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ON THE HARMONIC OPERATION OF MILLIMETERWAVE GUNN DIODES

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SUMMARY

The behavior of GaAs Gunn diodes having epitaxial layer thicknesses of the order of 2 µm has been investigated. A coaxial (radial disc) bias circuit provides a resonant circuit at the fundamental operating frequency of the diode (30-50 GHz). The circuit can be tuned over a wide frequency range by various means. The harmonic components have been measured up to 110 GHz.

INTRODUCTION

Gunn as well as IMPATT diodes are inherently nonlinear devices. When such devices operate in a fundamental frequency resonant circuit, the current waveform is highly nonlinear, as has been shown theoretically in the past[1,2] and must therefore contain a number of harmonics. The requirement for low noise oscillators in the 90 GHz range has prompted a number of experimental and theoretical investigations concerning fundamental and harmonic operation of GaAs and InP Gunn diodes in the millimeterwave range[3-8]. Because the power output at the fundamental frequency decreases rapidly, but in an experimentally still unknown, and by theory not precisely predictable manner, in the range 50-100 GHz for GaAs, and 50-150 GHz for InP, harmonic operation is of practical importance. It is the purpose of this paper to describe some experimental data on GaAs Gunn diodes, operating in a coax/waveguide mount, which exhibits tunable resonances at the frequencies (30-60 GHz) corresponding to the fundamental frequency[8], and which allows simultaneously efficient coupling at the harmonic frequencies[9].

COAX/WAVEGUIDE CIRCUIT

The oscillator circuit used, is illustrated in fig. 1. It consists of a full height waveguide with backshort and a coaxial bias line with filter section, post and disc. The device indicated, represents the packaged device. An approximate equivalent circuit is illustrated in fig. 2 for the bias line, and fig. 3 for the portion below the disc. Because of the many reactive elements, a number of resonances are possible. The susceptance seen by the active device (-r, fig. 3), because of the very complex circuit, can be expected to have more than one zero, such that several resonances are possible, depending of course on the values of the parameters indicated in fig's 2 and 3, as well as on the waveguide dimensions. However, several possible resonances are apparent:

I. A resonance of the entire coaxial line, including filter, post disc and device[8].
II. A resonance of the section below the disc, including the disc as a radial line.
III. A resonance due to the waveguide cavity formed by the diode and the backshort.
IV. A resonance due to the waveguide cavity formed by an effective iris (not shown) and the backshort[7,10].

IDENTIFICATION OF HARMONIC OPERATION

The experimental arrangement for identifying the frequencies emmitted by the diodes is conventional and illustrated schematically in fig. 4. It consists of a diode with disc bias circuit and an appropriate waveguide section. Various waveguide systems are attached to the oscillator in order to monitor the frequency and power. The devices were operated cw and pulsed (200 nsec) Care must be exercised in choosing the waveguide sec - tions and tapers with the proper cutoff frequencies. Standard tapers and specially designed tapers having well defined cutoff frequencies (75, 50, 33 GHz) were used with W(75 - 110 GHz), V(50-75 GHz), Q(33-50 GHz) and Ka(26-40 GHz) waveguide systems.

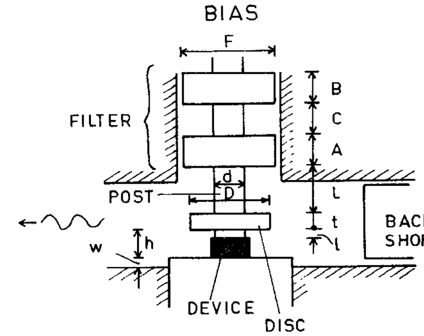
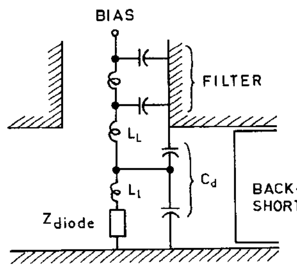
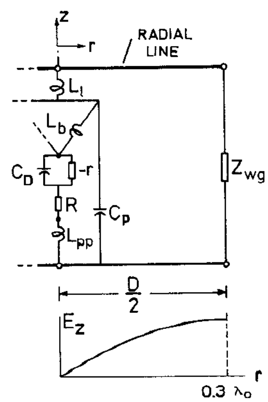


Fig. 1: Gunn oscillator with coaxial bias line



L_l = inductance of post L
L_L = inductance of section l
C_d = disc capacitance

Fig. 2: Approximate equivalent circuit of oscillator illustrated in fig. 1 at frequencies far away from $\lambda = 2D$.

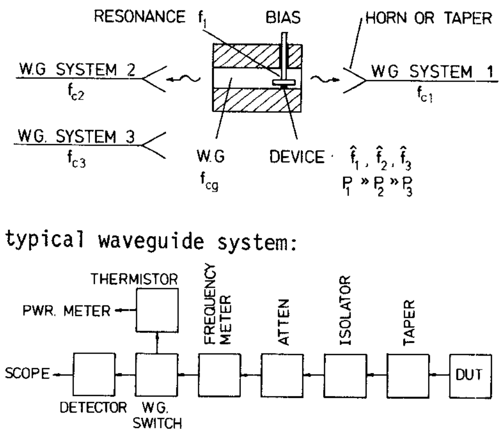


L_b = bonding wire inductance
C_D = diode capacitance
C_p = package capacitance
-r = diode negative resistance
R = diode parasitic positive resistance
L_{pp}= package post inductance
Z_{wg}= waveguide impedance (load)

Fig. 3: Approximate equivalent circuit of disc and packaged device. The disc is represented as a transmission line.

FREQUENCY MEASUREMENTS

Experimental results of the frequency components of two diodes having different active GaAs layer thicknesses are illustrated in fig. 5. The oscillators consisted of short (5 mm) sections of waveguide in order to pass also the frequencies lying below their cutoff. The disc diameter, as well as the length of the section L were varied in order to tune the fundamental resonance from 25 to 55 GHz. The observed frequencies are indicated and are identified as second or third harmonic. The line $D = \lambda_0/2$ indicates the frequency at which the disc couples the diode optimally to the load, for a given disc diameter (λ_0 is the free space wavelength).



f_c = cutoff frequency

$\hat{f}$ = frequency at power maximum $\hat{P}$

Fig. 4: Experimental system for determining the fundamental and harmonic components of a Gunn diode oscillator.

harmonic operation 1.8 µm GaAs Gunn diode

harmonic operation 2.4 µm GaAs Gunn diode

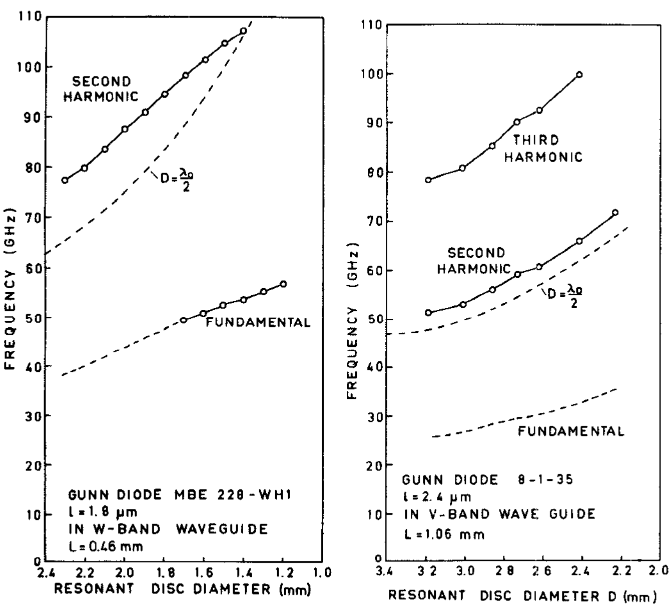


Fig. 5: Experimental results with 1.8 and 2.4 µm GaAs diodes illustrating harmonic components.

POWER MEASUREMENTS

Measurements of power for Gunn diodes (not Gunn oscillators) are an order of magnitude more difficult than frequency measurements. Optimum power output is obtained with discs corresponding to the relation $D \cong \lambda_0/2$, illustrated in fig. 5. Clearly, if the observed frequency does not correspond to the desired frequency, other parameters of the oscillator may be varied as discussed below. In fig. 6 are illustrated a portion of the fundamental and the second harmonic power output of an oscillator for several disc resonators which follow approximately the relation $D \cong \lambda_0/2$. Here a diode having an active length of 1.8 µm, grown in house by molecular beam epitaxy[11], was used. The true power levels are about 6 dB above those indicated. The peak fundamental power occurs at about 45-47 GHz, as was determined subsequently.

HARMONIC OPERATION-MBE GUNN DIODE

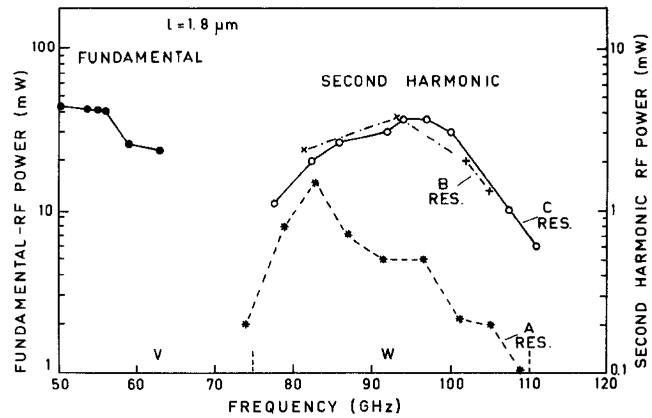


Fig. 6: Fundamental and second harmonic power of a 1.8 µm GaAs Gunn diode. Various disc sections were used to change the fundamental operating frequency.

HARMONIC OPERATION

For the harmonic operation of a Gunn diode, a complex circuit is required, fulfilling two requirements simultaneously:

1) A resonance circuit must be provided at the fundamental frequency. This is possible by means of a waveguide cavity, with the waveguide having a sufficiently low cutoff frequency[7,10]. It is also possible by means of a coaxial circuit, made up primarily by the inductance of the post (section L) and the capacitance of the disc and the device[8].

2) The harmonic must be coupled efficiently to the load by means of a low impedance reduced height waveguide and a backshort effective at the harmonic frequency, or a raidal line[9] of appropriate height h and diameter D (fig. 1 and 3). Best results were obtained with l = 0.

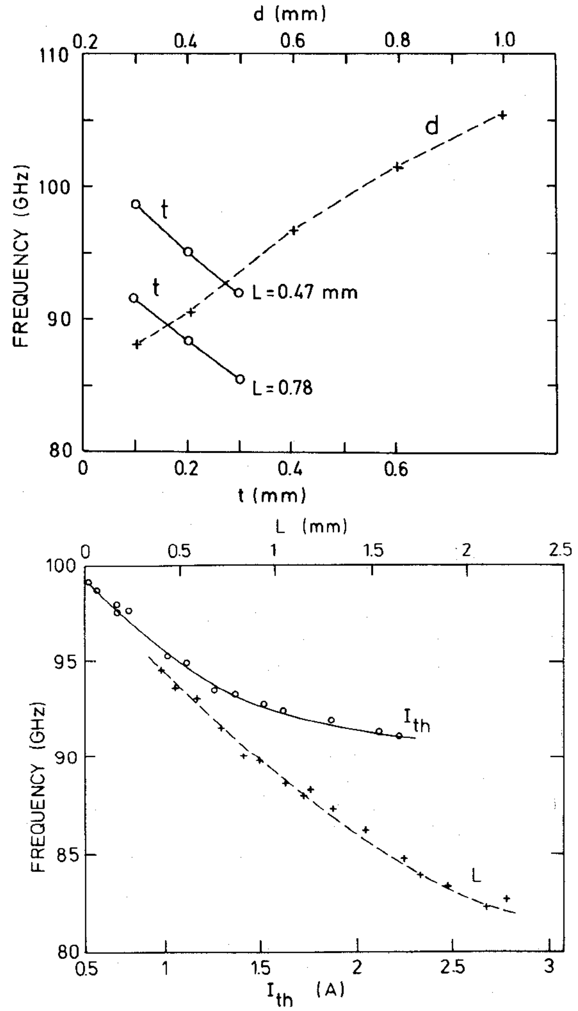
GUNN DIODES

Although we have investigated both InP and GaAs Gunn diodes, we shall report only on GaAs devices made at our own facilities. All devices were integral-heat-sink type mesa diodes, 30-130 µm in diameter, having mesa heights between 5 and 30 µm, bonded by means of single or cross type 12 x 50 µm gold ribbons into commercial packages having an alumina ring of approximately 0.4 mm inside and 0.8 mm outside diameter and 0.3 mm height. We have used GaAs epitaxial layers grown both by the conventional vaporphase epitaxy (Plessey Co.) as well as our own material grown by molecular beam epitaxy. One purpose of our investigation was to determine the power spectra of the devices at the fundamental and the harmonic frequencies for various active GaAs layer thicknesses and carrier concentrations, of which very little is known to date.

COAXIAL CIRCUIT - EFFECT OF PARAMETERS

As can be deduced from figures 1 thru 3, a change in the dimensional parameters of the coaxial circuit as well as of the package or the diode should effect the frequency. We have confirmed this for the parameters A, B, C, L, d, t, w, L_b, C_D and C_p. The variation of the frequency with four of these parameters is illustrated in fig. 7. I_{th} is directly proportional to the diode capacitance which was varied by chemically etching a diode successively smaller in cross section. In addition, it was observed that a reduction in the package capacitance from 160 fF to 40 fF caused a frequency increase of 7%. The variation with w was about 3%/mm, and with 1 about 10-15%/mm. The filter section which was designed for 90 GHz is an effective capacitance in the fundamental frequency range, such that primarily the parameter A will effect the frequency. We have observed a change of 3%/mm. By varying the bondwire inductance L_b, a considerable frequency change was observed; 5% by changing from a single ribbon to two crossed ribbons.

The disc capacitance can be continously varied electrically or mechanically[8] as illustrated in fig. 8. In fig. 9 we illustrate experimental results of a method of mechanical tuning by means of a metal pin. The invidual curves for discs of different diameters are the combined disc and diode response. The true diode power spectrum is the envelope of all responses. Two diodes individually tuned in this manner have been used by us in power combining circuits.



I_{th} = diode threshold current

Fig. 7: Experimental results of the second harmonic frequency variation with several parameters.

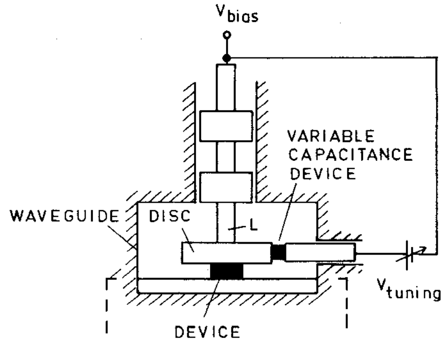


Fig. 8: Continuous frequency tuning by means of varying the disc capacitance.

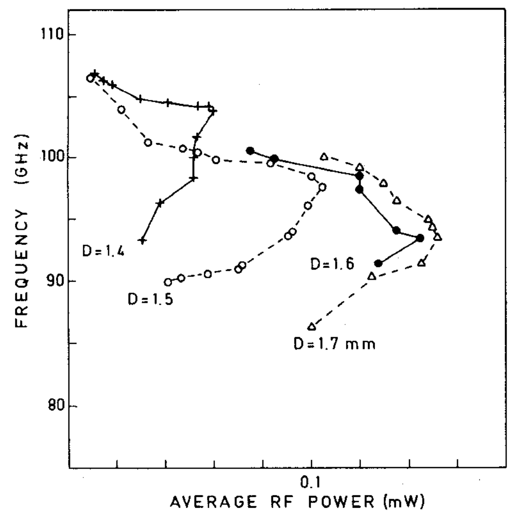


Fig. 9: Experimental results for mechanical disc capacitance tuning for four discs. The frequency shown is the second harmonic. The active length of the pulsed diode was about 2 µm.

THE SOURCE OF THE HARMONIC POWER

Harmonic generation in semiconductors having a non-linear velocity-field characteristic has been treated in the past[12]. Unfortunately, experimental details have been extremely scarce, and most theoretical treatments simply assumed a static nonlinear current-voltage characteristic, neglecting the very complex carrier dynamics occuring when the product of carrier density and active device length is about 10^{11} or higher[1]. The exact source of the harmonic components will require further theoretical and experimental investigations.

CONCLUSION

Coaxial disc circuits exhibit in conjunction with Gunn diodes tunable resonances in the lower millimeterwave range. Our experimental evidence indicates that the circuit of fig. 1 behaves in a certain frequency range like a lumped element circuit. Capacitances (mechanical or electrical) may be introduced at various points, such as the disc perifery, and successsfully used for broadband frequency tuning. The effect of a number of dimensional parameters of the coaxial bias line, as well as diode and package parameters, on the frequency has been presented.

An active GaAs layer thickness of 1.8 µm is well suited for diodes with maximum fundamental power output at 47 GHz. A 90 GHz diode would require a 1 µm layer. No reports of such a diode exist to date.

The true source for the harmonics observed in Gunn diodes is not clear at this time. If oscillators are to be incorporated in future planar circuits, such as integrated front ends, the results of our investigations indicate that fundamental frequency Gunn diodes are difficult to realize at 90 GHz. Since such circuits will make use of semi-insulating GaAs substrates, possible oscillators will be GaAs Gunn diodes, or GaAs field effect transistors operating at the second or third harmonic frequency. Another very promising device is the heterojunction bipolar transistor which may be capable of fundamental operation in excess of 100 GHz[13].

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