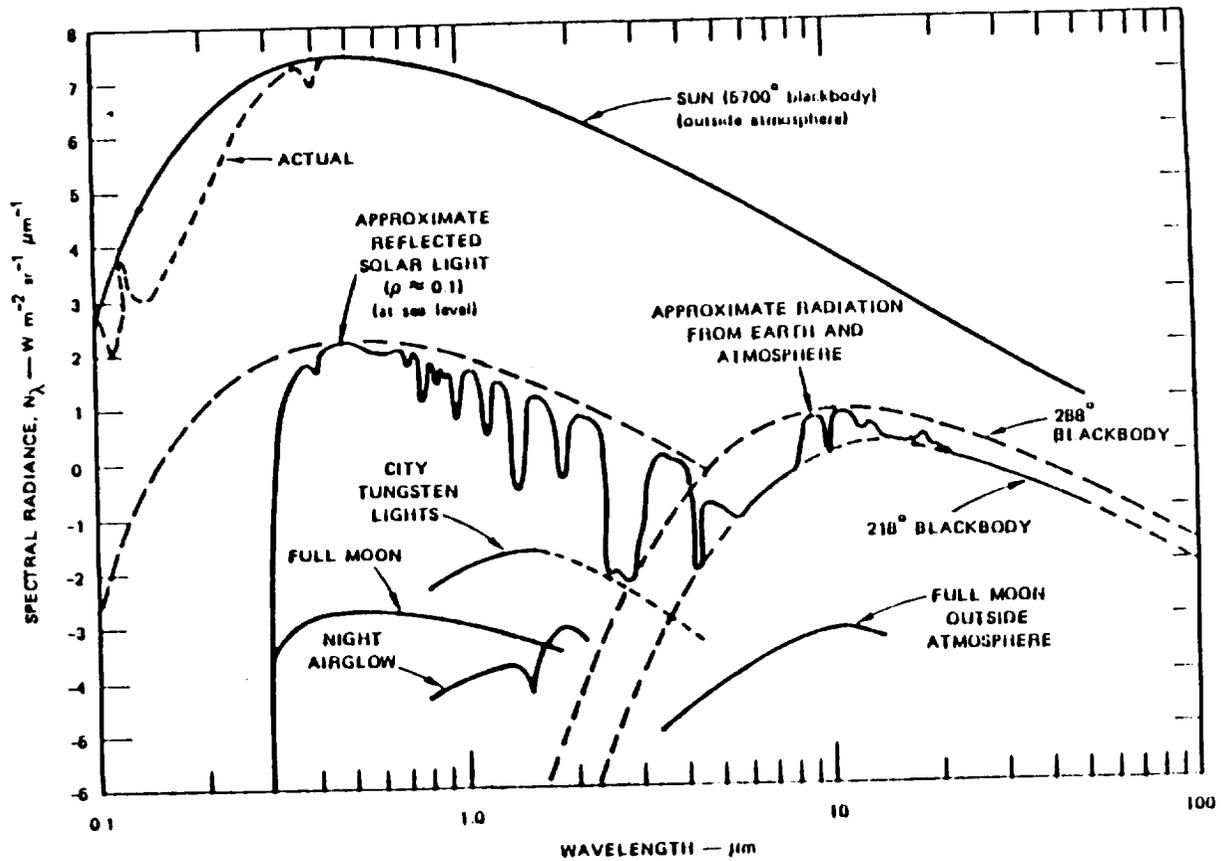


MILLIMETER WAVELENGTH RECTENNA DEVELOPMENT

James Gallagher and Mark Gouker
 Georgia Institute of Technology
 Atlanta, Georgia 30332

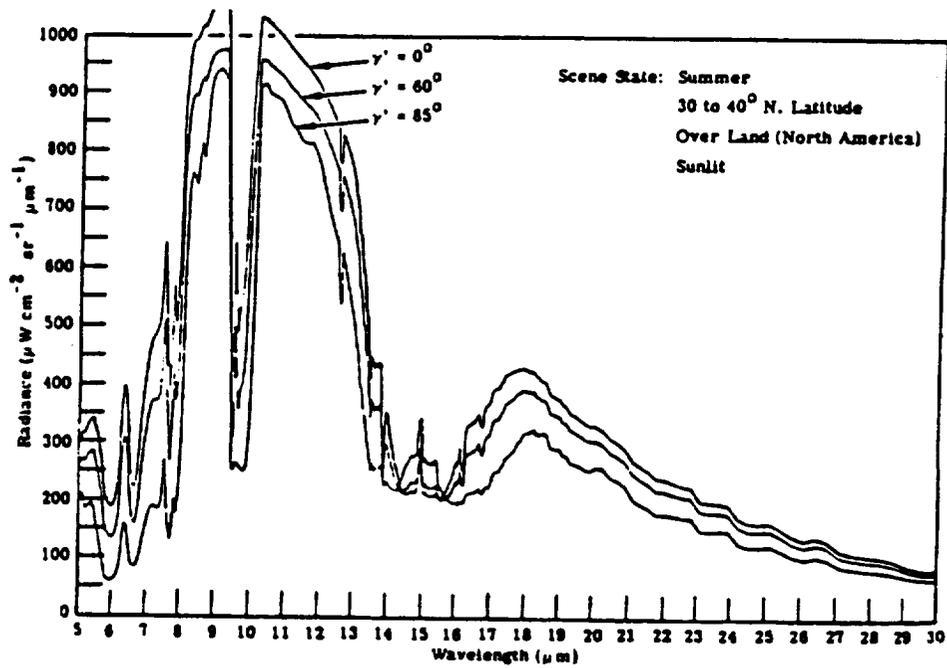
GEORGIA TECH STARTED STUDYING RECTENNAS WITH THE INTENT OF CONVERTING THE EARTH'S (BLACK BODY) RADIATION INTO DC POWER FOR SATELLITES IN EARTH ORBIT.



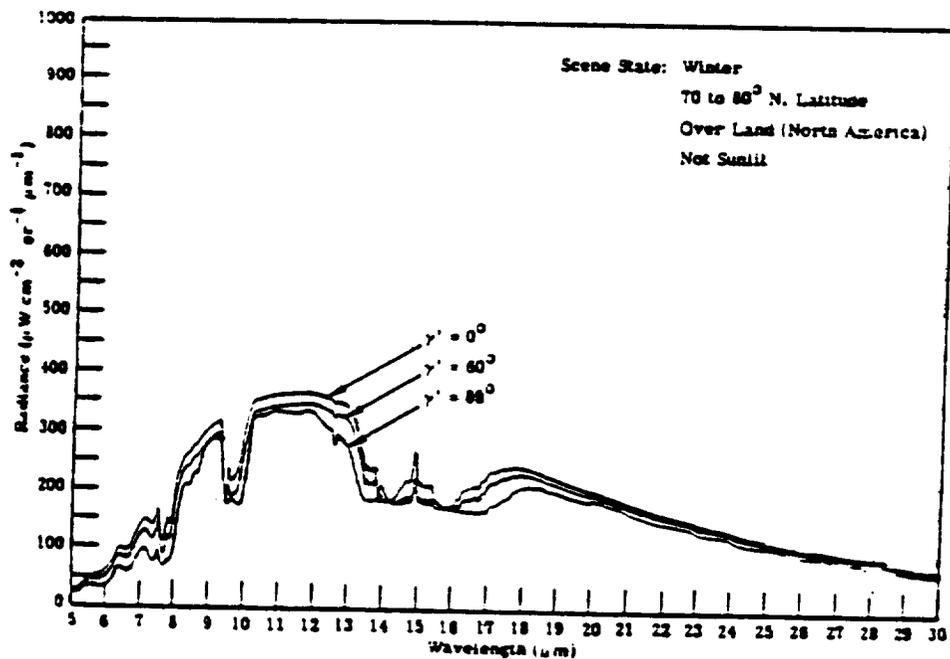
SPECTRAL RADIANCE OF SUN AND EARTH

ORIGINAL PAGE IS
 OF POOR QUALITY

LOW TRAN CALCULATIONS OF THE EARTH'S RADIANCE



SUMMER, 30 TO 40° N. LATITUDE, OVER LAND, SUNLIT



WINTER, 70 TO 80° N. LATITUDE, OVER LAND, NOT SUNLIT

**POWER DENSITIES AS FUNCTION OF
ALTITUDE FOR WAVELENGTH BAND 8-13 μM**

<u>ALTITUDE</u>	Θ_M	P/A_S (W/M^2)	
		<u>SUMMER</u>	<u>WINTER</u>
200 MILES	72 ⁰	134.13	45.27
300	68	127.52	43.04
622	59	110.05	37.14
932	54	96.82	32.68
1500	46	77.46	26.14
2000	42	64.94	21.92
22,996	26.8	31.17	10.52

POWER DENSITIES AS A FUNCTION OF ALTITUDE CALCULATED WITH THESE SPECTRAL RADIANCE FROM THE PRECEDING TWO GRAPHS. Θ_M IS THE FOV NEEDED BY THE RECEIVER TO CAPTURE ALL OF THE EARTH RADIATION.

THE ORIGINAL PLAN OF ATTACK WAS TO FABRICATE THE RECTENNAS AT 1.0 MM WAVELENGTHS AND THEN SCALE AND DESIGN FOR 100 μM WAVELENGTHS AND ULTIMATELY FOR 10 μM WAVELENGTH OPERATION.

THE PROBLEM WAS APPROACHED BY FIRST LOOKING AT THE ANTENNA AND THE DIODE SEPARATELY BEFORE ATTEMPTING TO FABRICATE THE RECTENNA.

THE IDEA OF FREE SPACE POWER TRANSMISSION MAKES THE MILLIMETER WAVE RECTENNAS A GOAL BY THEMSELVES. SEMICONDUCTOR RECTIFYING ELEMENTS SHOULD BE USED INSTEAD OF THE METAL-OXIDE-METAL RECTIFIERS WHICH WERE INTENDED FOR USE IN THE INFRARED REGION.

SCALING THE LOW FREQUENCY (2.45 GHz) RECTENNAS FOR OPERATION IN THE MMW OR INFRARED REGIONS IS NOT STRAIGHT FORWARD.

1) RECTIFYING ELEMENTS BECOME INEFFICIENT.

- PRESENT SEMICONDUCTOR DEVICES WILL ONLY WORK UP TO THE 100'S OF GHz.
- MOM DIODES ARE THE BEST (ALBEIT INEFFICIENT) CHOICE FOR HIGHER FREQUENCY WORK.

2) THE ANTENNA RECEPTION BECOMES COMPLICATED.

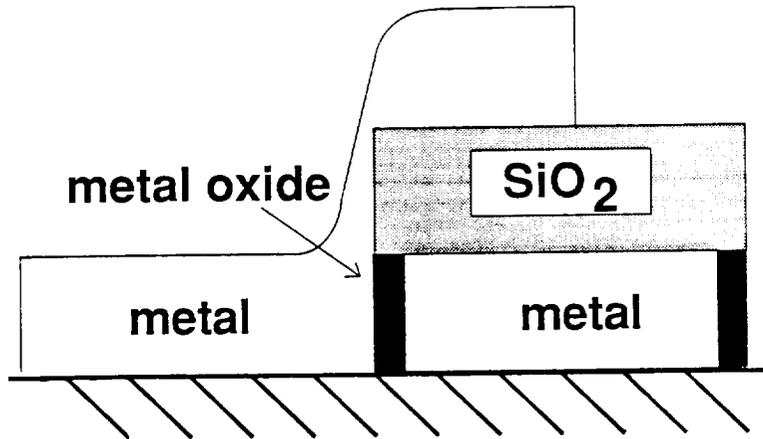
- AT SOME POINT IN THE MMW REGION IT BECOMES IMPRACTICAL TO ATTACH DIODES TO THE INDIVIDUAL ANTENNAS.
- THE RECTENNAS WILL HAVE TO BE MADE ON SEMICONDUCTOR SUBSTRATES WHICH ARE ELECTRICALLY THICK.
- ANTENNAS ON FINITE THICKNESS DIELECTRIC SLABS WITHOUT GROUND PLANES ARE NOT WELL UNDERSTOOD.
- THIS TYPE OF ANTENNA CANNOT EASILY BE MODELED AT X-BAND. THE MEASUREMENTS SHOULD BE MADE IN THE MMW REGION.

GEORGIA TECH MOM DIODE WORK

METAL-OXIDE-METAL (MOM) DIODES HAVE BEEN MADE AT GEORGIA TECH FOLLOWING THE WORK OF HEIBLUM, ET.AL.

THEY HAVE DEVELOPED A METHOD TO GET A THIN OXIDE LAYER AND A SMALL JUNCTION AREA.

THE TECHNIQUE IS BASED ON BUILDING THE DIODE Laterally INSTEAD OF VERTICALLY.



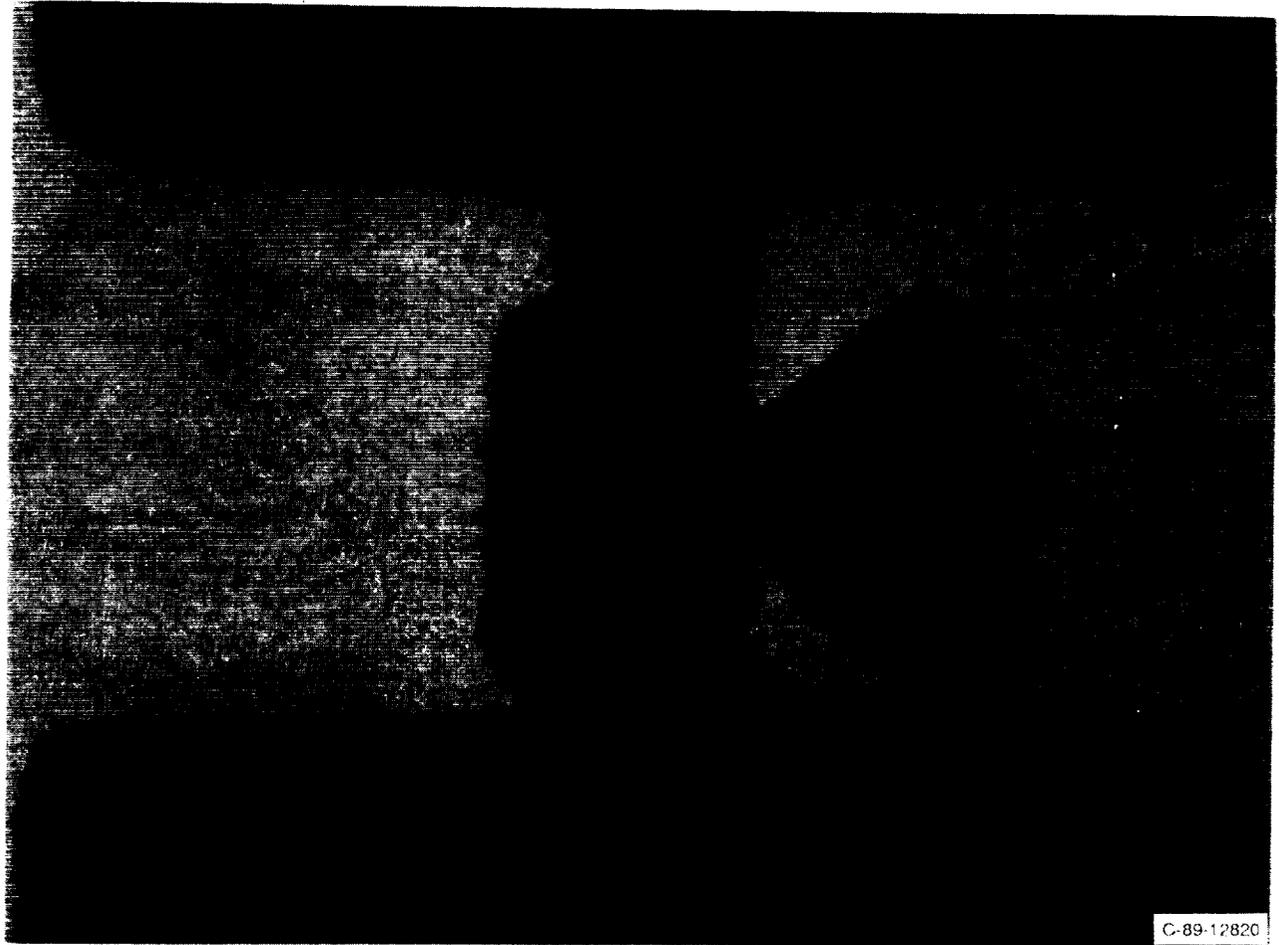
STRUCTURE OF THE EDGE MOM DIODE

TO GET EXTREMELY THIN (10-50 Å) OXIDE LAYERS AN EQUILIBRIUM PROCESS OF SPUTTER ETCH AND OXIDATION IS USED.

GEORGIA TECH HAS MADE NICKEL-NICKEL OXIDE - NICKEL AND NICKEL - NICKEL OXIDE - BISMUTH DIODES.

THE NICKEL WAS ALLOWED TO OXIDIZE IN THE ATMOSPHERE.

IN BOTH CASES THE SYMMETRIC I-V CURVES WERE OBTAINED INDICATING THAT A SELF BIASING RECTIFYING CIRCUIT WOULD BE NEEDED IN ORDER TO IMPROVE THE EFFICIENCY.



MOM DIODE FABRICATED AT GEORGIA TECH

METAL-OXIDE-METAL DIODE - THEORETICAL CONSIDERATION

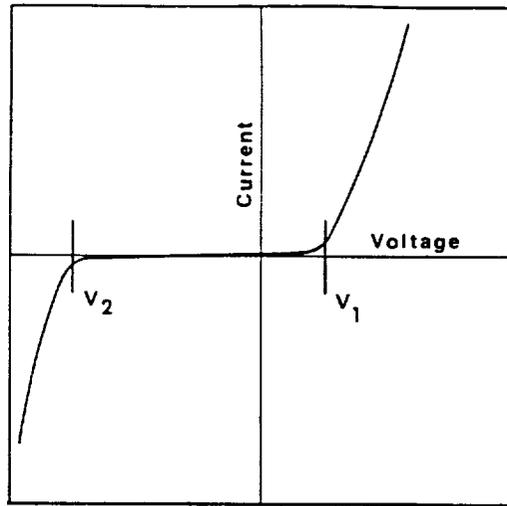
THE THICKNESS OF THE OXIDE LAYER CAN BE ESTIMATED FROM THE TRANSIT TIME OF THE ELECTRONCS THROUGH THE OXIDE.

<u>TRANSIT TIME</u>	<u>OXIDE LAYER</u>
10^{-14} S	10 A
10^{-13} S	100 A

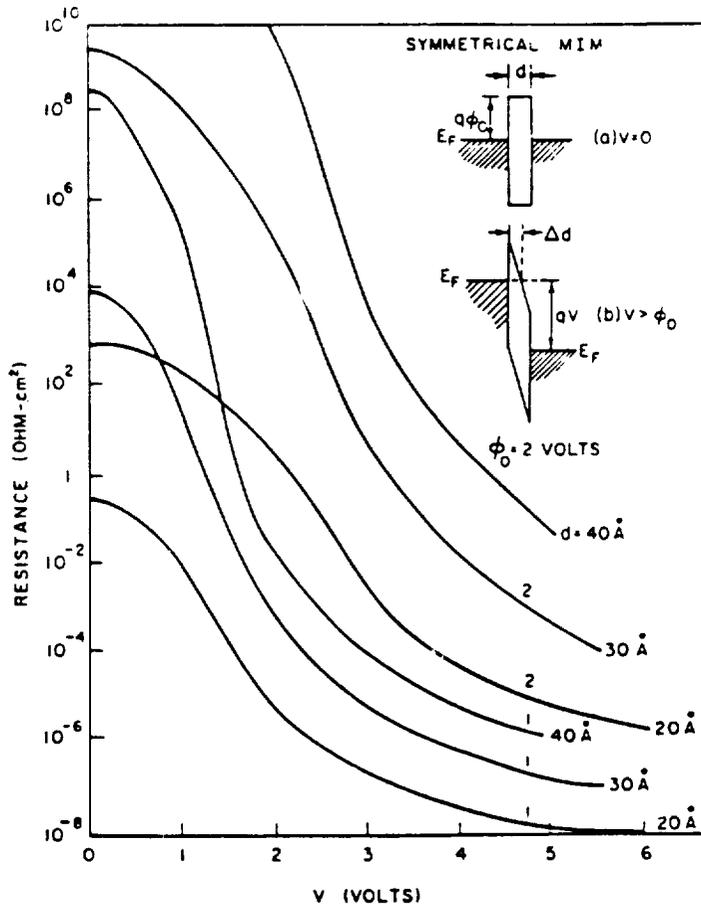
THE ORDER OF MAGNITUDE OF THE JUNCTION SIZE CAN BE ESTIMATED FROM THE RC-PRODUCT FOR OPERATION IN THE 10^{-14} - 10^{-13} SEC RANGE.

JUNCTION AREA $0.1 \mu\text{m}^2$

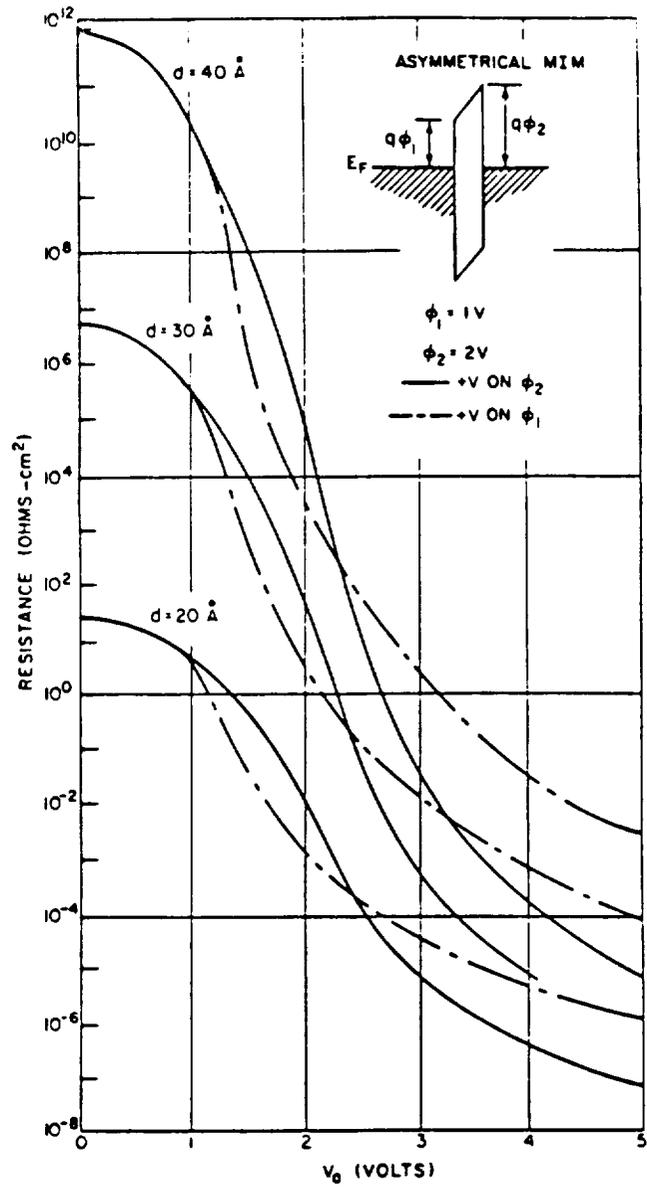
FOR A 10 A THICK, $0.1 \mu\text{m}^2$ DEVICE CAPABLE OF HANDLING 10^4 A/ cm^2 AT 1 VOLT, THE POWER HANDLING CAPABILITY IS ESTIMATED TO BE 10^{-6} WATTS.



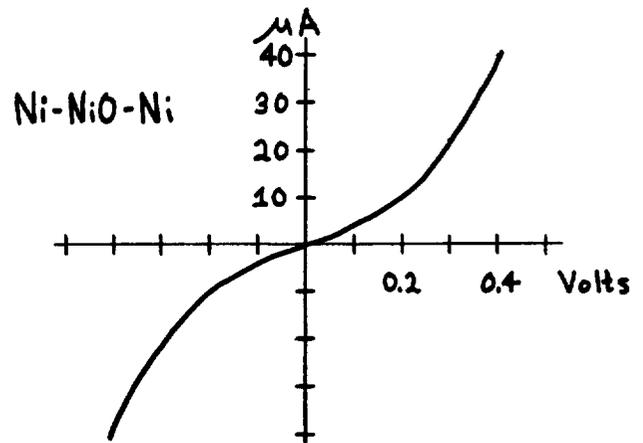
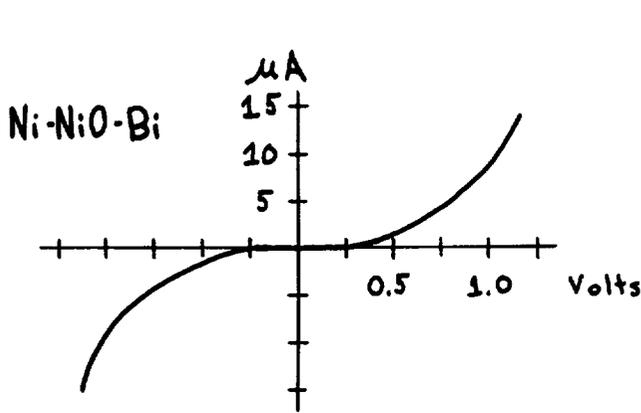
IDEAL CURRENT - VOLTAGE RELATIONSHIP FOR RECTIFYING DIODE



R-V CURVE FOR THE SYMMETRIC MOM DIODE IS VERY DEPENDENT ON THE OXIDE THICKNESS. (AFTER SIMMONS).



ASYMMETRIC MOM STILL HAS VERY SYMMETRIC R-V
 (AND THUS I-V) CURVES. (AFTER SIMMONS).



I-V CURVES FOR THE MOM DIODES FABRICATED AT GEORGIA TECH. NOTE THAT BOTH THE SYMMETRIC AND ASYMMETRIC MOM DIODES HAVE SYMMETRIC I-V CURVES.

ALTERNATIVES TO THE CONVENTIONAL MON DIODE

- 1) **APPLY THE BARRIER LAYER WITH A LANGMUIR-BLODGETT FILM.**
 - THIS ADDRESS THE DIFFICULTY OF PRODUCING A PIN HOLE FREE OXIDE LAYER THAT IS ONLY TENS OF ANGSTROMS THICK.
 - THE LANGMUIR-BLODGETT FILM IS A CONTINUOUS ORGANIC FILM ONLY ONE MOLECULE LAYER THICK.

- 2) **SEMICONDUCTOR VERTICAL STRUCTURE TUNNEL DIODES.**
 - THESE HAVE A BAND STRUCTURE VERY SIMILAR TO THE MOM DIODE, ONLY THESE CAN BE FABRICATED WITH EXISTING SEMICONDUCTOR PROCESSES.

- 3) **SEMICONDUCTOR QUANTUM WELL DEVICES.**
 - THESE DEVICES HAVE VERY NONLINEAR I-V CURVES. THEY EVEN CONTAIN A NEGATIVE RESISTANCE REGION WHICH MIGHT HAVE SOME APPLICATION FOR THE RECTIFICATION PROBLEM. THE ALTIMATE SPEED OF THESE DEVICES IS NOT KNOWN BUT IT IS PREDICTED THAT THEY WILL WORK UP TO 10^{13} Hz.

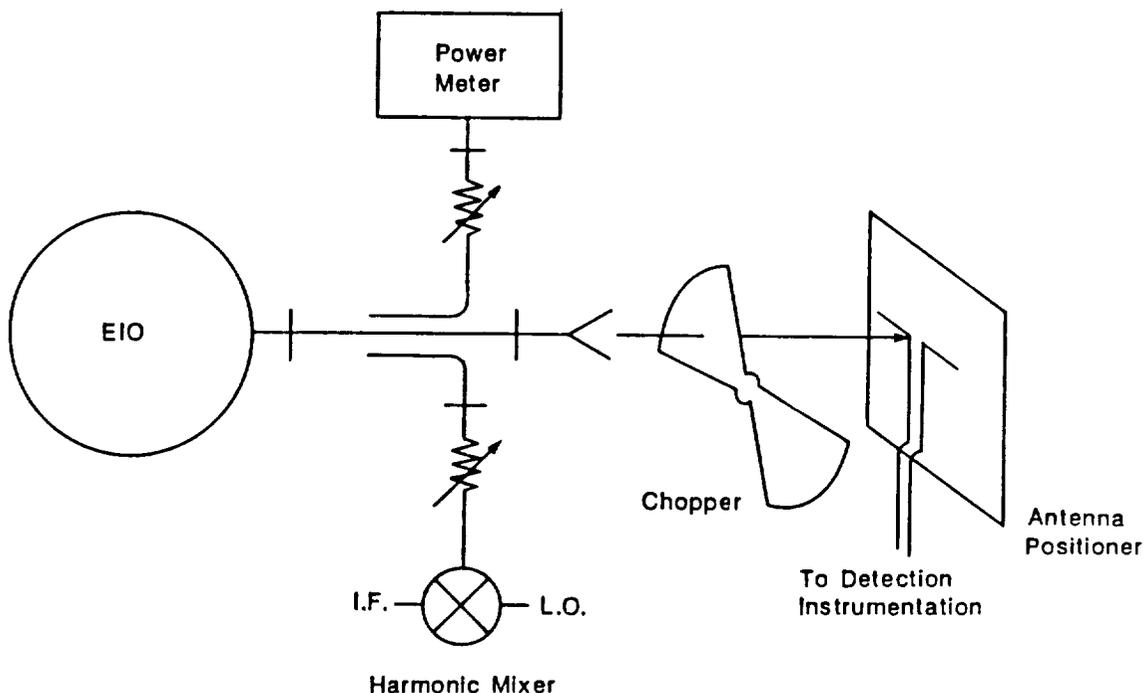
GEORGIA TECH SUBSTRATE MOUNTED ANTENNA WORK

BASIC CONFIGURATION IS A DIPOLE ANTENNA ON AN ELECTRICALLY THICK SUBSTRATE.

A CALIBRATED BISMUTH BOLOMETER IS THE DETECTOR.

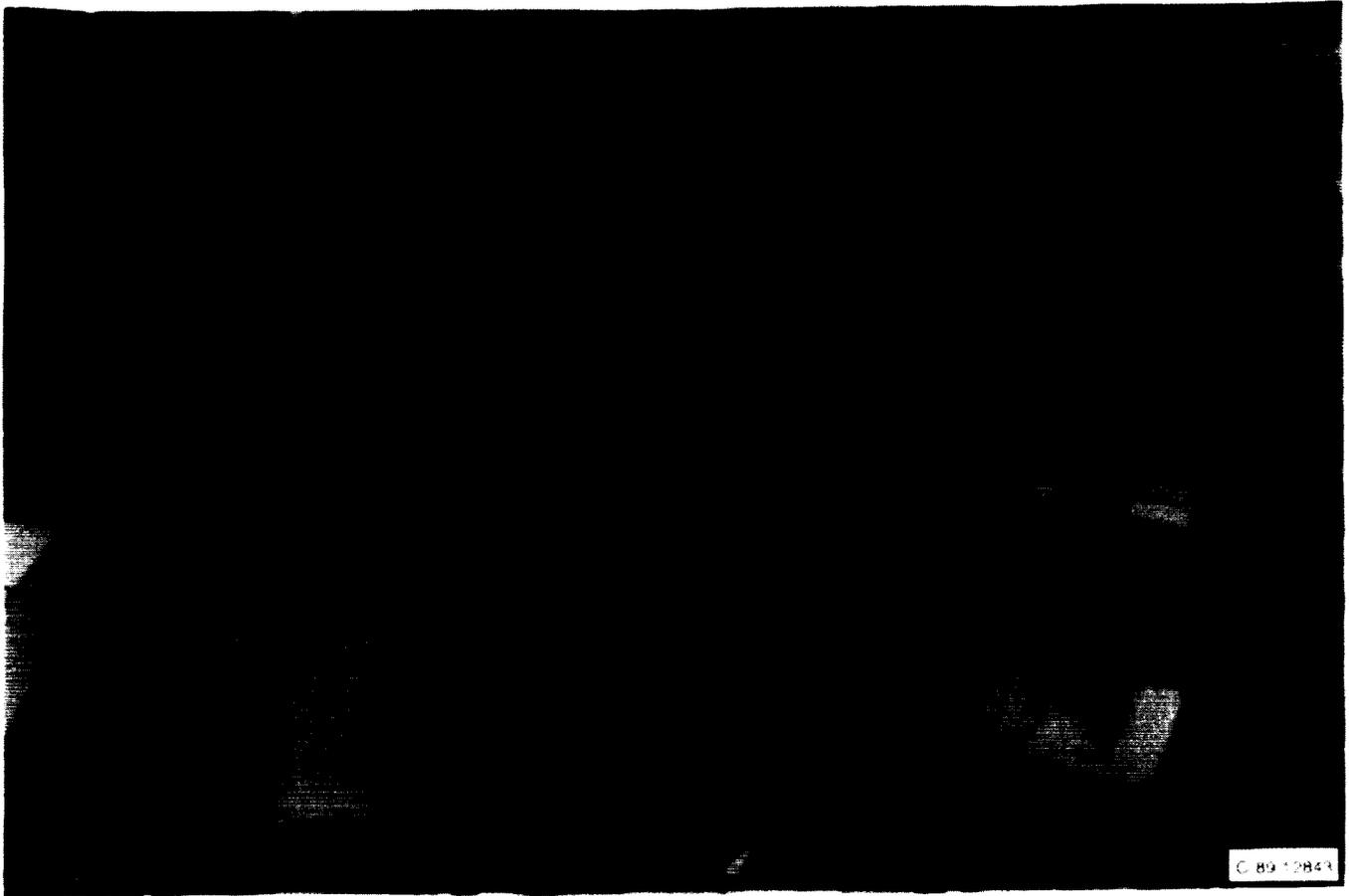
WORKING AT 230 GHz (1.3 MM WAVELENGTHS) HAS ITS ADVANTAGES AND DISADVANTAGES:

- THE COMPLETE FAR FIELD ANTENNA RANGE CAN BE PLACED ON TOP OF AN OPTICS TABLE.
- SCATTERING FROM THE ANTENNA POSITIONER AND FROM THE EDGES OF THE SUBSTRATE WHICH HOLDS THE ANTENNA IS A MAJOR PROBLEM.
- STRAY PICKUP ON THE LEADS WHICH CONNECT ANTENNA TO THE EXTERNAL CIRCUITS MUST BE ELIMINATED.
- THE ANTENNA MUST REMAIN STATIONARY (TO WITHIN $\lambda/16$ OR $80 \mu\text{M}$ UNDER ROTATION IN ORDER TO ASSURE IT IS SUBJECTED TO A CONSTANT INCIDENT FIELD.

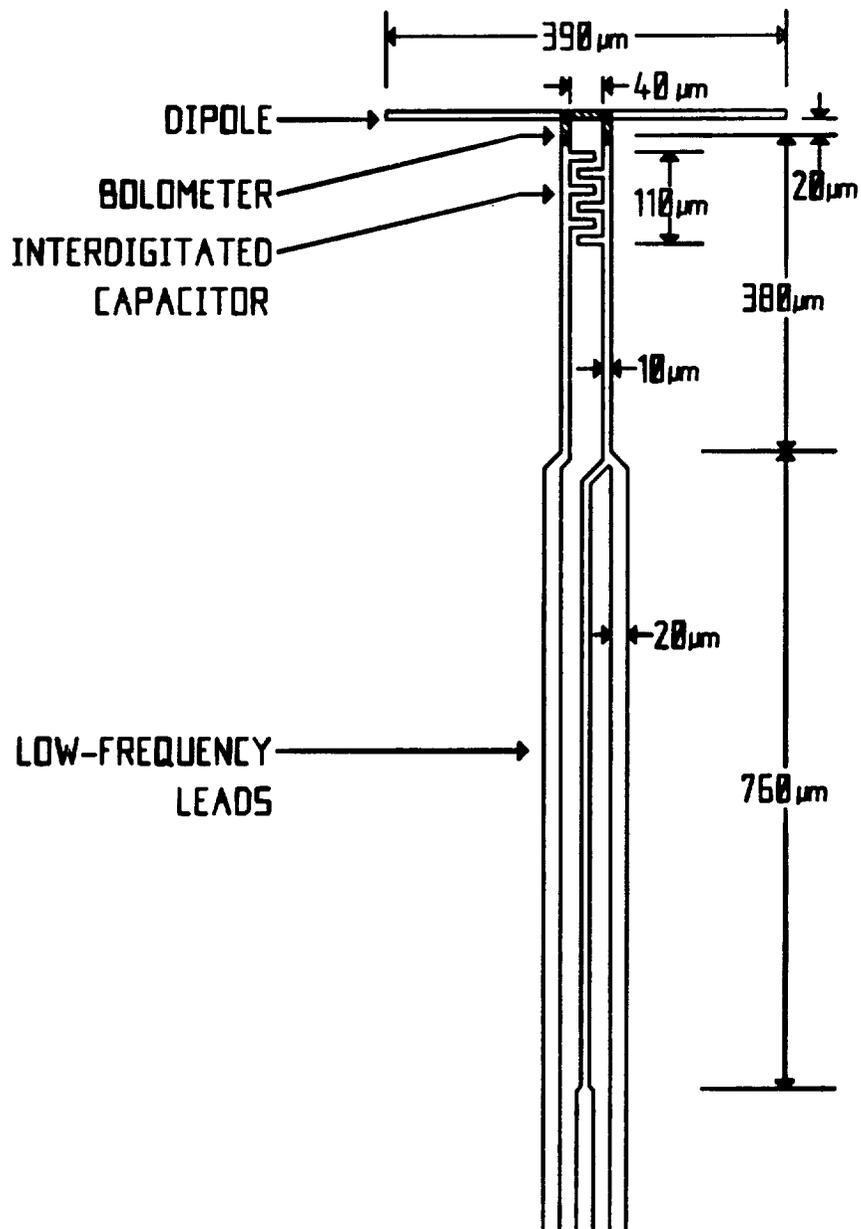


LAYOUT OF TABLE TOP ANTENNA RANGE

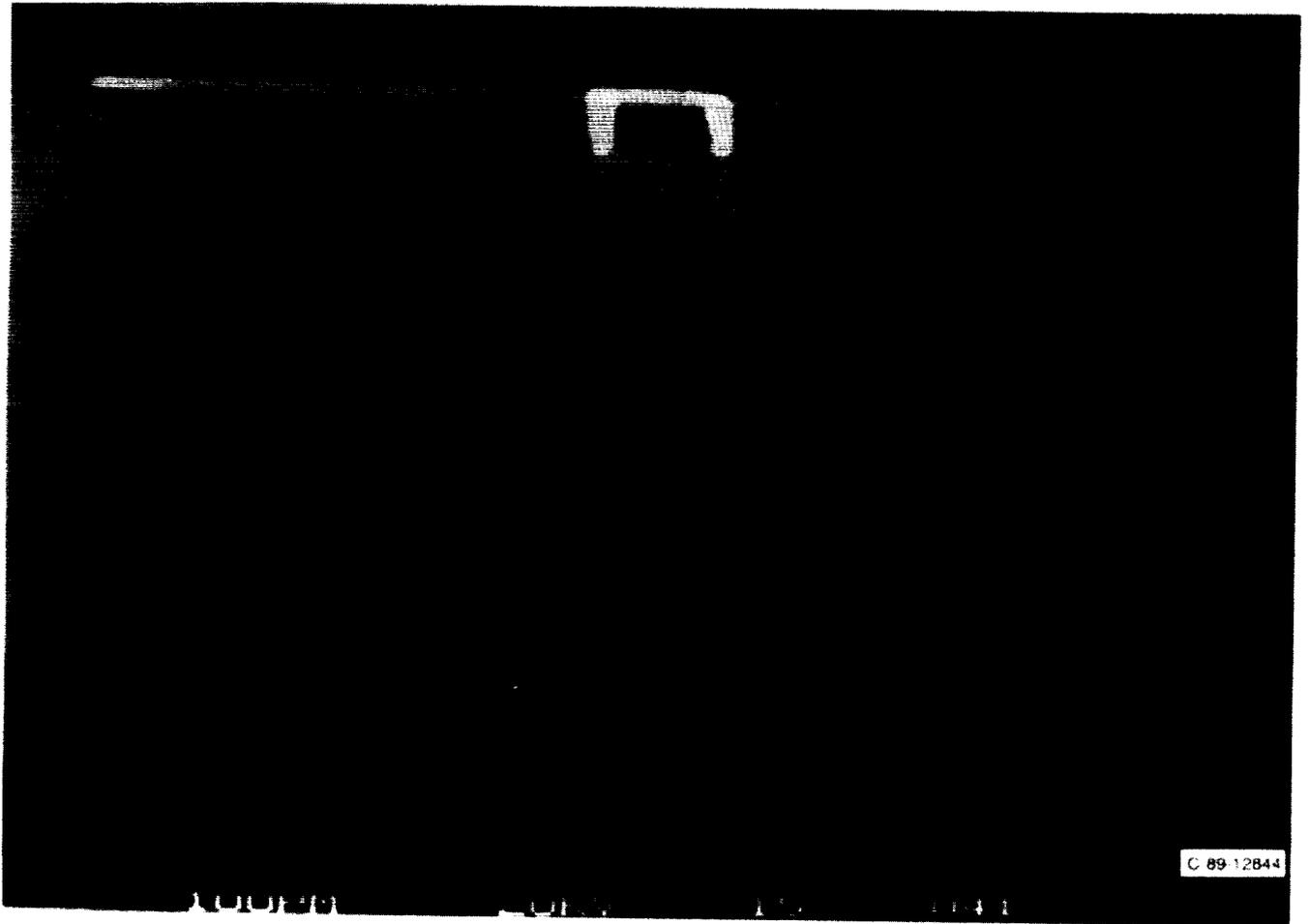
ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH



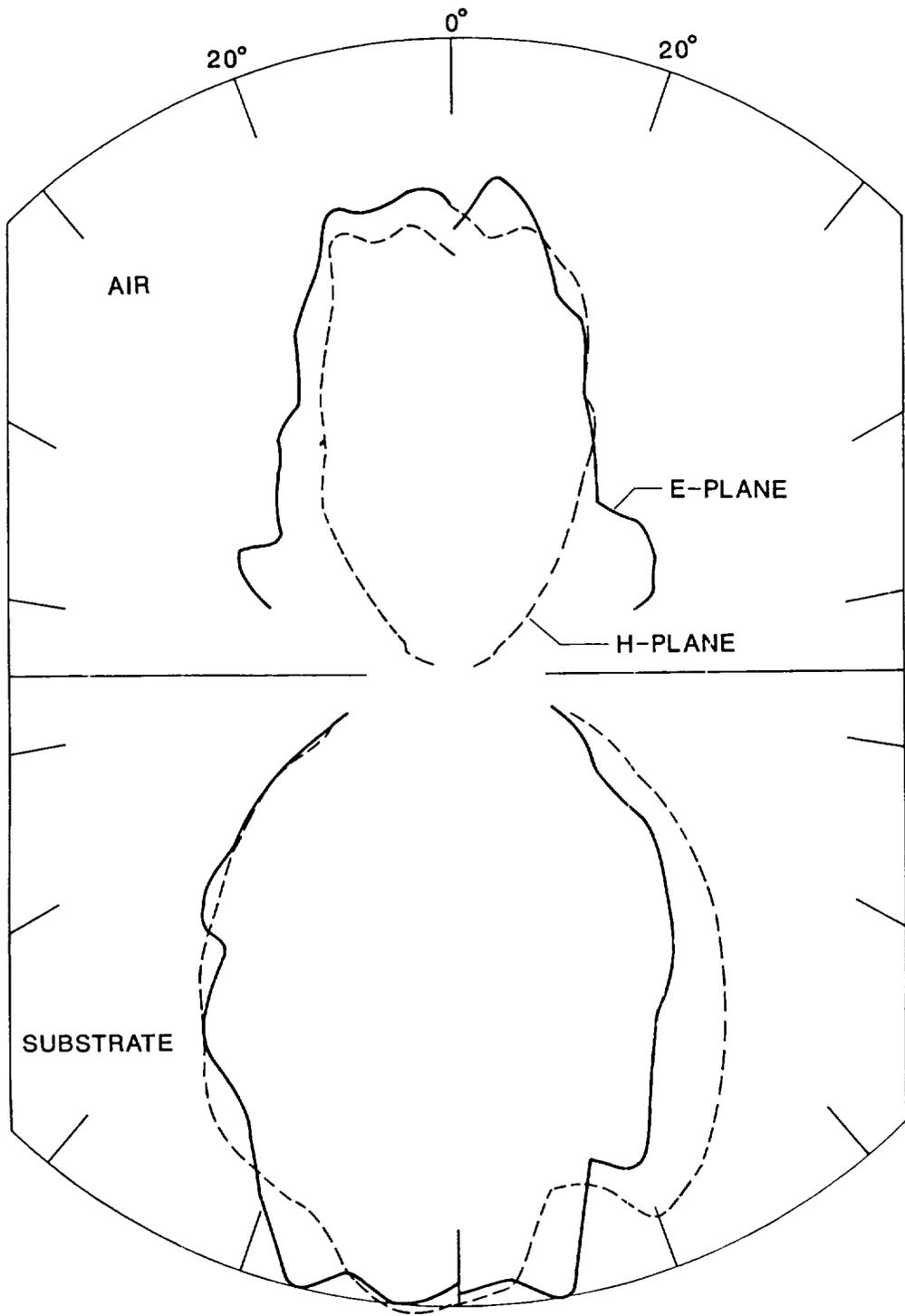
PHOTOGRAPH OF THE TABLE TOP FAR-FIELD RANGE USED FOR MAKING
THE FIELD PATTERN MEASUREMENTS OF THE SUBSTRATE MOUNTED
ANTENNAS.



LAYOUT OF THE ANTENNA STRUCTURE.



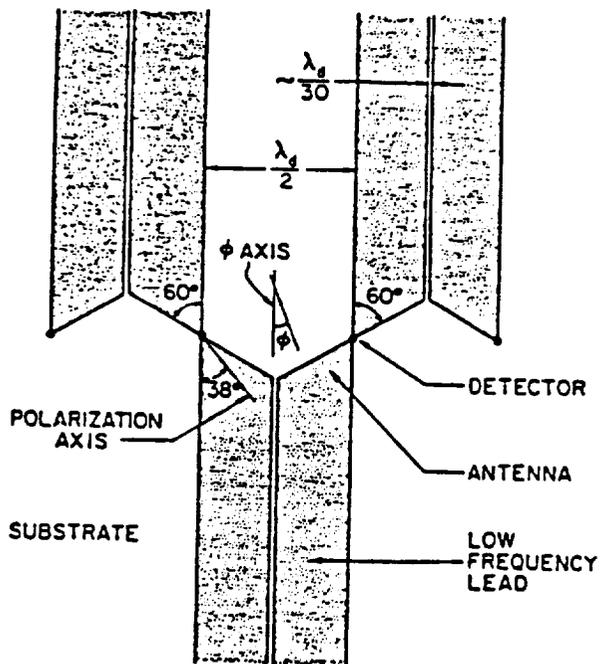
SCANNING ELECTRON MICROGRAPH OF THE ANTENNA STRUCTURE.



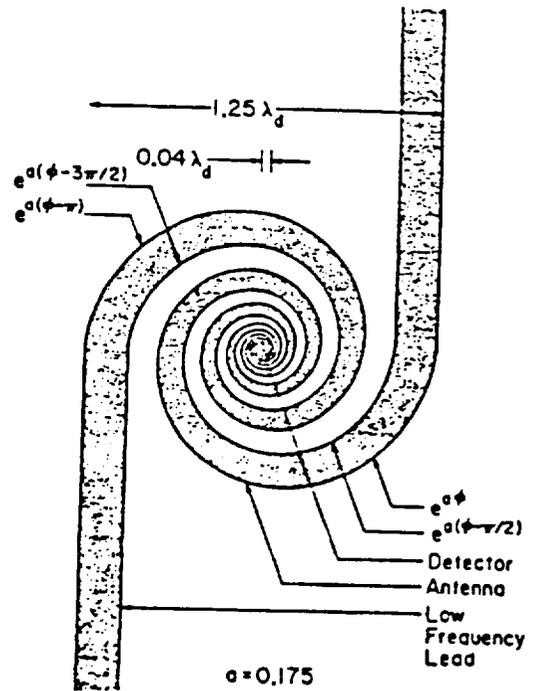
FIELD PATTERNS FOR A SUBSTRATE MOUNTED ANTENNA MADE AT GEORGIA TECH.

OTHER TYPES OF SUBSTRATE MOUNTED ANTENNAS

BOW-TIE

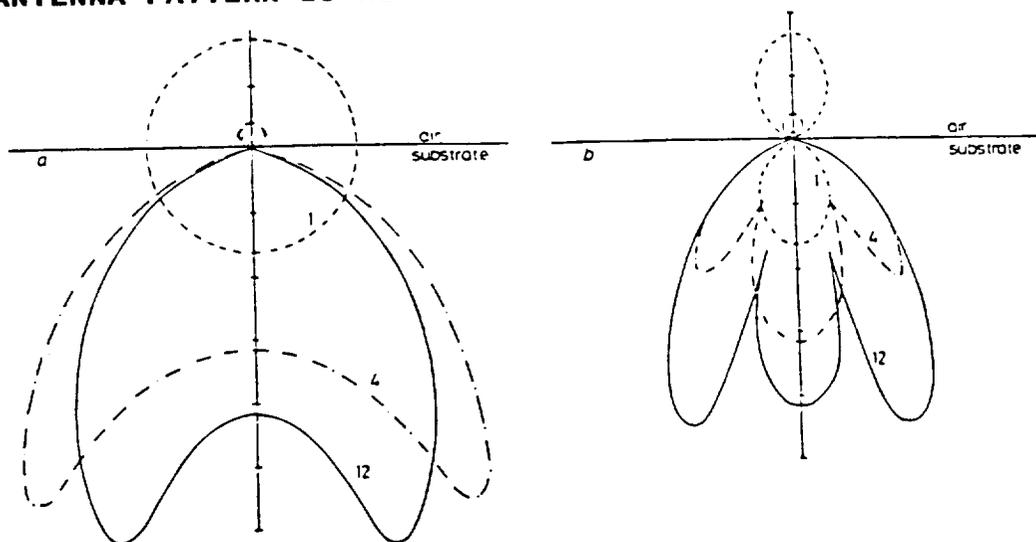


SPIRAL



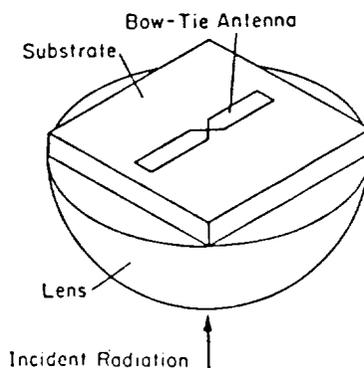
P.P.T. TONG, PH.D. THESIS, CALIF INST TECH, 1985

A GENERAL PROPERTY OF THE SUBSTRATE MOUNTED ANTENNAS IS THAT THE ANTENNA PATTERN IS HEAVILY WEIGHTED INTO THE SUBSTRATE.



C.R. BREWITT-TAYLOR ET AL, ELEC LETT, VOL 17, PG 729.

WE CAN USE THIS PROPERTY TO PERFORM TASKS, SUCH AS FOCUSING, WITH THE SUBSTRATE.



D.B. RUTLEDGE ET AL, INFRARED AND MM WAVES, VOL 10, PG 1.

DIRECTIONS FOR FUTURE WORK

- 1) **UNDERSTAND THE RECEPTION OF THE SUBSTRATE MOUNTED ANTENNAS ON ELECTRICALLY THICK SUBSTRATES.**
- 2) **LOOK AT WAYS TO INCREASE THE RECEPTION OF TAKING ADVANTAGE OF THE ELECTRONICALLY THICK SUBSTRATES.**
- 3) **INTEGRATE A SEMICONDUCTOR DIODE WITH THE SUBSTRATE MOUNTED ANTENNA.**

