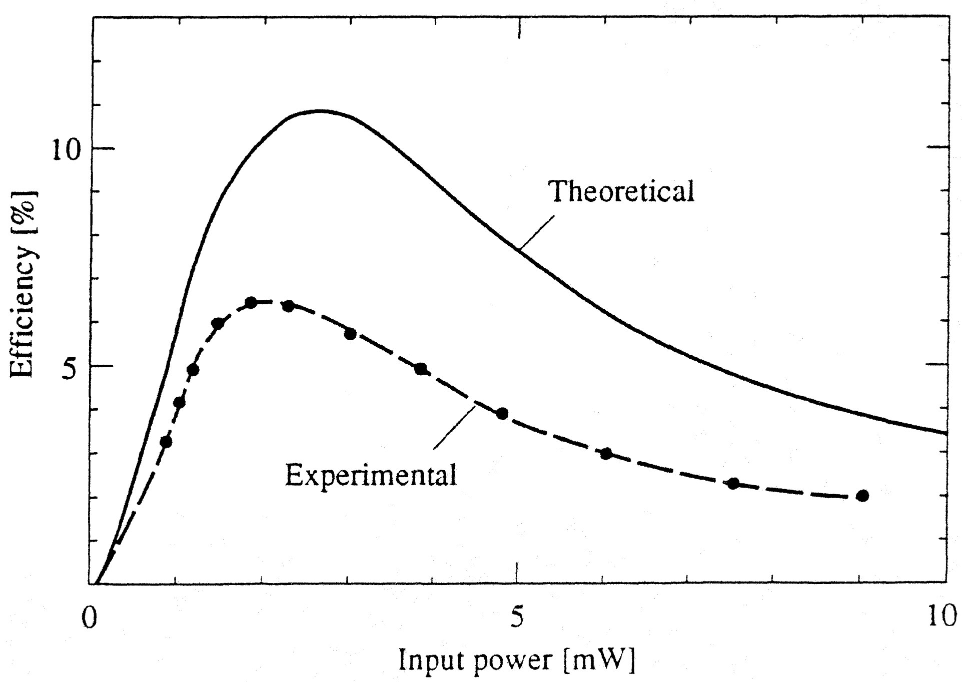

Figure 6. Experimental tripling efficiency of the Lincoln diode in compararison to theoretical performance.

below theoretical values. The peak efficiency of the Schottky-varactor was by a factor of four higher than that obtained with the single-barrier varactor diode. With 30 mW input power the output power of the Schottky-varactor tripler was 3.0–5.6 mW over 15 GHz frequency band and the maximum output power was around 6.5 mW obtained with (safe) input power levels of 40–50 mW. The maximum output power of the single-barrier varactor tripler was 150–200 μW over 5 GHz band obtained with pump power of 5–8 mW. Input power levels higher than 15 mW typically resulted in the diode failure.

In Figure 7 the theoretical performance of the Lincoln diode and Chalmers diode as a quintupler is presented together with experimental results. The theoretical results indicate clearly that the efficiency peaks at 3.7 % for the Lincoln diode and at 2.8 % for the Chalmers diode with input power level of around 3 mW. It is not fully understood why the shape of the experimental curves are completely different at low input power

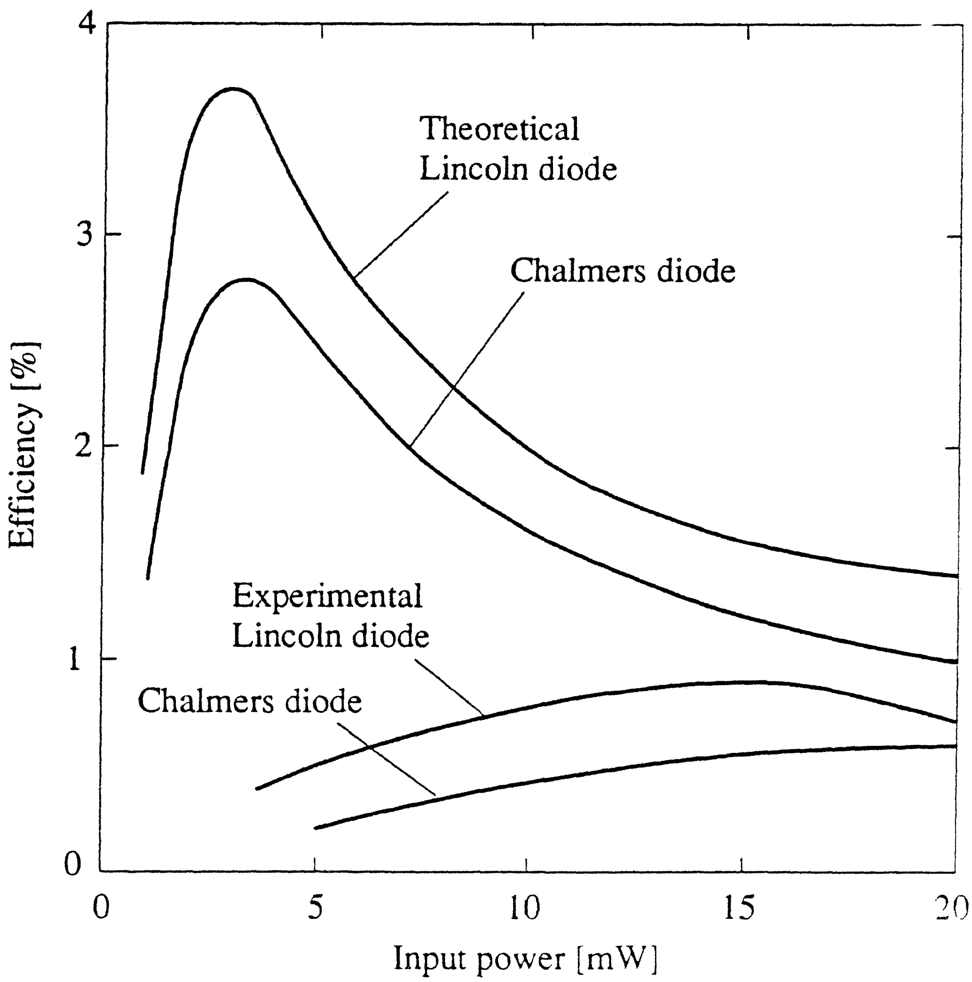

Figure 7. Experimental quintupling efficiency of the Lincoln and Chalmers diodes in compararison to theoretical performance.

levels. However, it is assumed that non-optimized terminations (especially at the idler frequency) results in this shortfall. It is well known that the multiplication efficiency of a varactor diode is critically dependent on the idler termination. The agreement is better at higher input power levels where the multiplication is mostly resistive and less sensitive to variations in the idler termination. At high input power levels the difference can be explained by the ohmic losses in the waveguide mount which are estimated to be around 2–3 dB.

Although the quintupling efficiency of the Lincoln diode exceeds that of the previous GaAs/AlGaAs single-barrier quintupler [2] by nearly a factor of five and that of the InGaAs/InAlAs diode slightly [4], it falls short of the best results for conventional Schottky-varactor quintuplers. In the same mount, a flange-to-flange quintupling efficiency of 4.2 % was measured from VD010 at 168 GHz with 10 mW of pump power [6]. Furthermore, with P_{in} of 40 mW an output power of 1.3 mW was available from VD010 at this same frequency and an output power over 700 μW was measured over the range from 165 GHz to 170 GHz. The single-barrier varactor diodes were able to provide an output power of 100-150 μW over 3–4 GHz frequency band.

VI CONCLUSIONS

A tripler for 115 GHz and a quintupler for 170 GHz with whisker-contacted single-barrier varactor diodes were tested. The highest observed tripling and quintupling efficiencies were 6.5 % and 0.93 %, respectively. These conversion efficiencies should improve considerably with better single-barrier varactor diodes having lower leakage current densities.

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