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Highly Efficient Frequency Triplers in the Millimeter Wave Region-Incorporating A Back-to-Back Configuration of Two Varactor Diodes

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ABSTRACT

This paper reports on the recent development of monolithic frequency tripler array employing a back-to-back configuration of varactor diodes. Even harmonic idler circuits are unnecessary in this design. Furthermore, no external dc bias is required. The arrangement results in highly efficient, easily-fabricated and inexpensive frequency triplers.

INTRODUCTION

Conventional sources of millimeter wavelength power for heterodyne receiver local oscillator applications are expensive and short-lived klystrons or Gunn devices which provide limited power at frequencies beyond ~ 90-120 GHz. An alternate approach is to use efficient, broad band frequency multipliers in conjunction with more reliable, lower frequency oscillators to provide power [1-3]. This paper reports the development of highly efficient frequency triplers which employ a back-to-back configuration of two varactor diodes. By monolithically fabricating large arrays of diode pairs, watt-level output powers may be obtained.

VARACTOR DIODE FREQUENCY TRIPLER

The varactor diodes we use incorporate an ultrathin electron-blocking barrier layer [4]. This blocking layer can be formed by an insulator, a semiconductor with a very wide band gap, or a Mott barrier. Therefore, the device can be switched rapidly between two capacitance states which correspond to accumulation of electrons at the barrier and depletion of the epilayer by the applied bias. This results in a highly nonlinear capacitance-voltage characteristic that is needed for efficient harmonic generation.

Due to the blocking barrier of the structure, two diodes can be operated back-to-back generating a sharp symmetric spike in the capacitance-voltage curve, which eliminates even harmonics and thus favors tripler operation. The symmetric capacitance-voltage curve experimentally observed from two diodes connected back-to-back demonstrates the concept of the back-to-back operation. The height and width of this capacitance-voltage curve can be adjusted by doping control alone. This arrangement needs no external ohmic contact and no even harmonic idler circuits resulting in highly efficient, easily fabricated and inexpensive frequency triplers.

In the past, we have proven the feasibility of near-millimeter wave operation with a silicon MOS diode used in a waveguide/whisker configuration as a frequency doubler [4]. This diode (Fig. 1) had an intrinsic cut-off frequency of 320 GHz. The capacitance-voltage characteristic is shown in Fig. 2. A maximum efficiency of 15% was experimentally obtained at 95 GHz which is in good agreement with the theoretical predictions [5,6].

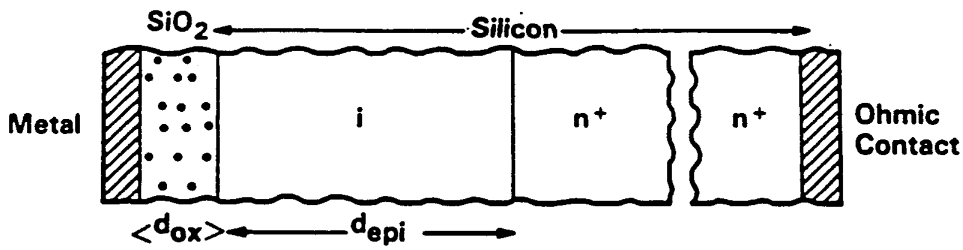

Fig. 1 Structure of the Si MOS diode.

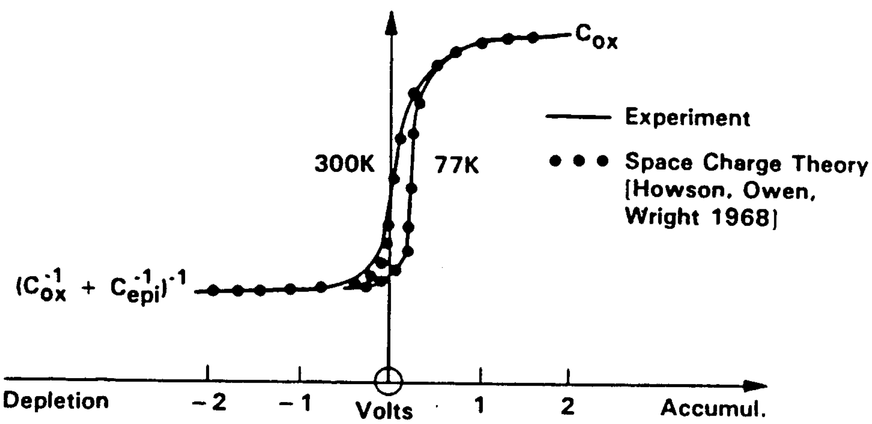

Fig. 2 Capacitance-voltage characteristic of the Si MOS diode.

Recently, a novel concept which allows the construction of a Barrier-Intrinsic-N^+ (BIN) diode on III-V compound semiconductor material entirely by selective doping during MBE growth (Fig. 3) has been described by us [4]. A Mott-barrier is formed by a thin intrinsic layer sandwiched between the top metal contact and a charge sheet created by selective doping. GaAs and InP are superior to Si (as used in the earlier studies) due to the higher mobility and maximum velocity which will reduce the transit time and render negligible the parasitic resistance of the back contact.

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 triple of the pump frequency) and (2) the ability to reach a high capacitance state before forward conduction sets in, making possible the capacitive tripler. As the steepness of the transition between the capacitance states increases with lower temperature, cooling will improve the efficiency of the frequency multiplication.

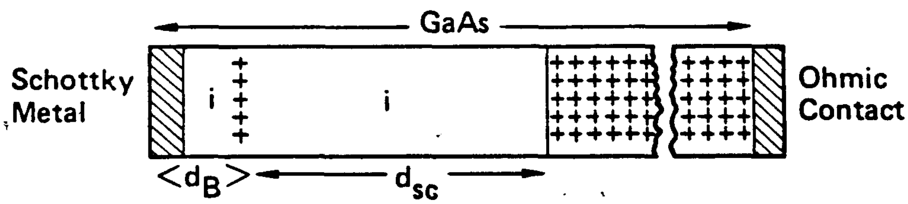

Fig. 3 Structure of the GaAs BIN diode.

The initial proof-of-principle BIN diode structure was grown on GaAs substrate with a 1500 Å epitaxial layer from a conservative fabrication design. This gives an intrinsic cut-off frequency of 640 GHz. The experimentally measured C-V curve is shown in Fig. 4. Projected improvement of the device performance can be obtained with realizable diode parameters by advanced design and improved fabrication technique. For example, a GaAs BIN diode structure with a 1000 Å thick epitaxial layer has an intrinsic cut-off frequency of 960 GHz.

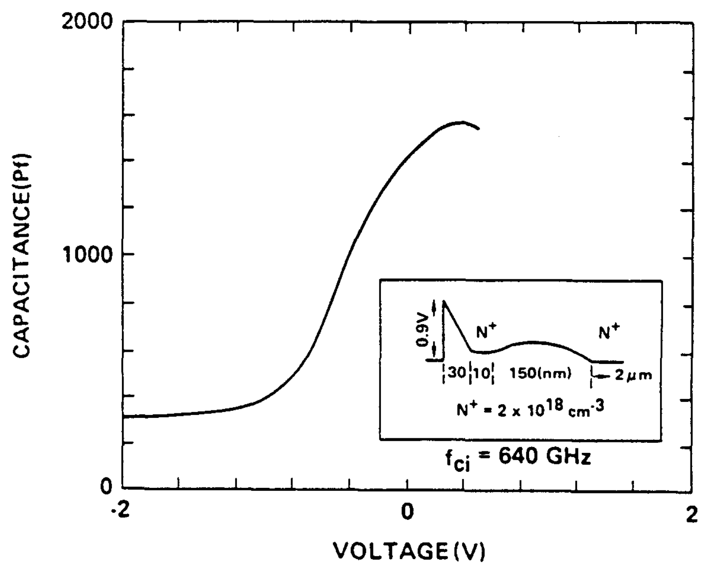

Fig. 4 Capacitance-voltage characteristic of the GaAs BIN diode.

The metal grid we have designed for the BIN diode tripler consists of a columnar mesh of aluminum strips with Schottky electrodes on each end as shown in Fig. 5. The period of the grid is chosen to be about half the dielectric wavelength to avoid exciting substrate modes. The two neighboring Schottky 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 fabrication. The symmetric capacitance-voltage and conductance-voltage curves from two back-to-back connected GaAs BIN diodes illustrated in Fig. 6 demonstrate the concept of the back-to-back operation.

In this work, we have extensively used a nonlinear analysis program [7] in order to investigate and optimize the efficient tripling operation from two BIN diodes under the back-to-back configuration. It should be mentioned that an interpolation sub-program has been developed and employed in the nonlinear analysis program in order to use the experimentally measured C-V data. The measured series resistance, R_S, is also used for the following computation cases.

Due to the symmetric capacitance-voltage characteristic of two back-to-back connected GaAs BIN diodes, even harmonic currents cancel, so that even harmonic idler circuits are unnecessary. This can also be shown from the large signal analysis results in Fig. 7, which shows that the efficiency is insensitive to second harmonic impedances.

It should be mentioned that the input power is 10 mW for the above analysis studies. In addition, Fig. 8 shows the tripling efficiency versus the input power level at various input frequencies. The input and output tuning was optimized at each frequency. As shown in Fig. 8, the efficiency is highest with low input power levels (5-10 mW). Over the output frequency range of 100-150 GHz, an efficiency greater than 15% is predicted for the GaAs BIN array which has recently been fabricated. The highest predicted efficiency is 24% at 100 GHz obtained with an input power of 9.0 mW, which shows excellent agreement with the analytical predictions [5,6].

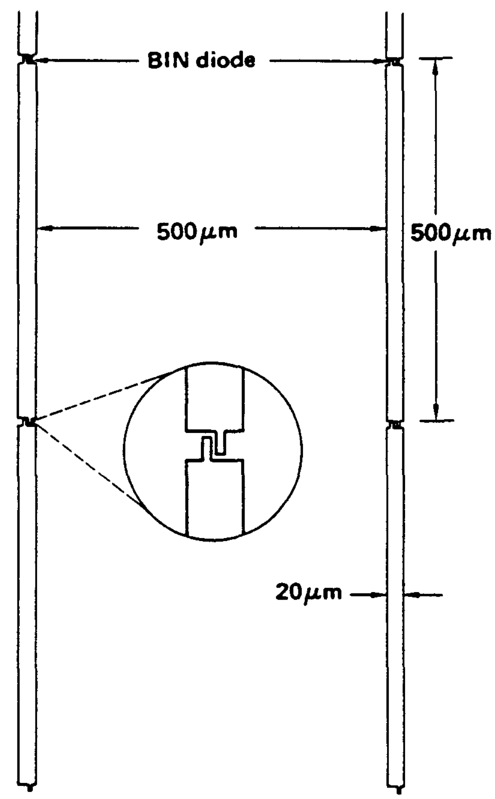

Fig. 5 Design of metal grid for the BIN diode tripler array.

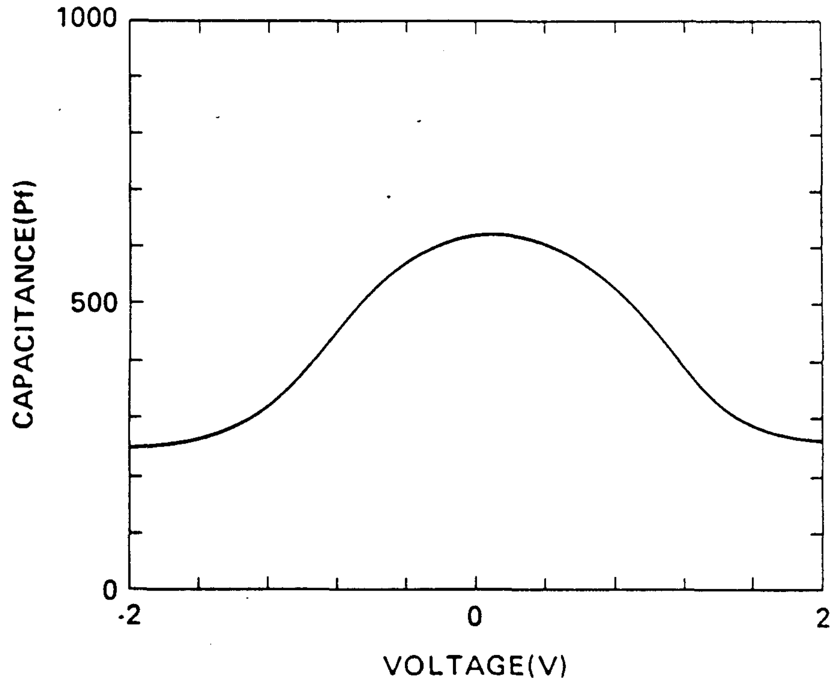

Fig. 6 Symmetrical capacitance-voltage characteristic of two GaAs BIN diodes with a back-to-back configuration.

Using the quasi-optical diode-grid tripler configuration shown in Fig. 9 for a proof-of-principle test, a watt output power at an output frequency of 100 GHz with a tripling efficiency 8.5% has been experimentally obtained with approximately 4 mW incident power on each diode. This experimental measurement is in good agreement with the large-signal nonlinear circuit analysis prediction (see Fig. 8). It should be mentioned that this preliminary result was performed in the low pumping power region. However, much higher efficiency (~ 24%) is predicted for higher input power level (~ 9 mW).

In addition, to direct the concept of the monolithic diode-grid frequency tripler array with a back-to-back configuration into advanced solid state structure such as heterojunction device, the capacitance-voltage relation of the heterojunction device has been studied in detail. To support this work we have developed the cabability to predict the capacitance-voltage characteristics which have been incorporated into the large-signal nonlinear circuit analysis program for efficiency studies and optimization. Here, it should be noted that the narrow width of the capacitance-voltage depedence for the AlGaAs/GaAs heterojunction should provide for highly efficient frequency multiplication even at low input power.

SUMMARY AND CONCLUSION

A watt output power at an output frequency of 100 GHz has been achieved for the grid fabricated in the proof-of-principle study of the tripling operation concept employing the back-to-back configuration. The device performance is limited by the parameters of the fabricated diodes. Significant improvement can be obtained with realizable diode parameters and optimized pumping conditions. In addition, the application of advanced heterojunction devices as highly efficient frequency multipliers is also under active investigation.

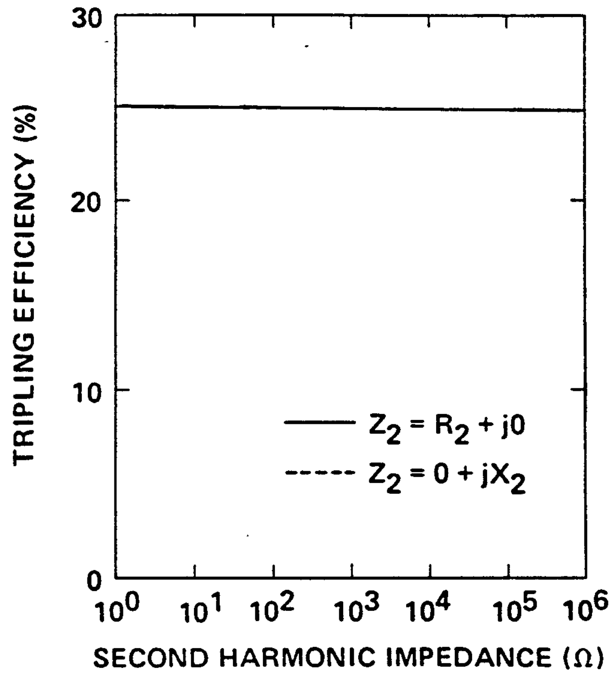

Fig. 7 Tripling efficiency versus second harmonic resistance and reactance.

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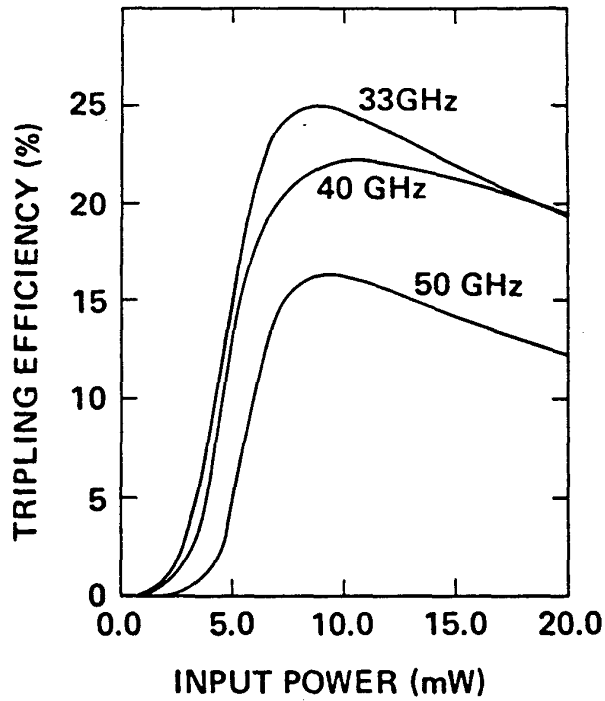

Fig. 8 Tripling efficiency versus input power at various input frequencies.

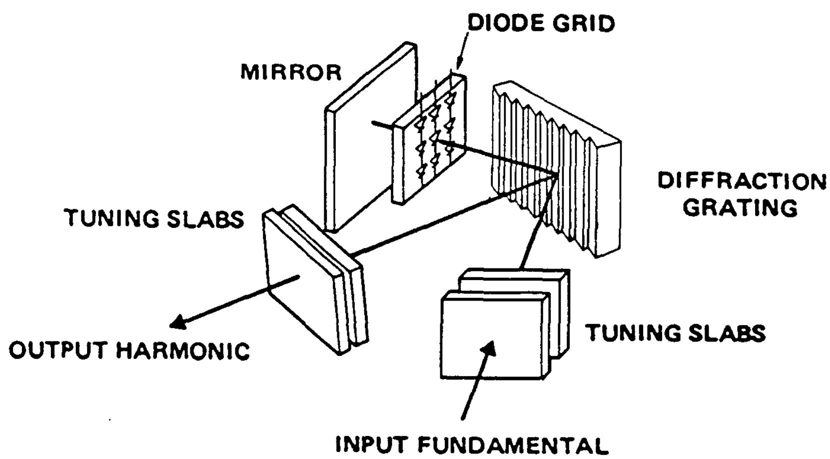

Fig. 9 Configuration of the quasi-optical diode-grid tripler.

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