WATT-LEVEL QUASI-OPTICAL MONOLITHIC FREQUENCY MULTIPLIER DEVELOPMENT

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ABSTRACT

Sources of millimeter wavelength power for heterodyne receiver local oscillator applications conventionally have been expensive and short-lived klystrons, or Gunn devices (both of which are limited to relatively low frequencies). An alternate approach is to use efficient, broad band frequency multipliers in conjunction with more reliable, lower frequency oscillators to provide power. To obtain sufficient power for large receiver arrays we have employed quasi-optical arrays of devices which have been fabricated monolithically. Multipliers devices under investigation include both varactor diodes and negative resistance devices.

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INTRODUCTION

Increased interest in the millimeter region has stimulated the development of receiver technology for a wide range of applications including radio astronomy(1), atmospheric radiometry(2), plasma diagnostics(3), millimeter wave imaging(4), nondestructive testing(5), radar(6), and high density, high directivity communications and data transmission(7).

The realization of a simple tunable local oscillator (LO) source, with adequate output power for use in Schottky diode mixer receiver systems at millimeter wavelengths presents a difficult problem. The traditional choice at longer wavelengths has been the reflex klystron. However, its highest operation frequency is limited to about 220 GHz with less than 10 mW output and it possesses limited tunability. In addition, the cost, today, of a tube, power supply and cooler is about thirty five thousand dollars(8). Conventional high-frequency 0-type carcinotrons or vane type backward-wave oscillators (BWOs) have been successfully developed at frequencies up to 1 THz(9). However, BWOs are noisy and therefore require sophisticated phase lock systems. In addition, they are expensive ($\succ$ \$100 k for tube and high voltage supply), and the lifetime is only about one or two thousand hours. Furthermore, the output power is only about 50 mW at 400 GHz dropping to about 1 mW at 1 THz(9). These problems may be eliminated with the development of planar interdigital slow wave circuit BWOs currently under way at NASA Lewis.

A solid state solution to the LO problem would be highly desirable since it can be expected to be low cost, compact and light weight, and to possess excellent reliability. Since the power of these solid-state sources falls off dramatically at higher frequencies, the combination of a high-power low-frequency source with a harmonic multiplier is an attractive alternative. The use of a frequency multiplier allows one to take advantage of the more favorable characteristics of low frequency sources: lower noise, larger tuning range, lower cost, and improved reliability. Current single Schottky diode multipliers are highly developed, and have achieved impressive conversion efficiency. Considerable effort has been made to combine the output power of these single multipliers.

Although multipliers with one or two diodes have been highly developed, they are basically limited to output power levels of milliwatts at frequencies of $\simeq$ 200 GHz with the power falling off dramatically at 1 THz. However, many applications call for significantly more power. For example, there is currently interest in developing focal-plane imaging arrays for radio astronomy and plasma diagnostics[11]. These arrays might contain from 10-100 Schottky diodes[10], and would require a total local oscillator power ranging from 100 mW to 1 W. Other applications in radar, and high order multiplier chains[12] also require higher power.

The major task of the present work is the development of quasi-optical millimeter-wave monolithic planar multiplier arrays for watt-level frequency multipliers[13,14]. This is an attractive approach to combine the power of each device by using monolithic integrated circuit techniques, thereby resulting in potentially low cost fabrication and small-size realization. Such a circuit has the inherent property of having a large number of identical devices which may then be combined to increase output power. Low-loss quasi-optical structures are used for filtering, matching, and terminating the multiplier circuit, because waveguide, stripline or coaxial structure become lossy and extremely difficult and expensive to fabricate as the frequency is increased beyond 100 GHz. In addition, the quasi-optical structures are eminently suited to LO applications in millimeter and submillimeter systems in which quasi-optical diplexing structures are commonly employed. The resulting array satisfies the need for a compact, low-cost, low-loss local oscillator for large heterodyne detector arrays.

WATT-LEVEL QUASI-OPTICAL MONOLITHIC FREQUENCY MULTIPLIERS

1. Schottky Diode-Grid Doubler Array

Monolithic Schottky diode grids have been fabricated on 4 cm^2 GaAs wafers in a proof-of-principle test of a quasi-optical varactor millimeter wave frequency multiplier array concept[13] (see Figs. 1 and 2). Efficiencies of 9.5% and output power levels of 0.5 W were achieved at 66 GHz when the diode grid was pumped with a pulsed source at 33 GHz. Furthermore, the diode-grid equivalent circuit model based on a transmission line analysis of plane wave illumination has been verified experimentally over a frequency range from 33 GHz to 140 GHz[14]. The equivalent circuit model together with a large-signal multiplier analysis of the nonlinear varactor impedances were used to predict the doubler performance and to facilitate detailed comparison between theory and experiment.

Excellent agreement was found between experiment and theory for a number of diode grids with a ratio of pump to cutoff frequencies ranging from 0.1 to 0.32. The major limitations to the proof-of-principle diode grid arrays were the low diode breakdown voltage ($\approx$ -3 V) and the high diode series resistance (= 25 Ω - 50 Ω). Currently, we are beginning fabrication of Schottky diode doubler arrays with increased voltage and decreased series resistance.

2. Silicon MOS Diode Doubler

In parallel with the GaAs Schottky diode doubler array studies, we investigated the use of a MOS structure having an undoped epitaxial layer, which is grown on a heavily doped substrate and isolated by a thin oxide layer (see Fig. 3). The space-charge-limited current which is injected into the epilayer from the heavily doped substrate produces a step-like capacitance-voltage characteristic resulting in increased harmonic generation efficiency (see Fig. 4). The thin MOS concept was tested by fabricating honeycomb arrays which were mounted in crossed waveguide mounts and whisker contacted. The experimental results show good agreement with the theoretical predictions[15,16] and the large-signal multiplier analysis. A maximum efficiency of 17% was predicted for the $3\mu m$ radius device which is in good agreement with the 14.7% obtained experimentally.

Another important feature of these devices is that, due to the blocking barrier, two diodes can be operated back-to-back generating a sharp spike in the capacitance-voltage curve. The height and width of this capacitance-voltage characteristic can, in principle, be adjusted by doping control alone thus eliminating the need for an external dc bias. This arrangement needs no external ohmic contact resulting in a highly efficient frequency tripler. However, defects in the epitaxial silicon layer deteriorated the thin oxide and limited the yield of the devices making array construction difficult.

3. Barrier-Intrinsic-N^+ Diode-Grid Tripler Array

Device Concept

Recently, a GaAs barrier-intrinsic-N^+ (BIN) diode has been developed[17] as shown in Fig. 5. This structure has an aluminum metal gate in intimate contact with a layered GaAs structure consisting of a 300 Å thickness of undoped GaAs, a 100 Å thickness of $2 \times 10^{18}\, cm^{-3}$ heavily doped n^+ GaAs, another 1000 Å thickness of undoped GaAs, and a 3 μm thick $6 \times 10^{18}\, cm^{-3}$ heavily doped n^+ GaAs region grown on top of a semi-insulating GaAs substrate. The GaAs BIN diode eliminates the problem of low fabrication yield associated with the thin MOS structure and takes advantage of the higher mobility of GaAs. It does not require an insulator layer as in the thin MOS structure, but instead relies on a Mott-type barrier formed between the metal gate and a sheet of positive charge created by a thin (100 Å) heavily doped n^+ region in the GaAs. The 3 μm thick layer is required to reduce the series resistance. The active region is the intrinsic layer between the Mott barrier and the 3 μm heavily doped ($6 \times 10^{18}\, cm^{-3}$) electron injection zone. An intrinsic cut-off frequency of 960 GHz can be achieved. A tripling efficiency of 35% at an output frequency of 100 GHz is predicted (as seen in Fig. 1) [15,16].

In summary, the advantages of the BIN diode over the Schottky diode are seen in (1) the stronger nonlinearity of the C-V curve, which generates harmonics more efficiently (especially the third harmonic without using an idler) and (2) the ability to reach a high capacitance state before forward conduction sets in, making possible the capacitive tripler[18,19].

Metal Grid Design

The metal grid employed for the BIN diode tripler consists of a columnar mesh of aluminum strips with Schottky electrodes on each end as shown in Fig. 6. The period of the grid is chosen to be about half the dielectric wavelength to avoid exciting substrate modes. A reasonable grid inductance is then achieved by choosing a strip width of 20 μm. The small dimension and rectangular shape of the Schottky electrode are designed to minimize the zero-voltage capacitance and series resistance of the device, respectively. This arrangement leads to a high cut-off frequency of the BIN diode. The two neighboring Schottky barrier electrodes are designed to provide the back-to-back configuration for two BIN diodes. The design requires only one metal pattern, which greatly facilitates the case of fabrication.

The initial BIN diode structure was grown with a 1500 Å epitaxial layer using a conservative fabrication design with relatively large dimensions ($\sim 2 \times 5\ \mu m$ diode area). This gives an intrinsic cut-off frequency of $\approx$ 600 GHz. The experimentally measured C-V curve is shown in Fig. 7. Figure 8 shows the symmetric capacitance-voltage characteristic measured from the back-to-back configuration of two BIN diodes. This measurement demonstrates the concept of tripling operation with two back-to-back connected BIN diodes. As can be seen from this figure, the capacitance measured from two diodes under a back-to-back configuration, which is only half of that from a single diode, again, proves the back-to-back configuration employed should result in efficient tripling operation.

Device Performance

A quasi-optical diode-grid tripler coupling and filter circuit design has also been developed as shown in Fig. 9, where power at the fundamental frequency enters from the bottom, through an input tuner. The blazed grating plate (which functions as a high-pass transmission filter) reflects the incident pump power at the fundamental frequency to the diode grid on the left of it, and the metal mirror behind the diode grid again reflects all the harmonics back to the grating plate. Different harmonics are then diffracted in different directions. The third harmonic is designed to exit in the desired direction passing through an output tuner. One should remember that due to the symmetric capacitance-voltage characteristic of two back-to-back connected GaAs BIN diodes, even harmonic currents cancel; therefore even harmonic idler circuits are unnecessary.

It should also be mentioned that the projected cut-off frequency of the experimental device is determined to be 600 GHz with the calculated series resistance of 35 Ω. A maximum tripling efficiency of 24% at an output frequency of 99 GHz is predicted for this GaAs BIN array that has recently been fabricated. Using the quasi-optical diode-grid tripler configuration, watt level output at 99 GHz with an efficiency 8.5% has been experimentally achieved from a total of approximately 6000 BIN diodes on the 15 cm^2 wafer. This experimental measurement is in good agreement with the theoretical prediction.

Large – Signal Multiplier Analysis Results

From the large-signal multiplier analysis study, using the measured capacitance-voltage data of two back-to-back connected BIN diodes, the tripling efficiency versus the input power level at various input frequencies is shown in Fig. 10. Both input and output tuning were optimized at each frequency. As also shown in Fig. 10, the efficiency is highest with low input power levels (5-10 mW). Over the output frequency range of 99-120 GHz, an efficiency greater than 20% is predicted for the GaAs BIN array which has recently been fabricated. The highest efficiency is 24% at 99 GHz obtained with an input power of 9.0 mW, which shows excellent agreement with the theoretical predictions[15,16].

Substantial improvements are possible for the performance of the BIN diode. Figure 11 shows the simulated tripling efficiency results as a function of the series resistance. The input and output impedances are the optimized values. The simulated results are in excellent agreement with the theoretical values predicted in standard references[15,16]. The simulation predicts 35% tripling efficiency for $R_a = 15\ \Omega$.

SUMMARY AND CONCLUSIONS

The submillimeter or terahertz wavelength region (300 GHz to 3 THz) is one of the last major windows in the electromagnetic spectrum to be explored. Its major application has been scientific research including astrophysics, atmospheric physics, plasma diagnostics,and laboratory spectroscopy. More recently, space-based radar and communications systems are emploring this spectral range to combine the frequency resolution and agility available in the microwave regime with the high spatial resolution of modest apertures typical of optical technology. Various methods have been proposed for generating submillimeter wave radiation using solid-state devices. The most probable solution, however, will be based on harmonic multiplication of lower frequency solid-state sources. This is due to the fact that the technology for both the low-frequency fundamental sources as well as that of frequency multipliers are fairly mature. Arrays of devices to increase power handling are also required to increase power. Quasi-optical monolithic solid-state diode-grid frequency multipliers are, therefore, highly desirable for generating submillimeter or terahertz wavelength radiation. Based on the studies of watt-level solid-state frequency multiplier arrays, prospectives of two-stage monolithic frequency tripler arrays are shown in Fig. 11 for obtaining watt-level submillimeter or Terahertz wavelength power.

ACKNOWLEDGMENTS

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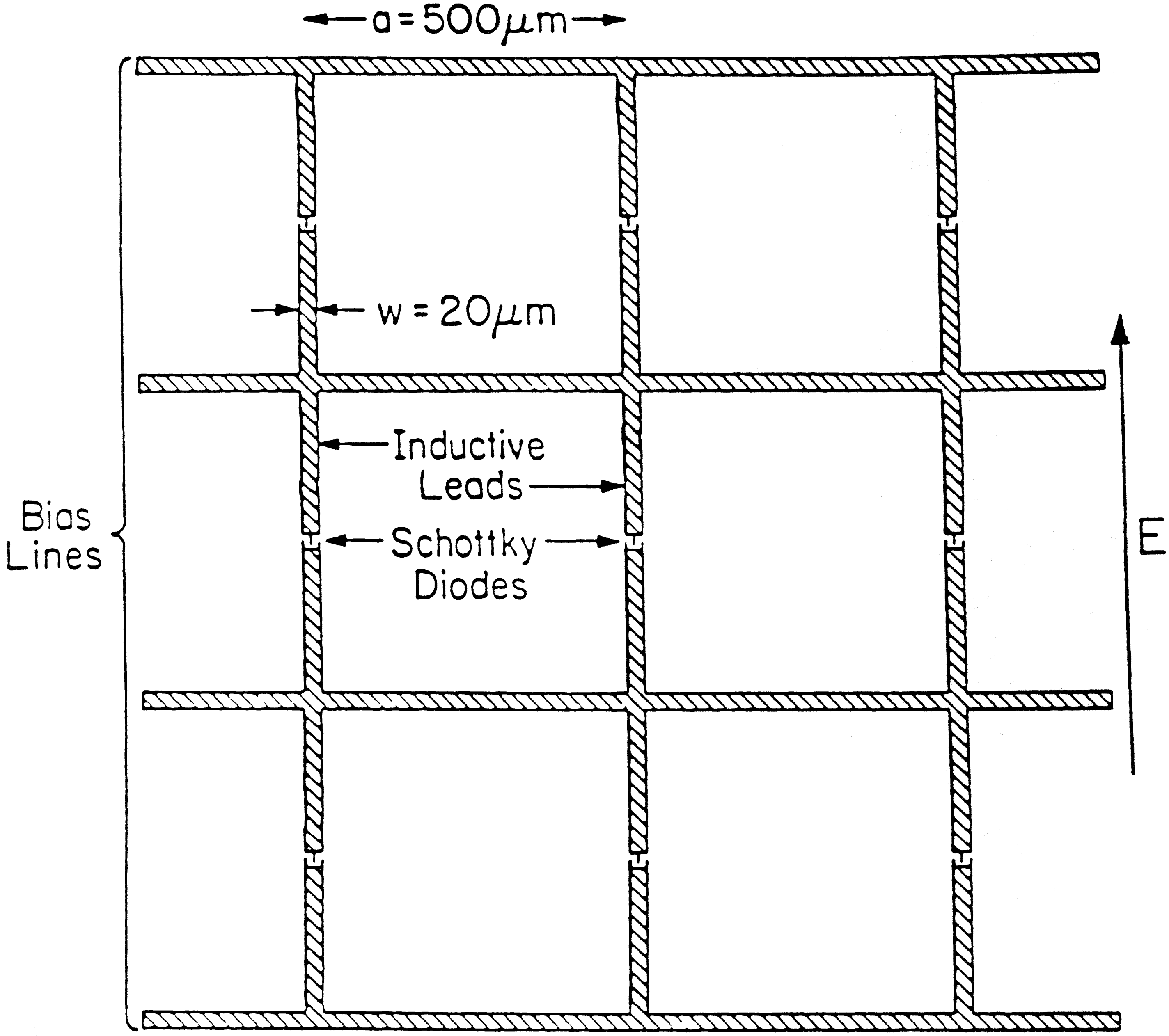

Figure 1. Metal grid design for Schottky diode doubler.

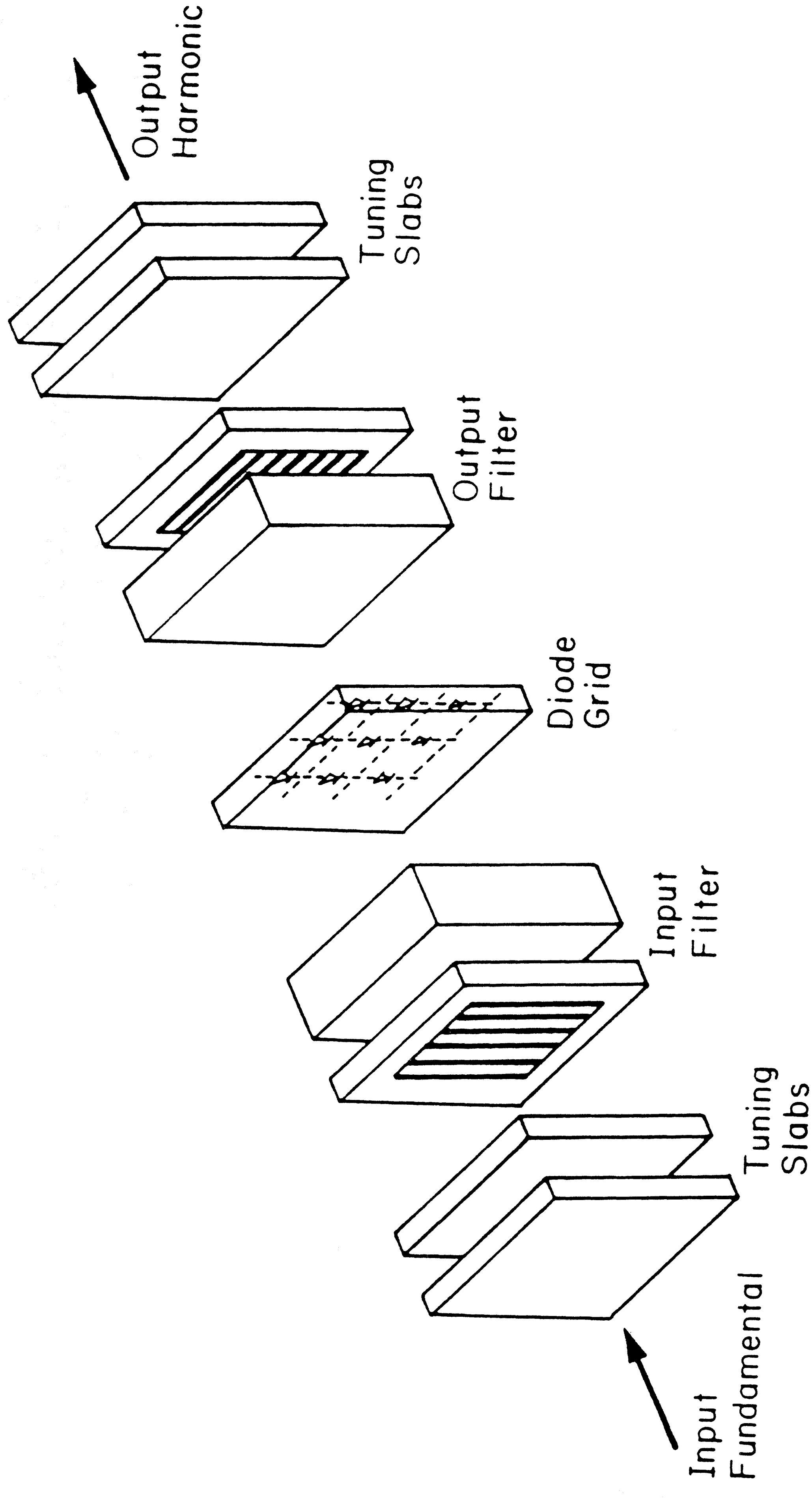

Figure 2. Quasi-optical diode-grid doubler configuration.

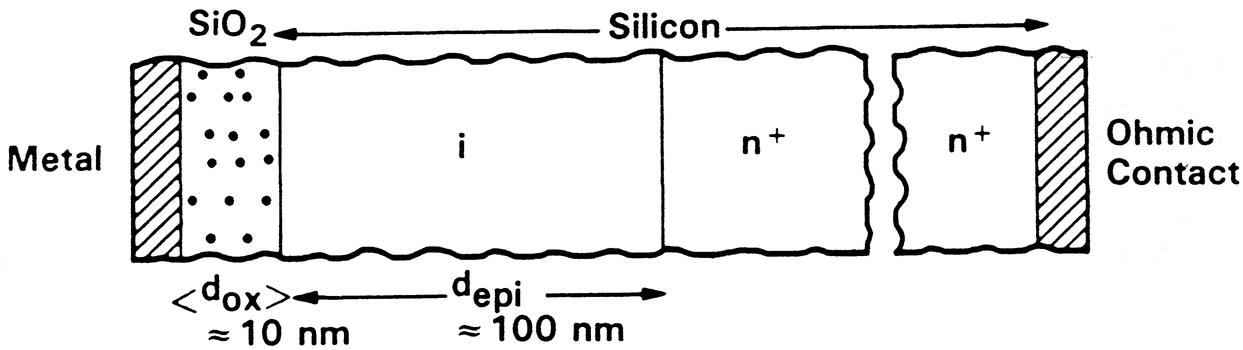

Figure 3. Structure of the thin MOS diode.

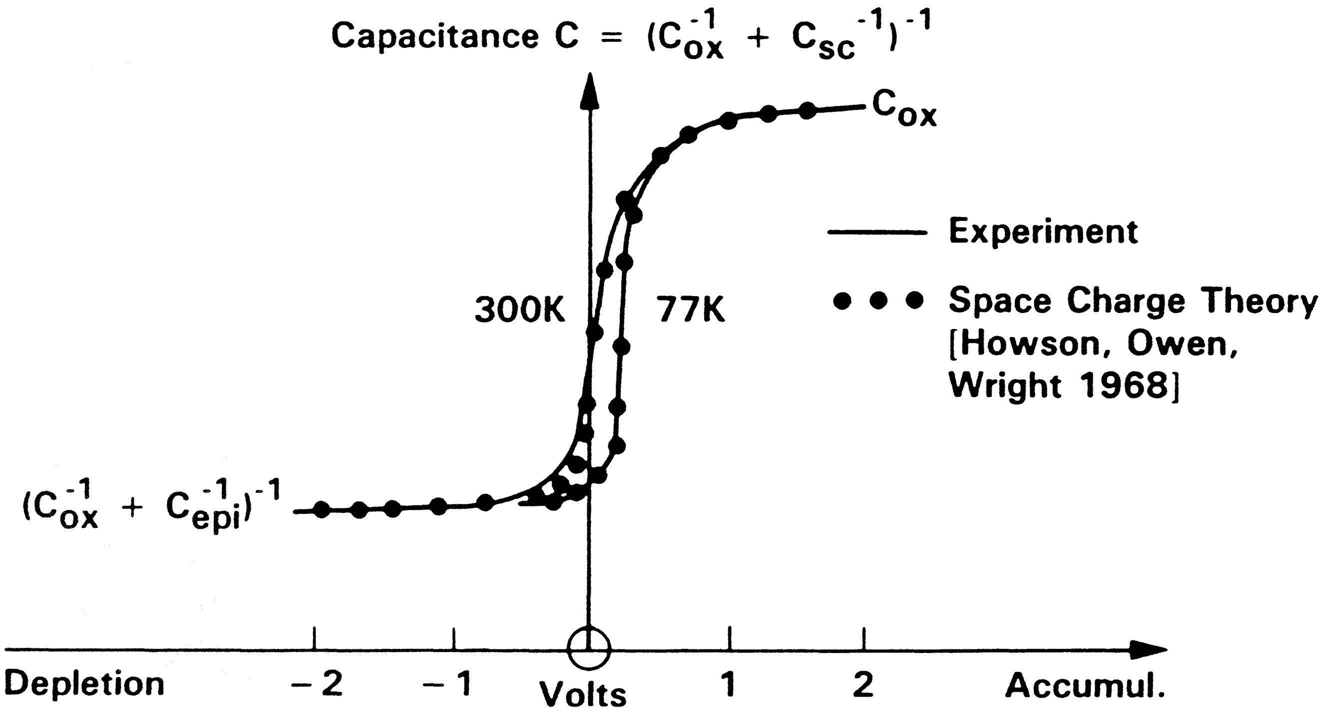

Figure 4. Capacitance-voltage characteristic from the thin MOS diode.

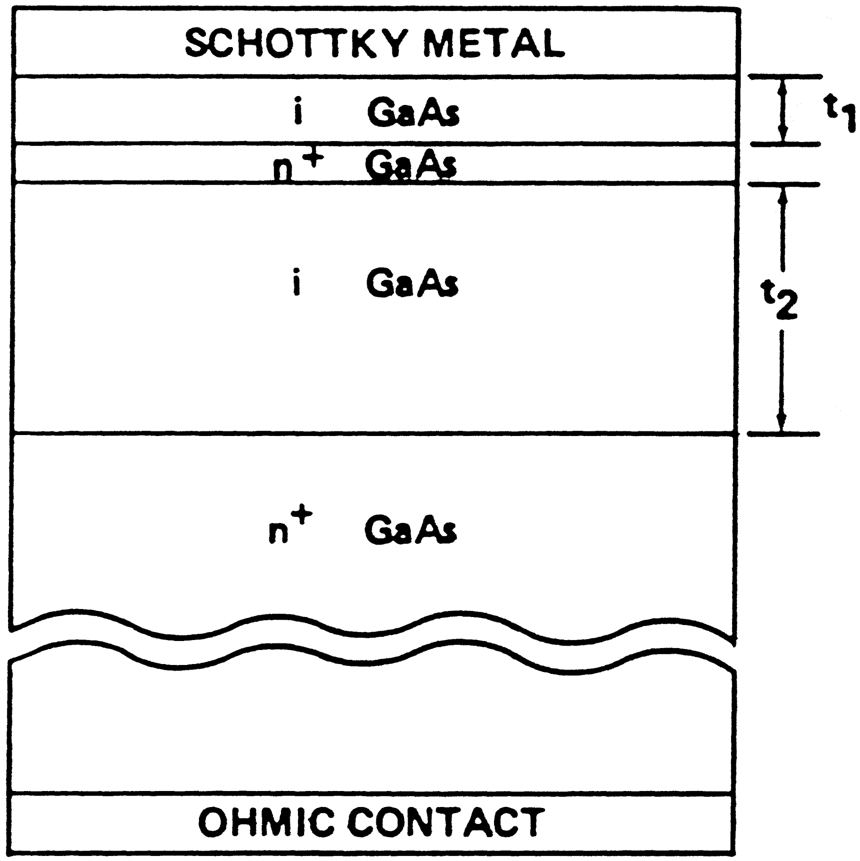

Figure 5. Structure of the GaAs BIN diode.

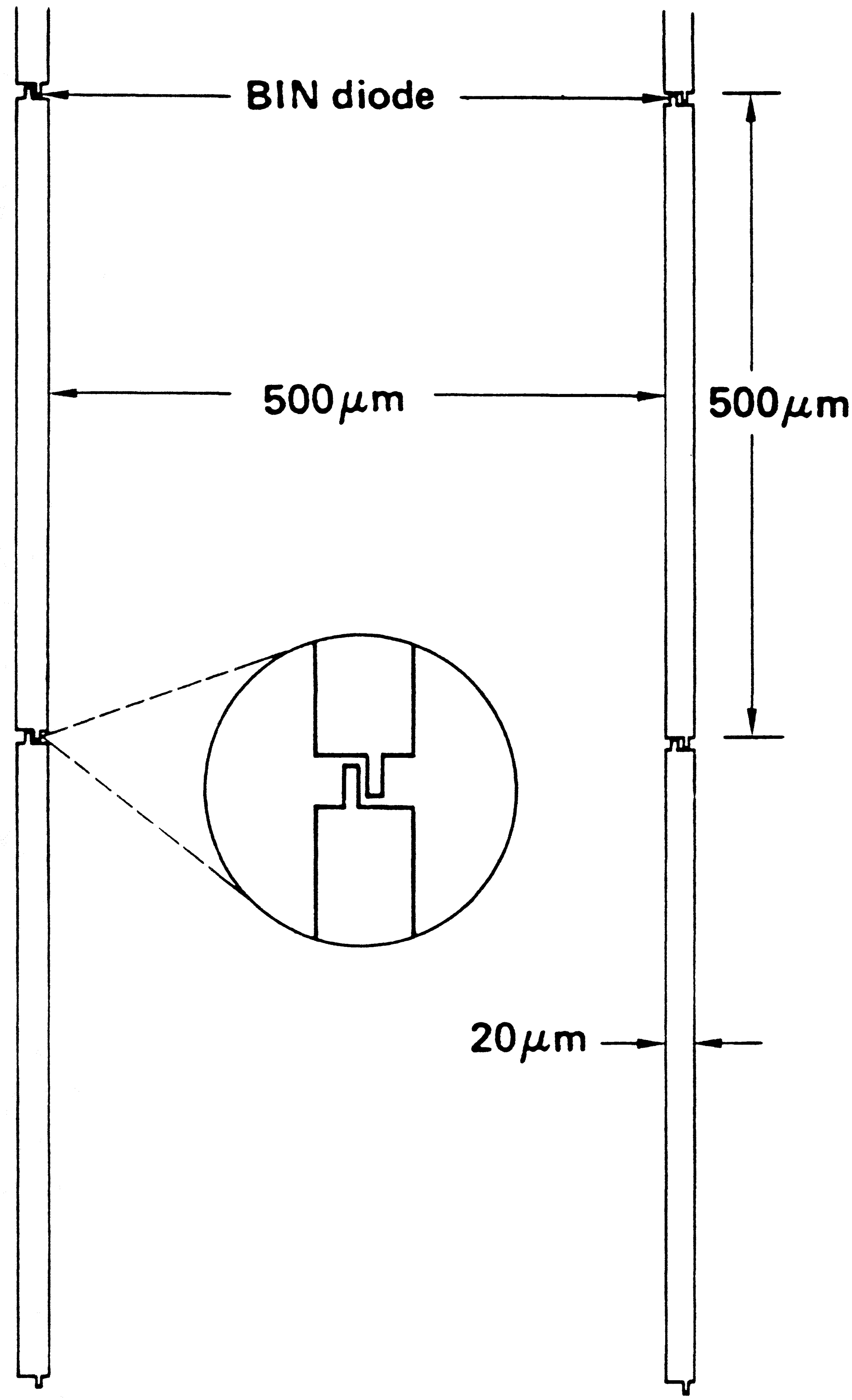

Figure 6. Metal grid design for BIN diode tripler.

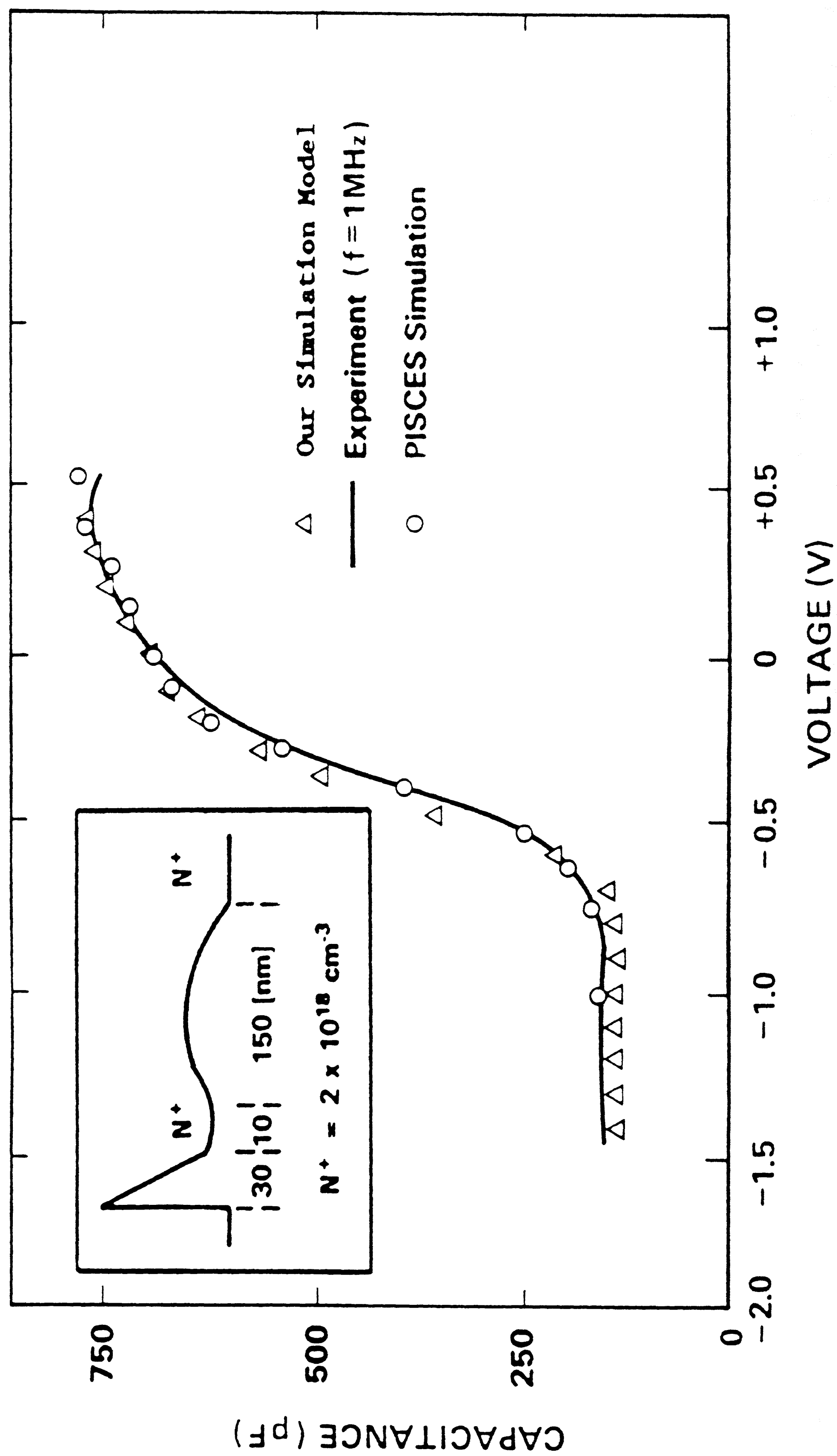

Figure 7. Capacitance-voltage characteristic from the GaAs BIN diode.

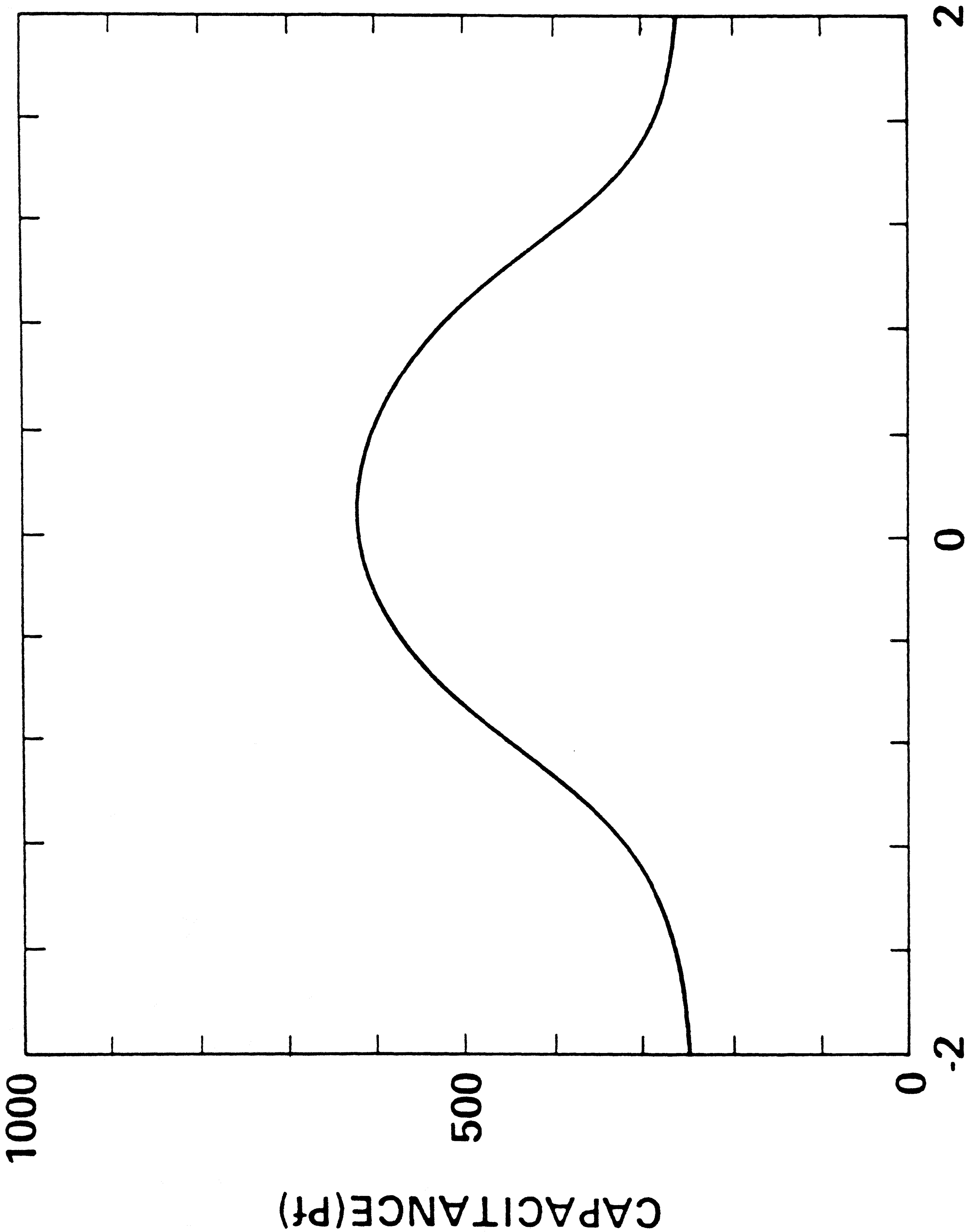

Figure 8. Symmetrical capacitance-voltage characteristic from two back-to-back connected BIN diodes.

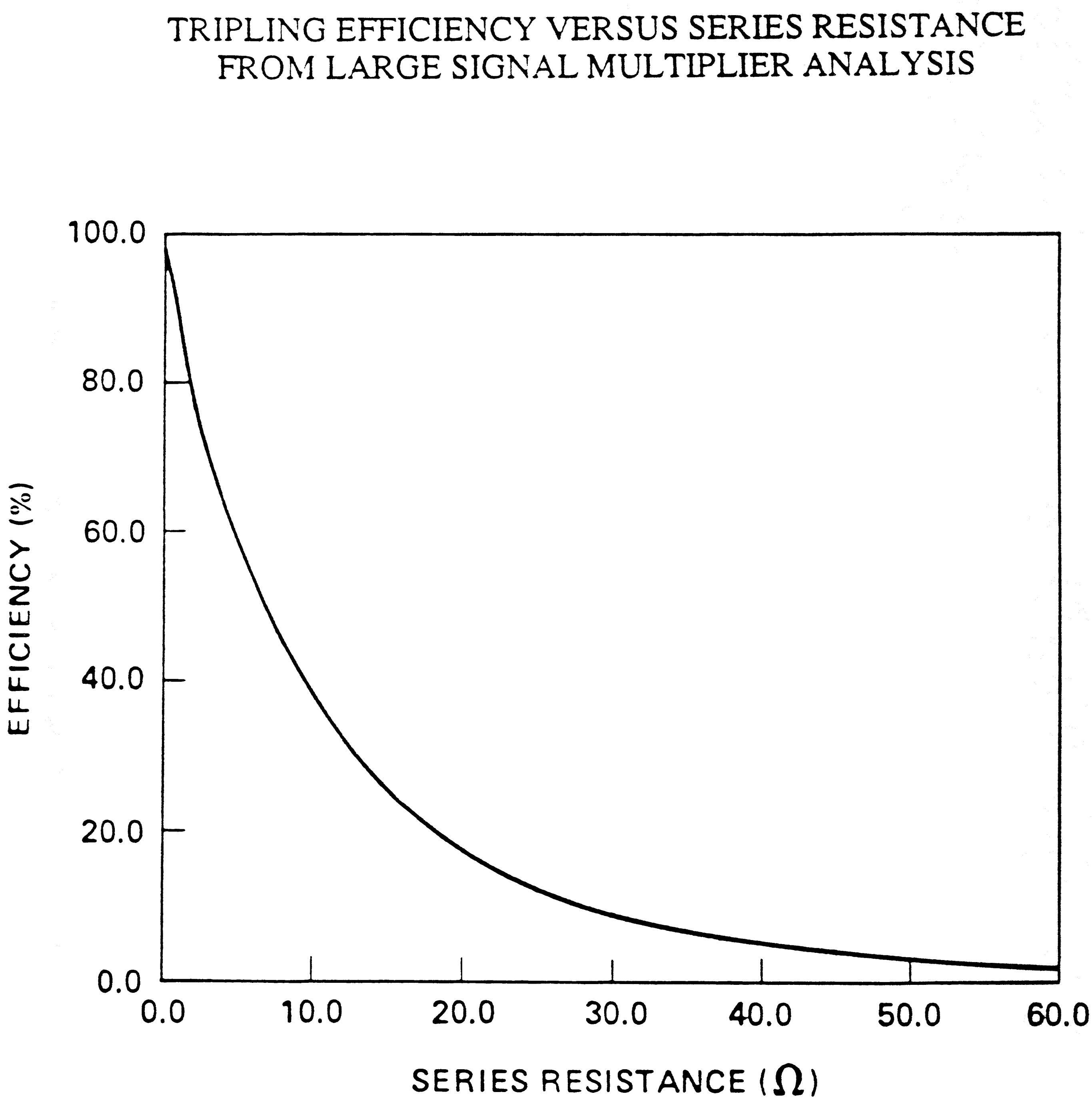

Figure 11. Two-stage frequency tripler for submillimeter and Terahertz wave generation.

back connected BIN diodes.

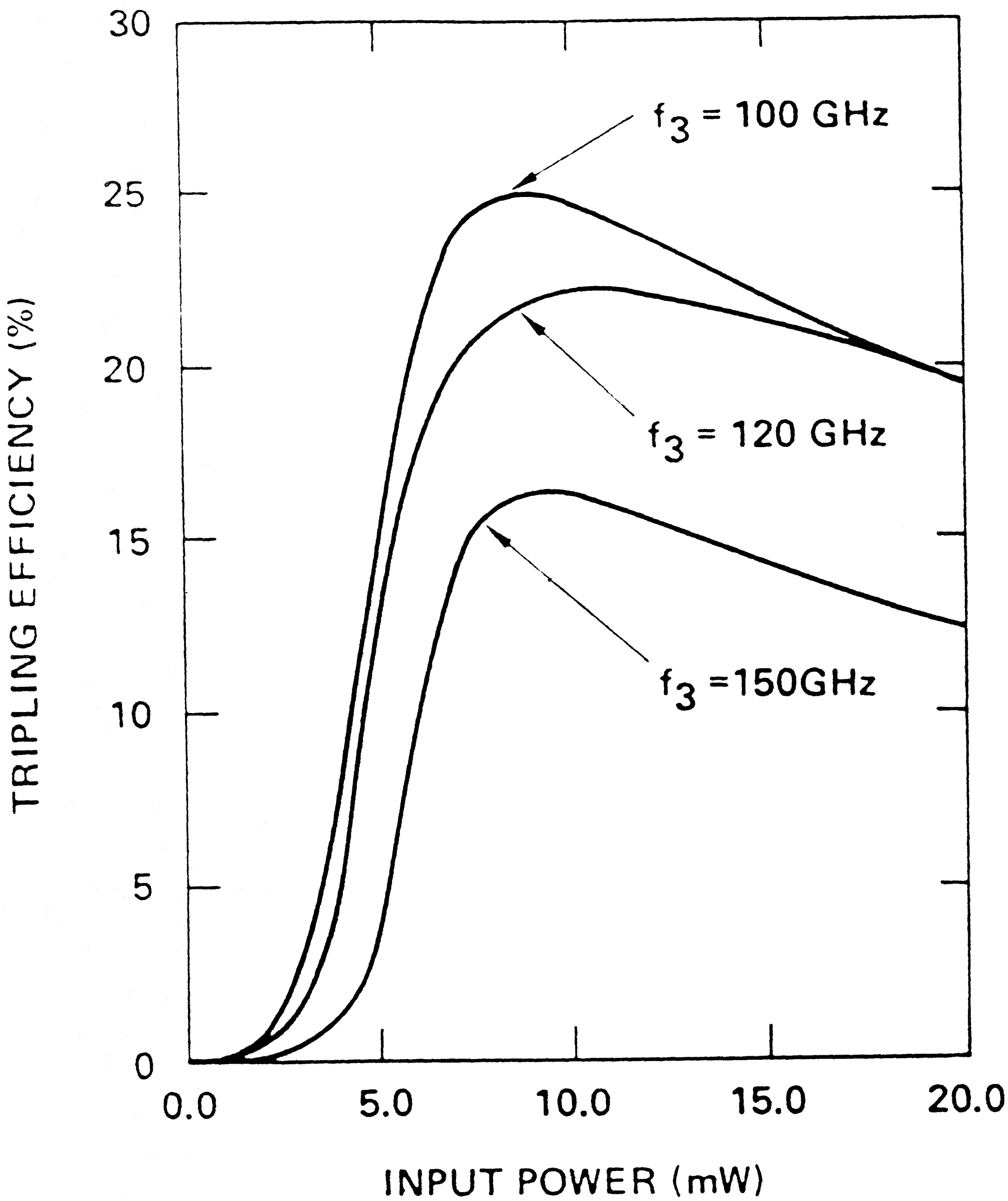

Figure 10. Tripling efficiency versus input power at different output frequencies.

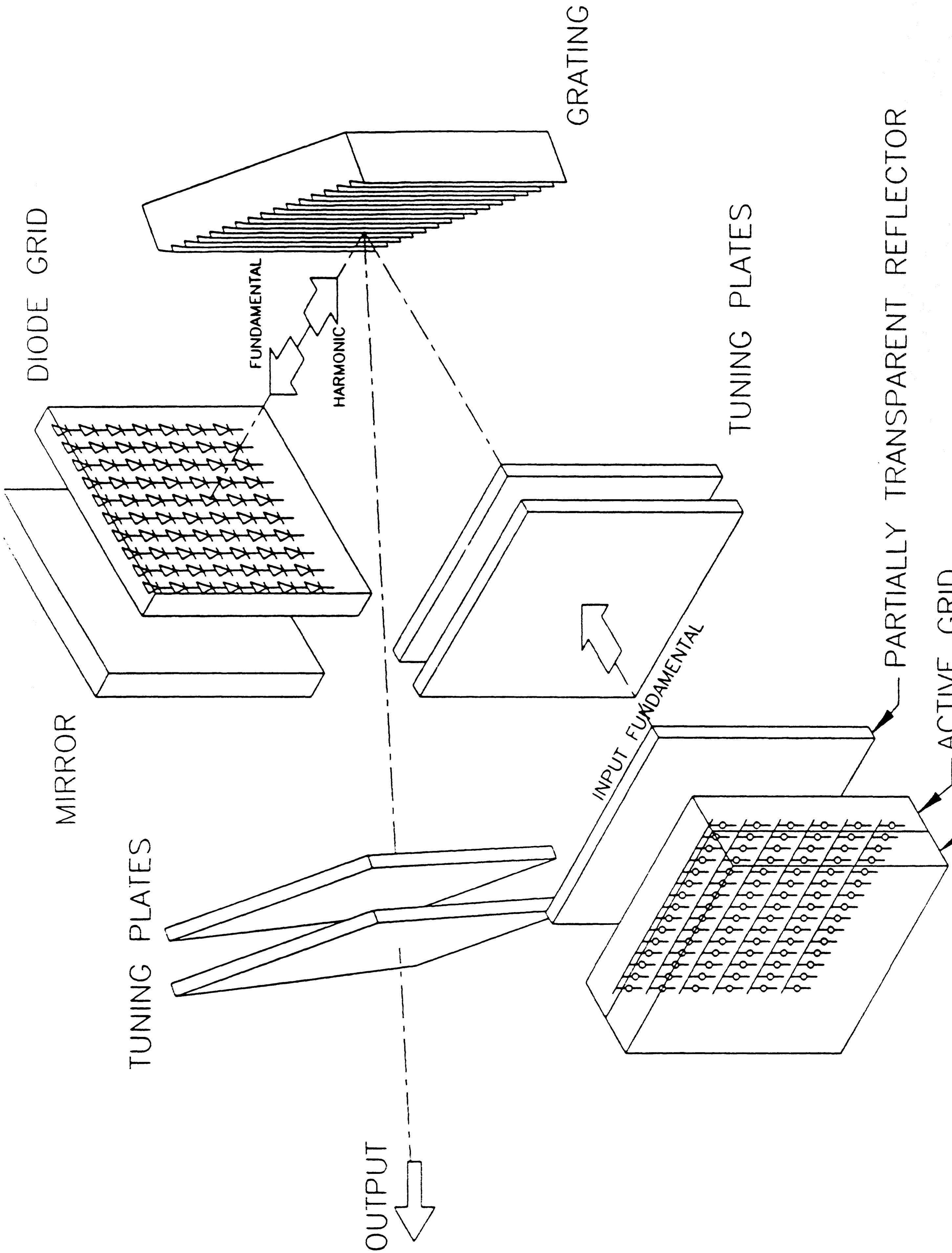

Figure 9. Quasi-optical diode-grid tripler configuration.