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Second Quarterly Progress Report

1 September - 31 October 1962

Report No. II

Contract No. DA-36-039-SC-89163

Department of the Army
Project No. DA-3A99-21-001

DISTRIBUTED JUNCTION TUNNEL DIODE OSCILLATOR

PHASE II.

U.S. Army Signal Research
& Development Laboratory

Fort Monmouth, New Jersey

MICROWAVE ASSOCIATES, INC.

FEB 26 1963
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U.S. Army Signal Research & Development Laboratory

Fort Monmouth, New Jersey

Prepared by:

C. Howell

C. Genzabella

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Approved by:

Dr. Kenneth E. Mortenson

MICROWAVE ASSOCIATES, INC.

Burlington, Massachusetts

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III PURPOSE

The purpose of this contract is to conduct a theoretical and experimental feasibility study for higher frequency high power tunnel diode oscillators. In particular, the design principles and criteria will lead to the design of a distributed junction tunnel diode oscillator capable of giving power outputs in excess of 10 mw at 10 KMc. Included as part of the study shall be the consideration of appropriate microwave circuit environments for maximum oscillator efficiency and stability.

IV ABSTRACT

Efforts to determine the feasibility of constructing 10 mw 10 KMc tunnel diode oscillators have been continued and diode requirements for these oscillators have been determined. Various materials, doping elements, and fabrication techniques have been investigated to determine the best combination of these to potentially meet the frequency and power requirements.

Three packaged and two distributed junction tunnel diode oscillators have been designed and built. The present oscillator study results have been concentrated on the packaged X-band oscillator and the integrated ring distributed tunnel diode oscillator. Using the packaged single diode oscillator, power outputs of 100 microwatts as been obtained in X-band and approximately ½ milliwatt at 5 - 6 KMc. Tuning problems have held back use of larger capacity, larger peak current diodes which have cutoff frequencies well in excess of 10 KMc. Some circuit changes have been made to eliminate these tuning problems. Using a ring distributed tunnel diode in the distributed oscillator power outputs of 3 mw have been obtained at low frequencies. Due to the similar inductive tuning problems found in the package oscillator, it was impossible to tune the distributed tunnel diode oscillator to oscillate at X-band. Modification of both these oscillators are in process with the hope of eliminating this tuning problem. In addition, a stripline package oscillator is being built. The low impedance of this system should eliminate some of the impedance matching problems with the waveguide oscillators.

An improved version of the distributed tunnel diode has been fabricated. Its structure will be discussed in detail in the body of the report.

V PUBLICATIONS, LECTURES, REPORTS, AND CONFERENCES

During the quarter there were two conferences held as a result of this contract.

On September 27, 1962, Mr. R. Tenenholtz, C. Howell, and Dr. K. Mortenson discussed the progress of this contract with Mr. Frank Brand and Mr. John Armata of the Signal Corps, at Fort Monmouth.

On October 22, 1962, Mr. John Armata visited Microwave and once again discussed the progress of this report with C. Genzabella, C. Howell and R. Tenenholtz.

VI FACTUAL DATA

A. INTRODUCTION

The purpose of this contract is to determine the theoretical and experimental feasibility of building a tunnel diode oscillator that will operate at 10 KMc delivering 10 or more milliwatts of output power with a 20% tuning range.

Oscillations occur in tunnel diodes in the negative resistance portion of the curve. The power obtainable from a tunnel diode during oscillation depends on the magnitude of the voltage swing in the negative resistance region and the magnitude of the current change. Available power from an oscillating tunnel diode (P) then depends on the $(V_v - V_p)$ $(I_p - I_v)$. For high peak to valley ratio tunnel diodes this value becomes approximately $(V_v - V_p)$ (I_p). The amount of this power that is available from the tunnel diode depends on the cutoff frequency of the diode and the operating frequency as follows:

$$P_o = P \left(1 - \frac{F_o}{F_r}\right)^2$$

Therefore, to make a high power, high frequency tunnel diode oscillator, two things are necessary. First, a large peak current tunnel diode must be employed and secondly, the resistive cutoff frequency of this diode must be well in excess of the frequency of operation so that the available power is not diminished too radically.

To produce a 10 kmc oscillator capable of power outputs of 10 or more milliwatts, the tunnel diode must have a peak current of approximately ½ ampere with a cutoff frequency approaching 20 KMc. The impedances associated with such large tunnel diodes are in the tenths of ohms, making the circuit stability problem almost impossible to solve. Two approaches to solving these impedance values are as follows:

1. To improve small tunnel diodes with reasonable impedances and employ these small tunnel diodes in a series lump distributed oscillator capable of producing 1 - 10 mw at X-band. This approach appears to be feasible for 1 - 2 mw at X-band without having to use a very large number of diodes. However, to produce 10 or more mw, it appears that the number of diodes required becomes quite large.

2. The second approach is to build a true distribued junction tunnel diode oscillator capable of producing 10 or more mw at X-band and to incorporate this distributed diode into an oscillator. To accomplish this, effort has been expanded in the following areas:

   1. Tunnel diode oscillator circuitry, fabrication and characterization.
   2. Fabrication of spot gallium arsenide and germanium tunnel diode for use in the single and multi-diode oscillators.
   3. Fabrication of distributed junction gallium arsenide tunnel diodes.
   4. Microwave characterization of all these diodes and oscillators.

B. <u>TUNNEL DIODE OSCILLATOR DESIGN, FABRICATION AND CHARACTERIZATION</u>

During the last quarterly period, a considerable effort was devoted to investigation of the conical cavity design as shown in Figure (1).

Basically this consists of a parallel plate conical cavity with the tunnel diode centrally mounted. At the edge of the cavity section is transformed into a low impedance coax section and tapered down to 50 ohms. The cavity itself is bounded by a flat surface on one side and a tapered plane on the other as shown. The flat plane is formed by a brass end cap insulated from the main body by a .002 mica sheet which forms the bypass capacitor. The value of this bypass was found to be in the 200 - 300μμf region, quite adequate above 4 KKMC. Diodes were introduced into the cavity by means of the diode retaining screw.

Due to the close mechanical tolerances involved, three nylon screws were used to line up the center conductor. The need for this can be appreciated when one realizes that Z_o at the entrance of the conical cavity has a value of 8.3 ohms. Alternately spaced between these nylon screws are brass screws that can be used to provide low inductance shorts at the entrance of the conical cavity. Use of these enables tuning of the cavity. Normally, frequency of oscillation increases with the number of low inductance shorts used.

Table I shows results acquired on a number of micro-pill packaged tunnel diodes when used in the conical cavity. Bias was applied between the end cap and outer conductor. In order to do this, a coaxial tuning stub was inserted in the line after the oscillator to provide a DC path between inner and outer conductor. The stub was also used to optimimize output match of the oscillator to 50Ω. Several diodes listed in Table I show two sets of results. This was achieved by changing the number of shorting screws used. As can be seen from results presented, lower capacitance diodes generally achieve high operational frequencies. Also shown are values of power out and theoretical power out expected at the actual frequency of oscillation. Percentage efficiency based on these two values is also tabulated.

In analyzing the data of Table I, a plot was made of percent efficiency versus the product of the diode capacitance and frequency of operation. This is shown in Figure (2). A definite trend is exhibited with two exceptions. These points can probably be attributed to non-optimum oscillator tuning or improper measurement of diode characteristics. The points that do fall in line indicate that the conical cavity requires tunnel diodes of extremely low capacitance for efficient operation.

Efforts to tune the conical cavity for X-band operation with the diodes listed in Table I usually required all three shorting screws to be used. Under this condition, power out was extremely low and usually less than 30μ watts. The one exception to this is unit No. 1 which had a capacitance of only 0.35μμf. A review of its performance shows an efficiency of 74% was achieved. This is certainly indicative of the necessity for low diode capacitance.

On the basis of Figure (2), performance of diodes should be predictable with respect to available output power. Assuming a micro-pill Ga As diode of the following characteristics:

I_p	20 ma
I_v	1 ma
C_v	0.8 μμf
R_n	15 Ω
R_s	1 Ω

The resultant cutoff frequency would be 50 KMc and maximum available power output under low frequency conditions would be 1.42 mw. For a desired 10 KMc operation theoretical power out would only be reduced to 1.36 mw. Now if this were inserted into the conical cavity and tuned for 10 KMc operation, performance could be predicted to a first approximation of the basis of Figure (2). The $C_v f$ product would be 8.0 which yields a 49% efficiency and therefore only 570µw output. Therefore, even with the excellent characteristics of a diode as described, a goal of 1.0 mw output power could not be reached.

In order to overcome this, two approaches can be taken. These are a re-design of the conical cavity structure or design of a radically new oscillator mount. Both approaches are planed and illustration exhibiting the latter is shown in Figure (3). This configuration consists of a stripline housing in which the tunnel diode is mounted between a low impedance center strip (8 - 15Ω) and one ground plane surface. The latter contact is actually DC insulated from the ground plane but sufficiently RF bypassed by the .002 mica sheet as shown. If diodes of sufficiently low capacitance are used, series resonance of the diode can be made to fall above 10 KMc. Therefore, operation at this frequency will result in a diode equivalent circuit of a negative resistance shunted by some small capacitive reactance. Locating a short behind the diode at a length Θ less than $\lambda/4$, enables tuning out this reactance leaving only the negative resistance. Matching the low impedance line to this negative resistance value will then enable maximum power output to be delivered.

In addition to tuning out diode capacitance, the short serves another purpose that is even more important. Since it will be located in very close proximity to the diode, it will serve as a mode suppressor. At lower frequencies it will appear as a short circuit and suppress any tendencies for oscillation.

As a final point, with respect to biasing provisions a stub tuner may be used at the oscillator output as in the conical cavity case. This will enable bias to be introduced between the diode mounting block and either ground plane.

C. SPOT TUNNEL DIODE FABRICATION AND RESULTS

Spot tunnel diode fabrication efforts during the past three months concentrated primarily on improving the mechanical reliability of these diodes and improving their cutoff frequency.

The principal mechanical problem encountered when using the tunnel diodes in spring holders is their mechanical fragility. Fragility is caused by the small area of the solder seal between the ceramic and the top. Failure occurs at this point by shearing of the top from the ceramic. Investigation showed that this weakness was primarily a solder wetting problem. Upon improving the wetting of the solder to the top by using a stronger solder and improving wetting with an alcoholic hydrazine flux, it has been possible to completely eliminate this shearing problem. When failure occurs now, the mechanism is always the fracture of the ceramic itself.

Packaged gallium arsenide diodes with peak currents of 10 - 100 milliamps and I_p/C_j of up to twenty to one and cutoff frequency of greater than 15 KMc were supplied to the circuit group. Due to circuit impedance problems it was found that the X-band oscillator could not use tunnel diodes with junction capacities of more than 1 pf and still oscillate at X-band. By using larger peak current larger capacity units which could not operate at X-band very much larger power outputs, of 3 milliwatt, were obtained at lower frequencies. Similar germanium spot tunnel diodes were also supplied. These diodes generally showed lower outputs as would be expected for similar peak currents. However the largest power output obtained to date at X-band was obtained with a 5 milliamp 25 KMc germanium tunnel diode. This diode gave more than 100 mw at X-band. This output approaches that which is theoretically possible from the germanium diode.

D. FABRICATION OF THE DISTRIBUTED JUNCTION TUNNEL DIODES

During the past quarter emphasis has been given to a novel design for distributed junction tunnel diode structures. The technique is a modification of the structure presented by Coupland and Hilsum (1). It consists basically of a p^+ epitaxial layer of gallium arsenide on a substrate of insulating or semi-insulating gallium arsenide. The construction is of particular advantage for low current, high frequency tunnel diodes as it leads to a robust structure of small active area and low inductance. Furthermore, the rapid cooling after alloying results in high cutoff frequencies.

Normal spot diode construction involves alloying a small impurity bearing sphere on the surface of suitable semiconductor substrate. For circuit considerations at high frequency applications, low capacitance diodes must be used. Therefore diode junction areas must be extremely small and for X-band are typically less than 10 micron in diameter. It can be readily observed that this type of structure is weak and the small size of the alloying sphere required leads to handling and fabricating problems.

The structure of Coupland and Hilsum alleviates these disadvantages.

Our adaptation of this structure utilizes P^+ gallium arsenide on a semi-insulating substrate for producing distributed tunnel diodes. Previously, our attention was focused on the structure shown in Figure (1) as the means of producing the distributed configuration. It required a P^+ layer on P substrate. This layer was obtained by diffusion from a high concentration of zinc into P type gallium arsenide having a resistivity of approximately 3 ohms cm for very short time periods. By alloying through the thin skin of highly doped material and into the high resistivity substrate, distributed diodes were made in which the junction is only that active area governed by the periphery of the alloyed section, and the width is determined by the thickness of the degenerate layer. As the contact to the alloyed section is increased in width, excess capacity is contributed. This excess capacity deteriorates the quality of the tunnel diode that is intended for high frequency operation. Our new design is primarily an effort to alleviate the problem of contact resistance and insure the highest possible I_p/C_v. Figure (4) is a cross-sectional view of the distributed structure.

<u>Construction</u>

The modification of the distributed diode shown in Figure (5) is made possible by the use of gallium arsenide of high resistivity. The "semi-insulating" gallium arsenide can be prepared by extensive float-zone purification (2) (3) or by doping n-type material with oxygen, cobalt, or nickel. The resistivity is usually greater than 10^5 ohm/cm The semi-insulating gallium arsenide can be grown on any desired plane and orientation.

A degenerate skin can be formed either by epitaxial deposition or by diffusion with zinc as the impurity. However, in some cases, the semi-insulating gallium arsenide substrate decreases in resistivity to approximately 10 ohm cm (4) during heat treatment. It is known that gallium arsenide sometimes is affected by heat treatment where the gallium arsenide becomes more p-type probably due to impurities such as copper which act as acceptors and/or rapid diffusants. Gooch, et al (5) have studied the properties of semi-insulating gallium arsenide.

The p^+ layer (4μ) on semi-insulating gallium arsenide was sliced in .020 inch strips having a thickness of 0.012 inch. The base contact is gold plated kovar platform 0.100 x 0.070 inch with an 0.008 inch pedestal along the center. The contact to the p^+ region was formed by alloying platinum or gold clad molybdenum to the skin. Two degenerate strips were alloyed with tin to the kovar platform flush against the center pedestal. 0.020 inch tin bearing tellerium dopant spheres, depending on the length desired, were alloyed to form the junction. Tunnelling occurs along both sides of the junction. By replacing one of the semi-insulating gallium arsenide strips containing the degenerate skin with a strip of only semi-insulating gallium arsenide, tunnelling occurs along one side. Oscillator measurement and characterization will be performed as soon as the holders modification are finished. Peak currents per cm^2 as high as 1500 ma/cm^2 have to be obtained.

I_p/I_v are approximately 5:1 and can be improved by etching with diluted hydrochloric acid.

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1. Hilsum C., Coupland, IRE - A.I.E.E. Solid State Device Res Conference, Stanford, June 1961
2. Whelan, J. J., and Wheatley, G. H., J. Phys. Chem. Solids, 169(1958)
3. Weisberg, L. R., Rosi, F. D., and Herkort, P., A.I.M.E. Conference, Boston, 1959
4. Forrest Williams, Monsanto Chemical Co., Private Communication
5. Gooch, C. H., Hilsum, C., and Holeman, B. R., JAP supplement to 32 2069 (1961)

VII CONCLUSIONS

Considerable progress has been made in the development of both distributed and packaged X-band oscillators. The packaged oscillator is the most advanced, to date power outputs in excess of a tenth of a milliwatt have been obtained at X-band. Capacity problems have plagued the use of large capacity (C_j greater than 1 pf) diodes and have prevented their use at X-band.

Capacitive tuning of the oscillator has helped but not solved this problem. Power outputs in excess of $\frac{1}{2}$ mw have been obtained at 6 KMc. With improvement in the tuning range from the use of our strip line approach power outputs from present diodes in excess of $\frac{1}{2}$ mw per diode at X-band appears feasible in the near future. Using the lumped distributed diode oscillator approach power outputs at X-band in excess of 1 mw appear obtainable in the future. Distributed tunnel diode oscillator suffered from excess series resistance in the diode and the tuning problems. The series resistance problems appear to be largely solved by use of the Hilsum diode approach. The capacity tuning problem still remains to be solved. Power outputs of more than 3 mw at low frequencies have been obtained with these diodes however.

VIII PROGRAM FOR NEXT INTERVAL

The program for the next quarter will consist of the following:

1. Continued design and circuit improvements in both the single diode X-band cavity and stripline oscillators.

2. Maximize the power output obtainable from a single diode X-band oscillators and by employing the design and circuit experience gained from these X-band oscillators to build a multi-diode lumped X-band oscillator capable of producing more than 1 mw at X-band.

3. Efforts will be made to improve the fabrication of the ring and strip type distributed tunnel diodes and to obtain the power outputs in the X-band region from oscillators containing these diodes.

4. Ring distributed and line distributed tunnel diode oscillators will be modified from the experience gained from both the single diode, stripline and multi-diodes packaged oscillators.

5. Material investigation will be continued to further improve the fabrication of both distributed and spot tunnel diodes. In addition those diodes which are required for the packaged diode oscillators will be fabricated.

IX IDENTIFICATION OF PERSONNEL

The following key technical personnel contributed to this study:

Name	Title	Hours
Dr. Kenneth E. Mortenson	Project Director	16
Charles M. Howell	Project Engineer	42
Carmen Genzabella	Semiconductor Engineer	176
Robert Galvin	Circuit Engineer	59
Robert Tenenholtz	Circuit Engineer	62

Biographies of these people have been given in previous quarterly reports during Phase I of this contract.

LIST OF ILLUSTRATIONS

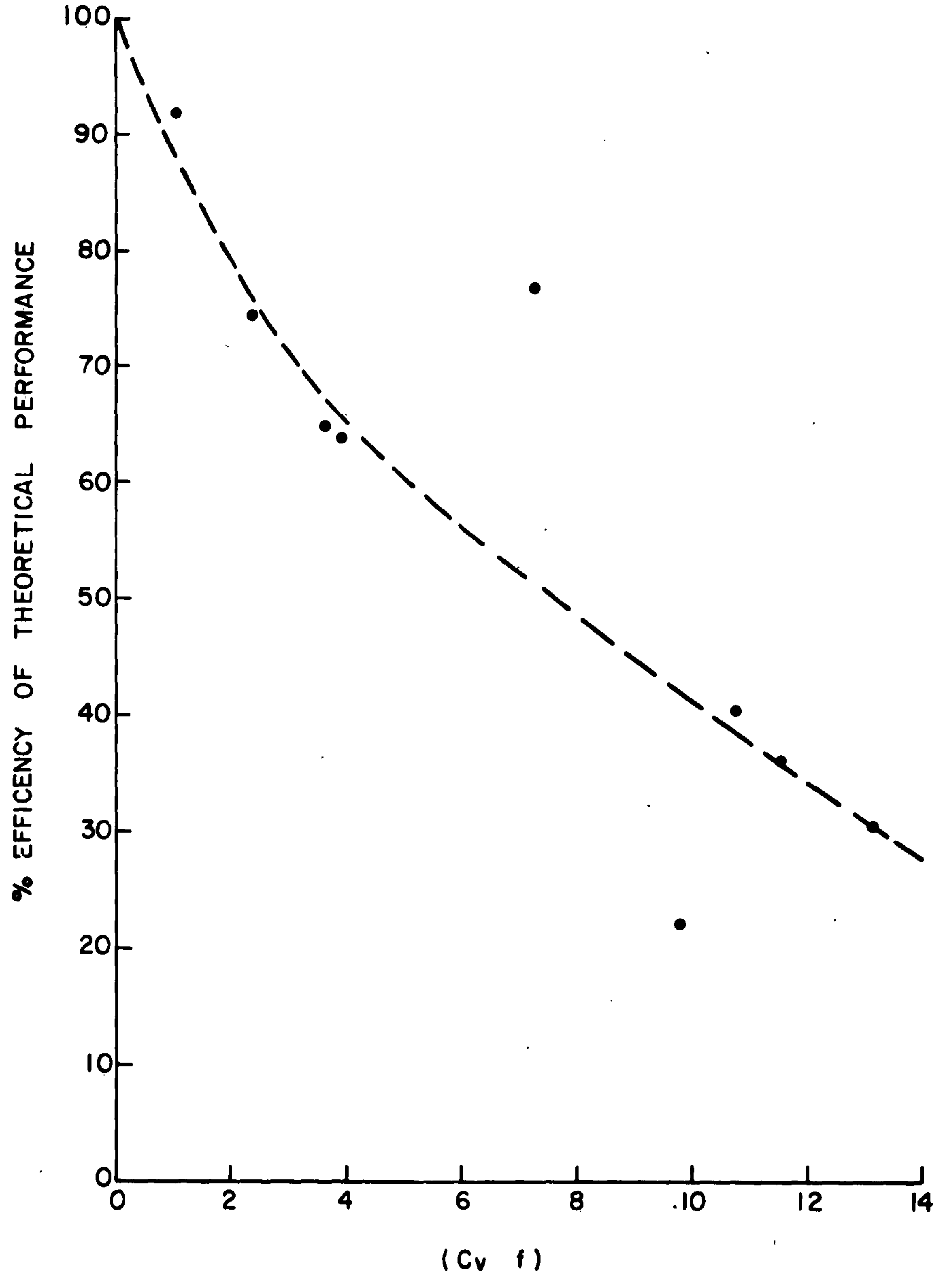
TABLE I

CHARACTERISTICS OF VARIOUS TUNNEL DIODES USED IN THE CONICAL CAVITY AND PERFORMANCE DATA

UNIT NO.	TYPE	I_P ma	I_V ma	C_V $\mu\mu f$	R_S Ω	R_n Ω	f_c kMc	FREQ. of OSC. in kMc	P_{OUT} in MW (MEAS.)	P_{OUT} in MW (THEORY)	% EFF
1	Ge	5.95	0.75	0.35	8	21	12.8	7.1	0.100	0.135	74
2	Ge	12.0	1.5	0.75	—	—	—	4.0	0.600	—	—
	"	"	"	"	—	—	—	5.2	0.220	—	—
3	Ga As	20	1.2	1.0	—	—	—	2.52	1.00	—	—
	"	"	"	"	—	—	—	5.0	0.480	—	—
4	Ge	10.5	1.5	3.2	2.0	3.0	11.8	2.3	0.250	.325	77
	"	"	"	"	"	"	"	3.4	0.120	.305	39.5
5	Ge	17	1.5	1.7	1.0	4.7	38.4	2.35	0.370	.580	64
	"	"	"	"	"	"	"	5.8	0.130	.570	23
6	Ga As	10	0.5	2.7	3.0	4.0	8.5	<0.5	0.650	.710	92
	"	"	"	"	"	"	"	4.9	0.150	.475	31.5
7	Ga As	110	10	10	0.5	2.0	13.8	1.16	2.70	7.5	36
8	Ga As	2.0	1.0	3.0	1.5	10	12.8	1.26	0.900	1.4	64

FIGURE 2

CORRELATION CURVE OF CONICAL CAVITY OSCILLATOR % EFFICENCY VS. THE PRODUCT OF CAPACITANCE AND OSCILLATION FREQUENCY OF VARIOUS TUNNEL DIODES (SEE TABLE I)



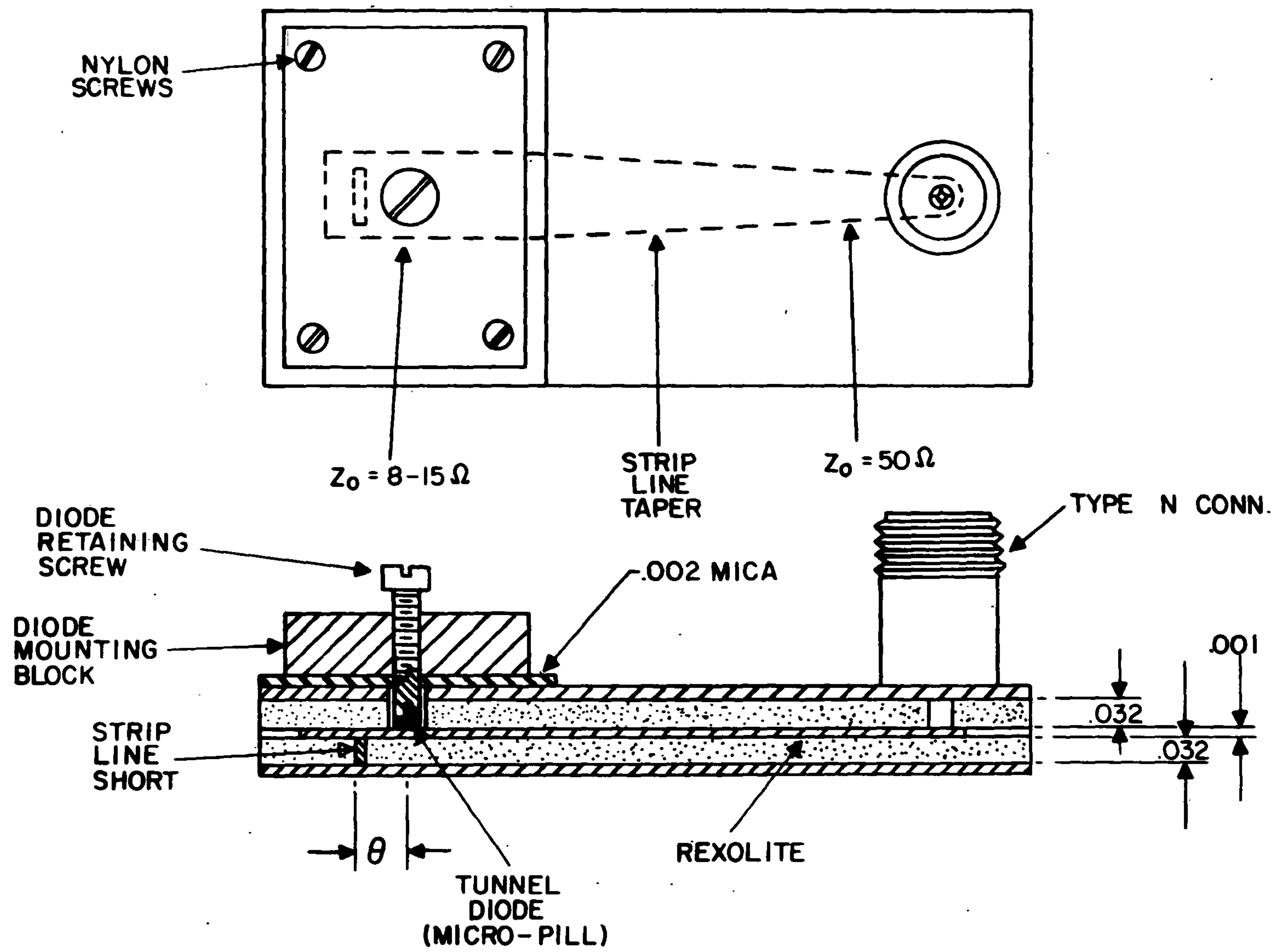


FIGURE 3
STRIP LINE TUNNEL DIODE OSCILLATOR

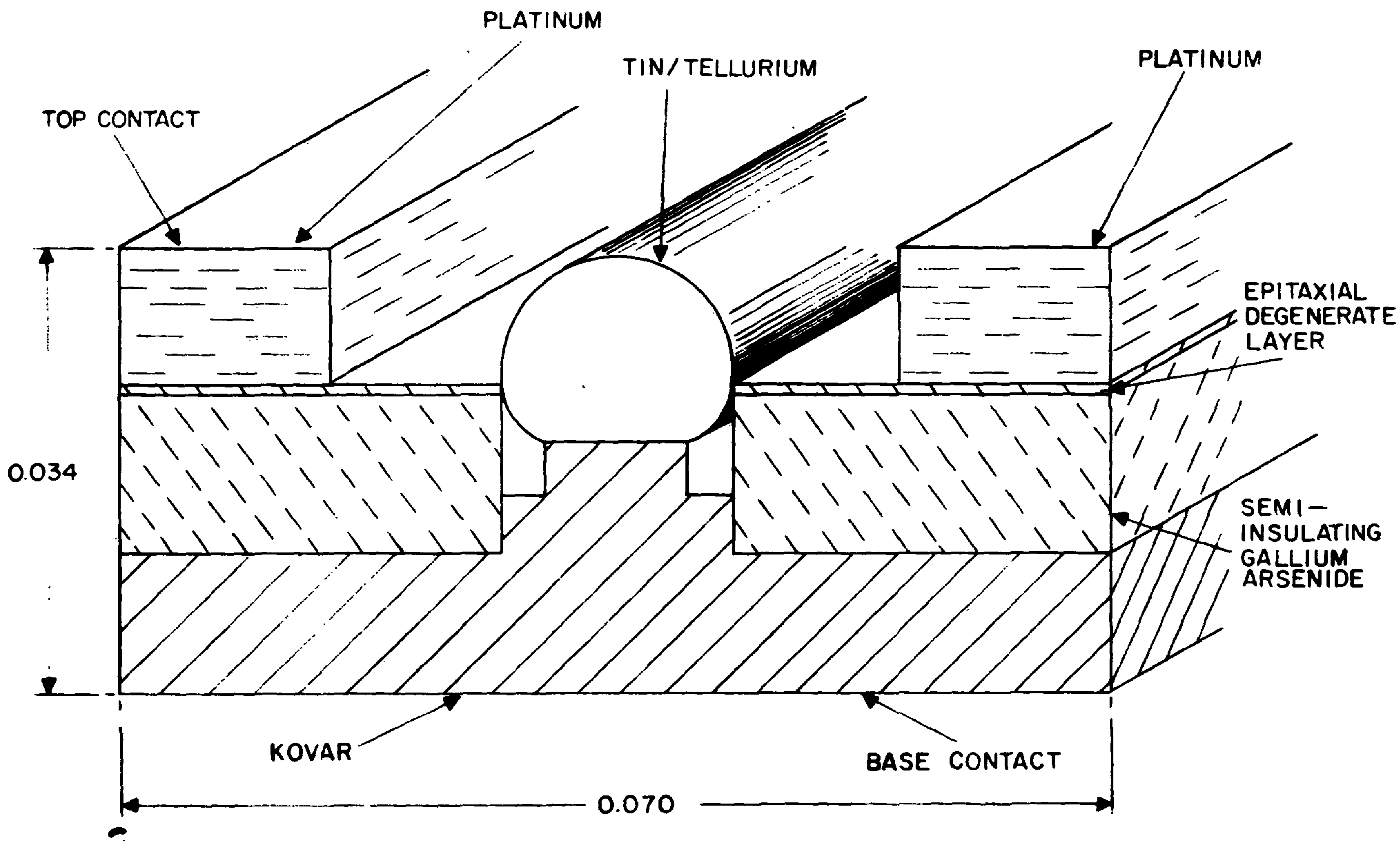


FIGURE 4
DISTRIBUTED TUNNEL DIODE

FIGURE 5
DISTRIBUTED TUNNEL DIODE (PHOTOGRAPH)

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DISTRIBUTED JUNCTION TUNNEL DIODE OSCILLATOR - PHASE 2

C. Howell, C. Genzabella, R. Tenenholtz

Second Quarterly Progress Report,

25 pp. - Illus., Signal Corps Contract DA-36-039-SC-89163

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Three packaged and two distributed junction tunnel diode oscillators have been designed and built. The present oscillator study results have been concentrated on the packaged X-band oscillator and the integrated ring distributed tunnel diode oscillator. Using the packaged single diode oscillator, power outputs of 100 microwatts has been obtained in X-band and approximately ½ milliwatt at 5 - 6 KMc. Tuning problems have held back use of larger capacity larger peak current diodes which have cutoff frequencies well in excess of 10 KMc. Some circuit changes have been made to eliminate these tuning problems. Using a ring distributed tunnel diode in the distributed oscillator power outputs of 3 mw have been obtained at low frequencies. Due to the similar inductive tuning problems found in the package oscillator, it was impossible to tune the distributed tunnel diode oscillator at X-band. Modification of both these oscillators are in process with the hope of eliminating this tuning problem. In addition, a stripline package oscillator is being built. The low impedance of this system should eliminate some of the impedance matching problems with the waveguide oscillators.

An improved version of the distributed tunnel diode has been fabricated. Its structure will be discussed in detail in the body of the report.

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1. Distributed Junction Tunnel Diode Oscillator - Phase 2
2. Contract No. DA-36-039-SC-89163

AD Accession No.

MICROWAVE ASSOCIATES, INC.
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