GEORGIA INSTITUTE OF TECHNOLOGY — OFFICE OF CONTRACT ADMINISTRATION

PROJECT ADMINISTRATION DATA SHEET

[x] ORIGINAL [ ] REVISION NO. ______

Project No. E-21-J21 R5962-AC1 GTRC/GIT DATE 10/23/86

Project Director: Dr. D. T. Paris School/~~XXX~~ EE

Sponsor: Naval Coastal Systems Center, Panama City, FL 32407

Type Agreement: Delivery Order No. 0021 Under IOC N61331-85-D-0025 (OCA File 9:

Award Period: From 9/29/86 To 5/29/87 (Performance) 5/29/87 (Reports)

Sponsor Amount:

	This Change	Total to Date
Estimated:	$	$ 36,048
Funded:	$	$ 36,048

Cost Sharing Amount: $ ______ Cost Sharing No: ______

Title: ~~Investigate~~ Optically-Induced Superconducting Switches and Optically Pumped Squids

ADMINISTRATIVE DATA

OCA Contact E. Faith Gleason X. 4820

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Defense Priority Rating: DO-C9 ✱

Military Security Classification: Unclassified

(or) Company/Industrial Proprietary: ______

RESTRICTIONS

See Attached Gov't Supplemental Information Sheet for Additional Requirements.

Travel: Foreign travel must have prior approval — Contact OCA in each case. Domestic travel requires sponsor approval where total will exceed greater of $500 or 125% of approved proposal budget category.

Equipment: Title vests with Government

COMMENTS:

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FORM OCA 65:285

GEORGIA INSTITUTE OF TECHNOLOGY OFFICE OF CONTRACT ADMINISTRATION

SPONSORED PROJECT TERMINATION/CLOSEOUT SHEET

N-T SR-300

Date 9-30-87

Project No. E-21-J21 School/Lab EE

Includes Subproject No.(s) N/A

Project Director(s) Dr. D.T. Paris GTRC / GIT

Sponsor Division NAVY

Title ~~INVESTIGATE~~ OPTICALLY-INDUCED SUPERCONDUCTING ~~SWITCHES~~ Switches & OPTICALLY PUMPED SQUIDs

Effective Completion Date: 5-29-87 (Performance) 5-29-87 (Reports)

Grant/Contract Closeout Actions Remaining:

- [ ] None
- [X] Final Invoice or Final Fiscal Report already summited
- [X] Closing Documents
- [X] Final Report of Inventions already summited
- [X] Govt. Property Inventory & Related Certificate
- [ ] Classified Material Certificate
- [ ] Other ______

Continues Project No. ______ Continued by Project No. ______

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FORM OCA 69.285

Progress Report on Subcontract No. E-21-J21-S1

between

Georgia Institute of Technology

and

University of Virginia

for work on

Optically-Induced Superconducting Switches

and Optically Pumped SQUIDs

for the Period 9/29/86 - 2/28/87

Principal Investigator:

Date 8/31/87

Bascom S. Deaver, Jr.
Professor of Physics
Physics Department
University of Virginia
Charlottesville, VA 22901
804-924-6574

Optically-Induced Superconducting Switches

and Optically Pumped SQUIDs

I. Introduction

Optical irradiation of a segment of thin film superconducting line can destroy superconductivity in the segment and interrupt the flow of supercurrent in the line. Such superconducting switches should be capable of operating in times less than 10^{-10} seconds and with relatively low energy required to actuate them. They may be very useful in circuits for superconducting magnetometer applications for directing currents among pickup loops and for modulating the supercurrent in a superconducting ring to produce, in essence, an optically pumped SQUID.

This report describes progress made on the design of some experiments to observe optically induced switching in very small microbridges in superconducting niobium films by using an optical fiber to focus the light from a laser diode onto the microbridge. The work at UVa has been done by B. Deaver and by Lindsay Faunt, who is a graduate student in the Physics Department.

II. Experiments to Study Optically Induced Switching

Two kinds of experiments will be undertaken. For the first the very simple geometry of Fig. 1 will be used. A current biased microbridge will be irradiated with light and the voltage ϵ across the link measured as a function of optical intensity, bias current, temperature and frequency of modulation of the intensity of the irradiating light. Although microbridges are typically extremely hysteretic, particularly those dominated by heating, for sufficiently low bias currents the switching is expected to be reversible and some indication of switching times and recovery times should be obtained.

A more interesting geometry is that of Fig. 2 in which the microbridge is contained in a superconducting ring and the bridge optically switched in and out of

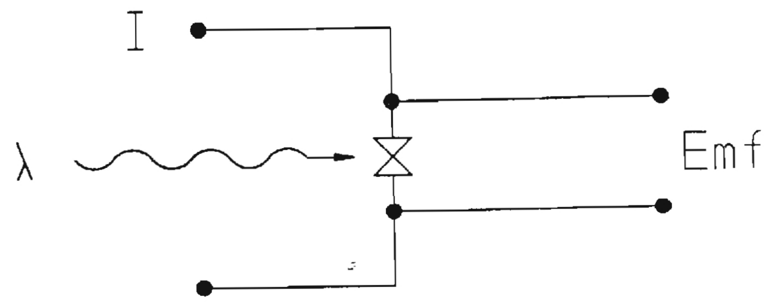

Fig. 1 Optically irradiated microbridge in a current biased superconducting line.

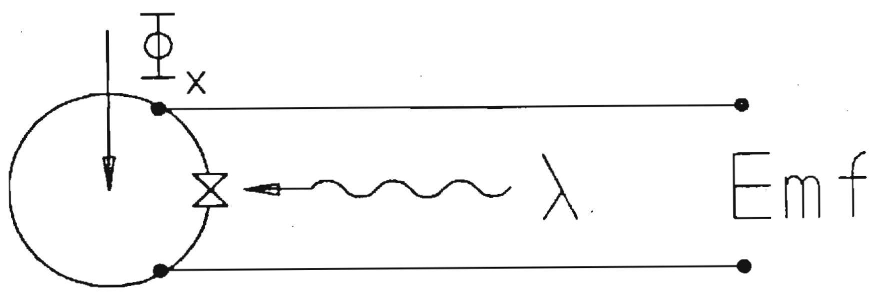

Fig. 2 Optically irradiated microbridge in a superconducting ring with externally applied flux ϕ_X.

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For a single pulse, the total energy E available across the terminals of the pickup loop is just $\Phi_X{}^2/2L$ where L is the inductance of the loop. This amount of energy is generally insufficient to be detected. However if the switching is done periodically at fairly high frequency, an easily detected amount of energy can be available since the signal power available is $P_S = 1/2$ Ef, if the emf is assumed to be sinusoidal. In fact the signal power is just the same as that from an rf SQUID of the same inductance operating at frequency f. In the rf SQUID switching is accomplished by an induced circulating rf current which exceeds the critical current of the bridge each cycle. In this case there is a large oscillating energy in the coil due to the pumping rf, but the available signal power resulting from the external flux Φ_X is just the same as that for the optically switched ring. Thus the ring can be quite properly considered to be an optically pumped SQUID.

III. Ring Configurations and Characteristic Parameters

For our first experiments, superconducting rings of the type shown in Fig. 3 have been chosen. From our past measurements on niobium thin film microbridges, we expect the resistance of the bridges to be 0.1 - 1 ohm and the critical current I_S to be a few hundred microamps. For the 10 μm-square ring, the applied magnetic field to produce one flux unit is 0.2 Gauss. The inductance of the ring is approximately 10^{-10} henry and, as an indication of the energy stored in the ring, one flux unit trapped in the ring provides an energy $\Phi_0^2/2L$ of $\sim 10^{-19}$ J. To trap a flux unit in a ring of this size requires a current of 200 microamperes, which is consistent with the critical current of the ring. The L/R time of the ring will be $\sim 10^{-11}$ to 10^{-10} s which is consistent with operating the ring at microwave frequencies.

The impedance level at which the emf is generated is very low, however by resonating the line which couples the emf to the first amplifier it should be possible to match reasonably into the 50 ohms of the amplifier. At low frequencies we expect to accomplish tuning by a small variable capacitor across the line at the input of the amplifier. At higher frequencies the length of the coplanar transmission line can be a quarter wavelength and therefore serve to match the low impedance of the ring to the input of the amplifier.

To establish some energy scale for the amount of light required to switch the superconductor we note that the energy required to break all the pairs in one coherence length of the link is just the Josephson coupling energy $\Phi_0/2\pi I_c$ or about 3×10^{-20} J. Supplying this energy in about 10^{-11} s would require an optical power of 3×10^{-9} watts, which is clearly a lower limit to what is actually required. As another possible limit, we might assume that we must heat the entire link above the

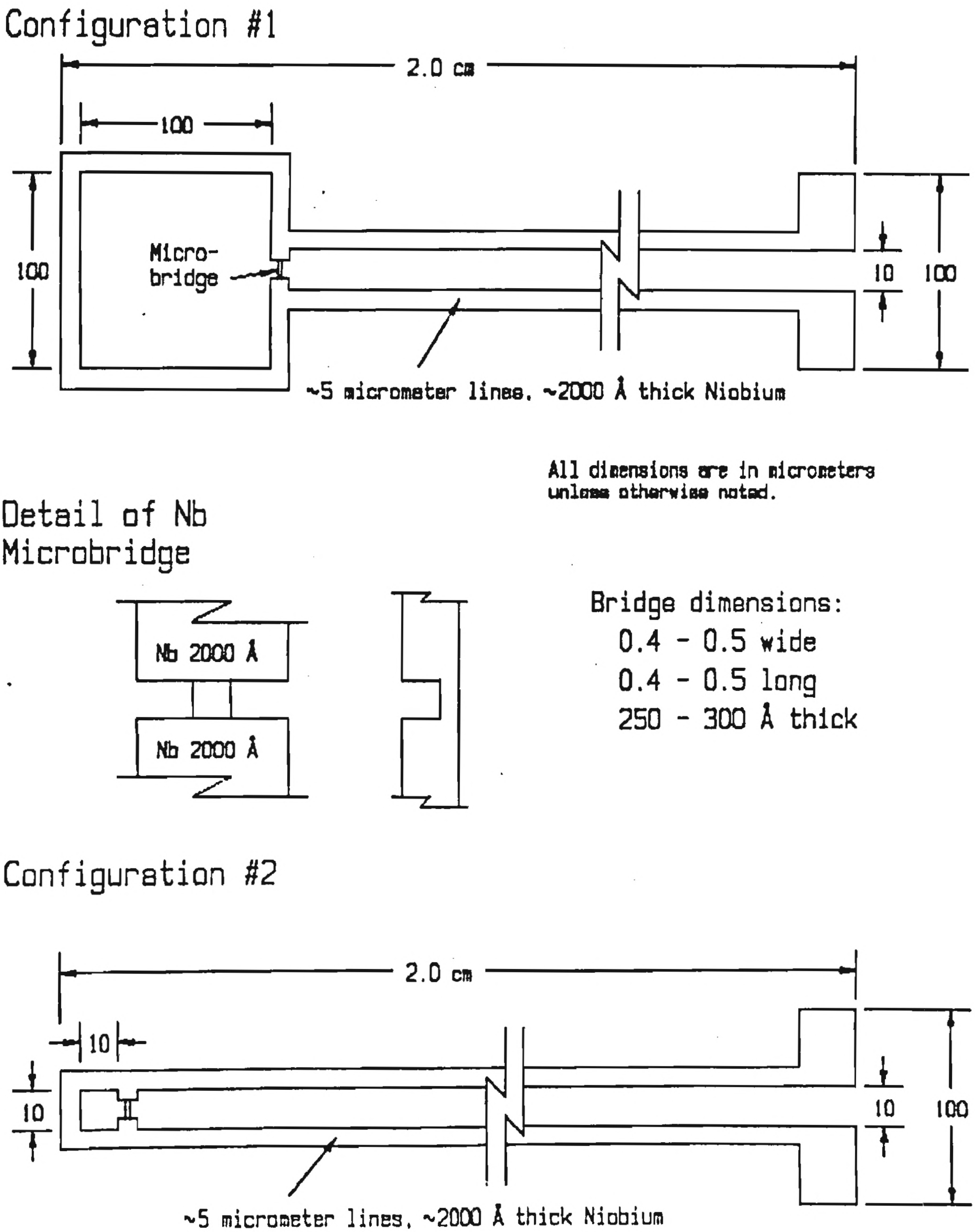

Fig. 3 Nb Ring with Nb Microbridge and Coplanar Line on Sapphire Substrate.

transition temperature of niobium. Assuming a heat capacity of 2×10^{-3} J/gm K and a density of 8.4 gm/cm^3, and assuming the bridge must be heated through a temperature change of 5K, the energy required is $\sim 10^{-17}$ J, which if supplied in 10^{-11} s would require ~1 microwatt of optical power. At 1 GHz the signal power is about 10^{-10} watt.

IV. Fabrication of Superconducting Rings

Rings of the type shown in Fig. 3 were fabricated at the National Research and Resource Facility for Submicron Structures at Cornell University during the third week of December 1986. All the crucial steps in the fabrication were carried out by the extremely helpful staff of the Submicron Facility including particularly Brian Whitehead, Nellie Whetten and Timothy Whetten. Kenneth Brown from the University of Cincinatti, who was working at the Submicron Facility during this same week, was also very helpful in assisting with the photolithography.

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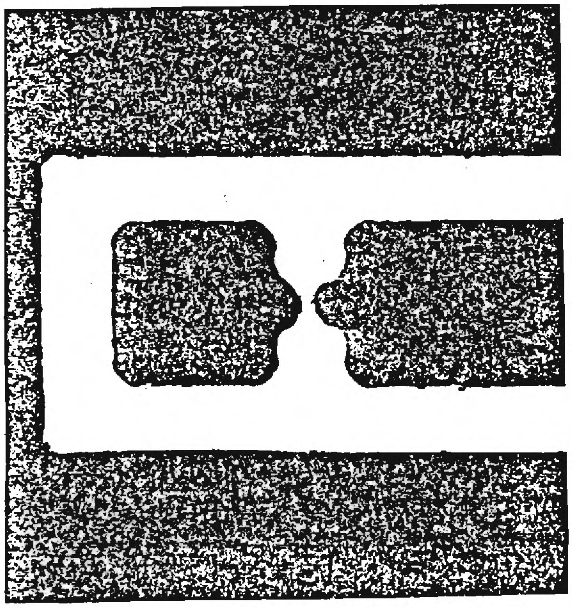

Fig. 4 Scanning electron microscope photograph of Nb thin film in configuration #2 at 2000x magnification.

Final Report on Subcontract No. E-21-J21-S1

between

Georgia Institute of Technology

and

University of Virginia

for work on

Optically-Induced Superconducting Switches

and Optically Pumped SQUIDs

Principal Investigator:

Bascom S. Deaver, Jr.
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Physics Department
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Charlottesville, VA 22901
804-924-6574

Date 6/25/87

Optically-Induced Superconducting Switches and Optically Pumped SQUIDs

I. Introduction

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This report describes the design of some experiments to observe optically induced switching in very small microbridges in superconducting niobium films by using an optical fiber to focus the light from a laser diode onto the microbridge. The work at UVa has been done by B. Deaver and by Lindsay Faunt, who is a graduate student in the Physics Department.

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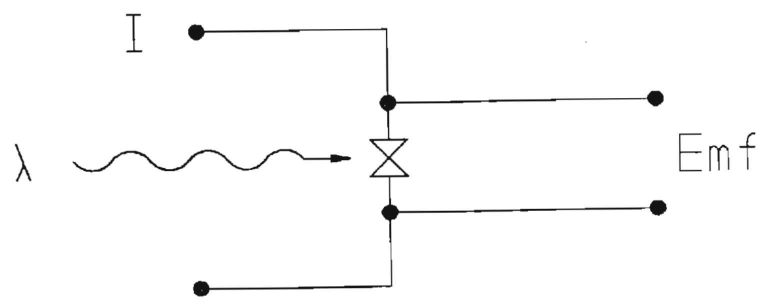

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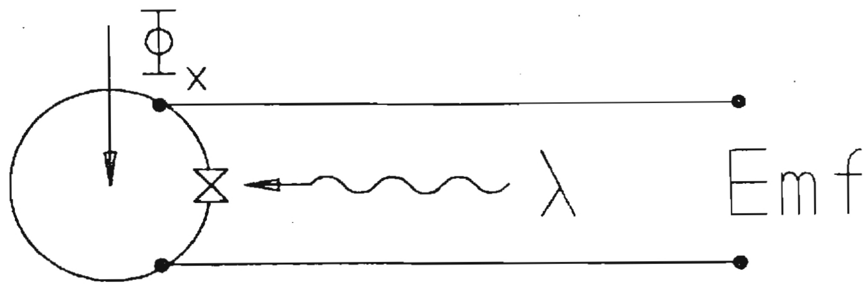

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For a single pulse, the total energy E available across the terminals of the pickup loop is just $\Phi_X{}^2/2L$ where L is the inductance of the loop. This amount of energy is generally insufficient to be detected. However if the switching is done periodically at fairly high frequency, an easily detected amount of energy can be available since the signal power available is $P_S = 1/2$ Ef, if the emf is assumed to be sinusoidal. In fact the signal power is just the same as that from an rf SQUID of the same inductance operating at frequency f. In the rf SQUID switching is accomplished by an induced circulating rf current which exceeds the critical current of the bridge each cycle. In this case there is a large oscillating energy in the coil due to the pumping rf, but the available signal power resulting from the external flux Φ_X is just the same as that for the optically switched ring. Thus the ring can be quite properly considered to be an optically pumped SQUID.

III. Some Related Experiments and Characteristic Switching Times

Many years ago Kwiram and Deaver[1] and subsequently Henry[2] performed experiments in which thin walled superconducting cylinders about 25 μm in diameter were switched periodically in and out of the superconducting state with an electrical heater inside the cylinder. In their experiments a many turn pickup coil surrounded the cylinder and, even at audio frequencies, there was ample signal power available to be observed. The periodic variation in the magnitude of the induced emf as the applied flux Φ_X was smoothly increased was used to measure the fluxoid quantum.

These relatively bulky cylinders could be operated at frequencies up to several hundred kilohertz. One can ask how fast a niobium thin-film ring can be expected to cycle. The rate, of course, depends on both the detailed mechanism of the destruction of superconductivity in the bridge as well as the recovery mechanisms. For example, it might be assumed that for a sufficiently thin bridge the electric field penetrating the film might depair the electrons without actually heating the lattice. The recovery processes will include diffusion of the quasiparticles out of the weak link region into the bulk banks of the film, and diffusion of pairs into the bridge. Within the bridge there will be recombination of pairs, and the resulting binding energy will appear as gap phonons which must escape from the bridge in order for it to return to equilibrium. Because of the mechanical mismatch between the film and its substrate, the dominant mode of escape of the phonons is along the length of the bridge into the banks. In many cases the recovery to the superconducting state has been shown to be dominated by the time required for these phonons to dissipate. The complete process is very complicated including other times like the time for the quasiparticles to scatter down to energies just above the Fermi surface before they recombine. There is also an electromagnetic time constant involved, the L/R time of the ring, where L includes not only the magnetic inductance of the ring but the kinetic inductance of the bridge. The recovery time for bridges that are extremely short, for example one coherence length long joined by bulk films on each side, has been shown to be extremely short, approaching 10^{-12} s. There are some direct measurements of times related to the recovery time of microbridges. Wang and Deaver[3] studied in great detail the properties of niobium variable thickness bridges approximately 0.5 μm long, 0.5 μm wide and 300 Å thick joining bulk films approximately 2000 Å thick. A detailed analysis of heating effects in these bridges including temperature dependence of the subharmonic gap structure, thermally induced hysteresis, a self sustaining hot spot and bolometric mixing of 90 GHz signals, all indicated that the thermal response time was between 10^{-9} and 10^{-10} s. Measurements made at the Naval Research Laboratory[4] indicated similar kinds of recovery times for microbridges. Thus we expect that optically induced switching might operate at frequencies well into the microwave range, and large signal powers could be expected like those in microwave SQUIDs. As a magnetometer being switched at 10^9 - 10^{10} Hz, the device could be used to observe rapidly changing fluxes Φ_X.

IV. Ring Configurations and Characteristic Parameters

For our first experiments, superconducting rings of the type shown in Fig. 3 have been chosen. From our past measurements on niobium thin film microbridges, we expect the resistance of the bridges to be 0.1 - 1 ohm and the critical current I_S to be a few hundred microamps. For the 10 μm-square ring, the applied magnetic field to produce one flux unit is 0.2 Gauss. The inductance of the ring is approximately 10^{-10} henry and, as an indication of the energy stored in the ring, one flux unit trapped in the ring provides an energy $\Phi_0^2/2L$ of $\sim 10^{-19}$ J. To trap a flux unit in a ring of this size requires a current of 200 microamperes, which is consistent

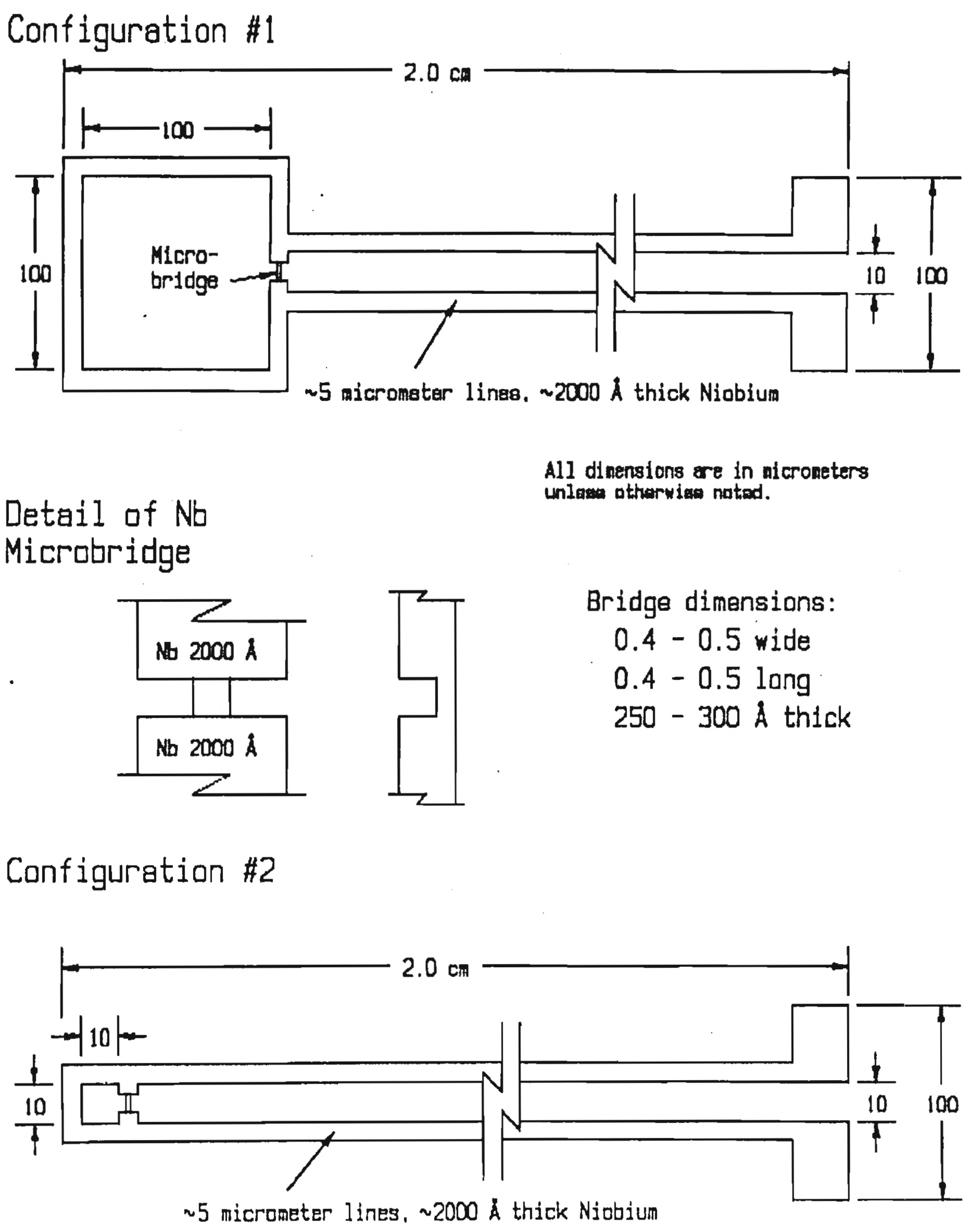

Fig. 3 Nb Ring with Nb Microbridge and Coplanar Line on Sapphire Substrate.

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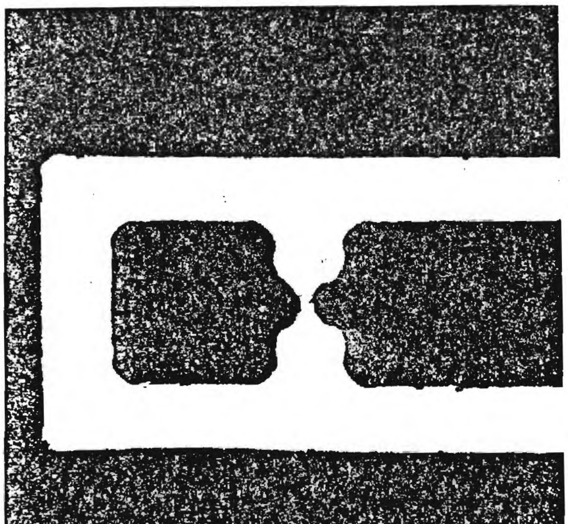

Fig. 4 Scanning electron microscope photograph of Nb thin film in configuration #2 at 2000x magnification.

VI. Design of Experiments to Observe Switching

Because during this phase of the contract no funds were available for equipment, only a conceptual design for the experiments to test the switching of these rings was completed. Key features of the design are shown in Fig. 5. The sapphire substrate will be attached with GE7031 varnish to a copper deck cooled to 4.2K. Separated by a small gap from the sapphire substrate is a fiberglass circuit board with coplanar transmission lines connecting to an integrated circuit wide band amplifier (2-1250 GHz). The part of the circuit board containing the amplifier is heat sunk at room temperature while the end nearest the superconducting circuit is anchored to a liquid nitrogen cooled baffle. An ultrasonic bonder will be used to connect fine gold wires between the pads at the end of the niobium coplanar line and the copper line feeding the wide band amplifier.

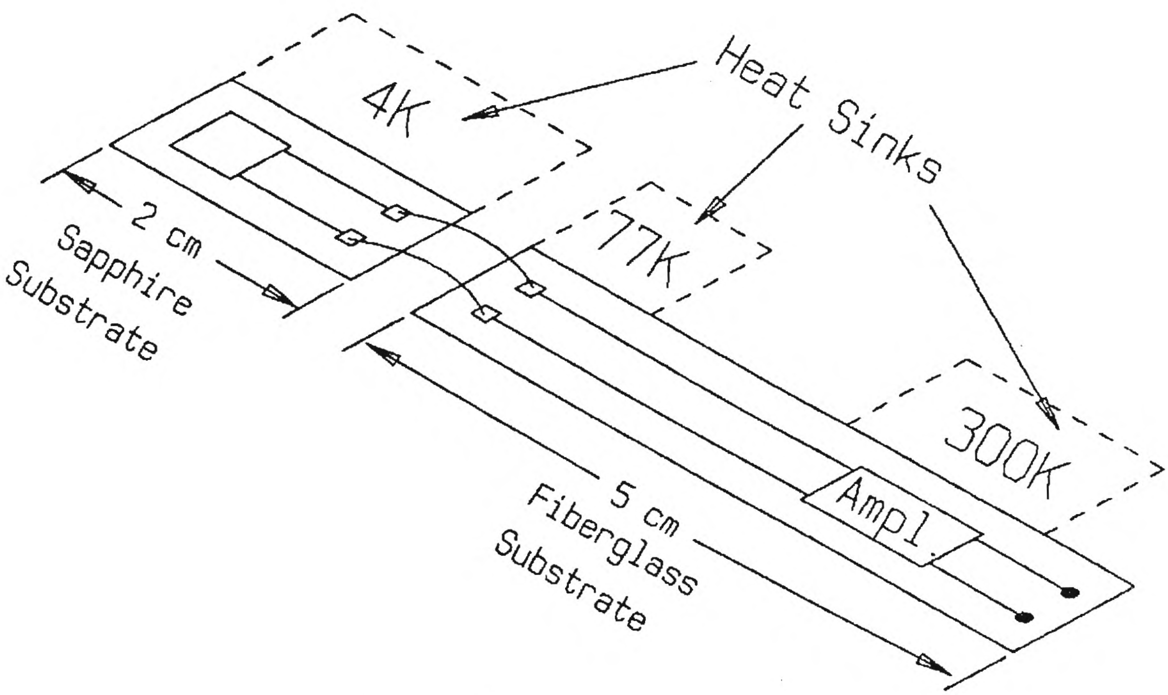

Fig. 5 Diagram of the superconducting ring with coplanar transmission line connecting to a wide band amplifier.

A 5 μm diameter single mode optical fiber is to be used to guide the light from a laser diode to the weak link. The end of the fiber will be drawn down to ~1 μm diameter or less and this small tip mounted just above the weak link in an xyz translation stage so that the tip can be positioned precisely over the bridge after cooling to liquid helium temperatures. This entire assembly is to be mounted inside the base of an Infrared Laboratories Model HD-3 dewar with an enlarged work space like that of the HD-3 with temperature controlled work stage (see Fig. 6) but without the temperature controlled stage. The optical fiber is to pass through an access port to the outside of the dewar where it will be coupled with a lens assembly to a Mitsubishi Model 3101 laser diode. This laser produces ~3 mW at a wavelength of 815 nm. (Other possibilities are the Mitsubishi Model 4402 which gives 3 mW at 780 nm or Model 5101 giving 15 mW at 830 nm.) By applying both a dc bias and an rf modulation the intensity of the laser can be adjusted and modulated at frequencies up to 1.5 GHz. Adjustments for the translation stage pass through other access ports on the dewar and are designed to be detachable once the adjustment has been completed so that they do not provide a large heat leak to the substrate. As a possible aid in aligning the fiber over the bridge, a hole is provided through the copper heat sink immediately beneath the link so that the link can be viewed optically through the sapphire substrate.

The same arrangement will be used for measurements of the first kind on current biased weak links which will be formed by simply opening the superconducting ring.

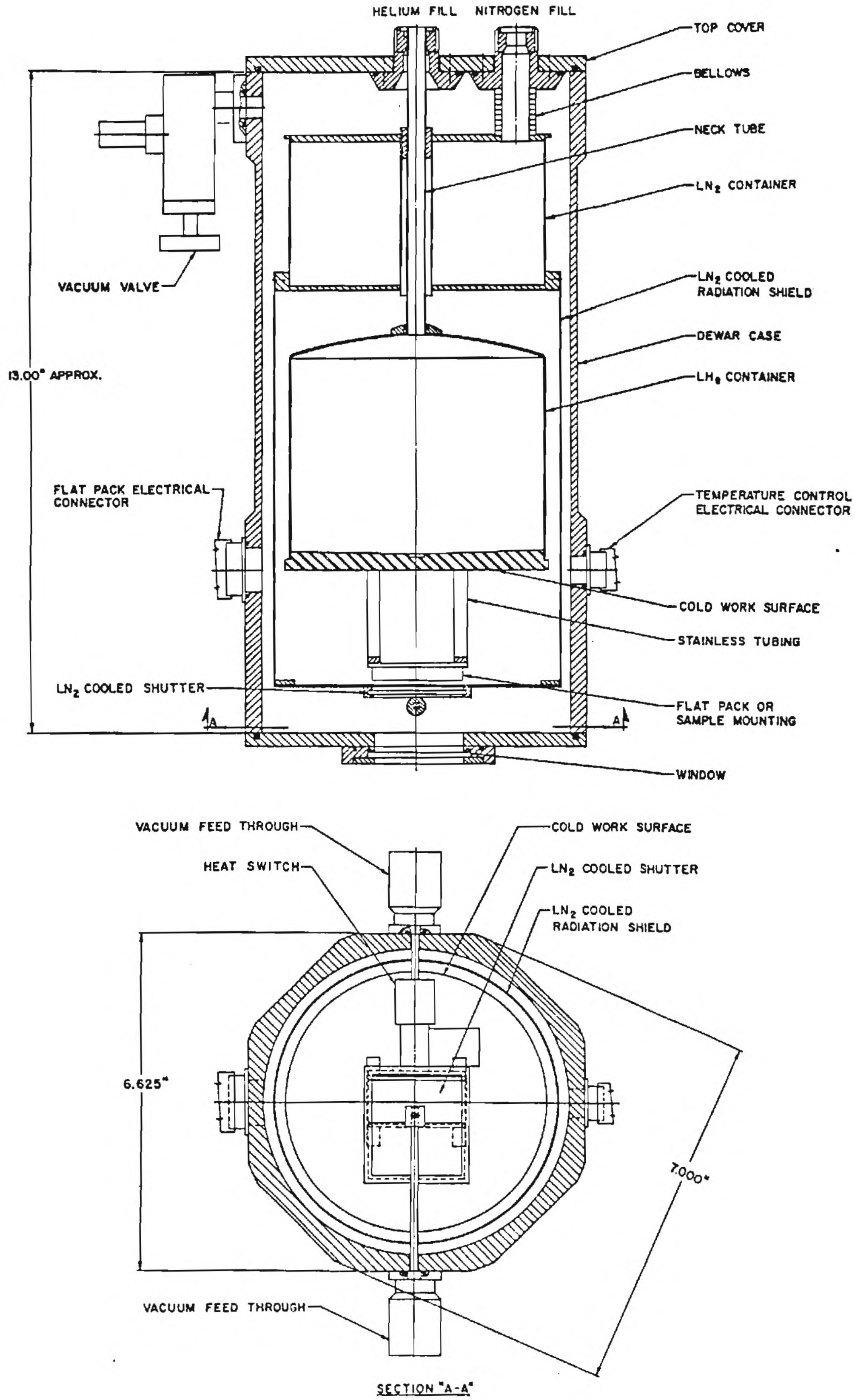

Fig. 6 Infrared Laboratories, Inc. Model HD-3 Dewar with temperature controlled stage.

VII. Alternative Geometry and Arrays for Magnetic Measurements

To have some hope of completing initial experiments within the constraints of time and funding the simple planar design described above has been chosen. However, a much more attractive configuration is possible using strip line geometry shown in Fig. 7. In this scheme techniques of integrated optics would be used to form an optical wave guide in a dielectric material lying on top of a superconducting stripe. By milling away the dielectric down to the superconducting film a sharp step would be formed at the end of the wave optical guide and the weak link then deposited directly on the end of the guide. The superconducting ring would be

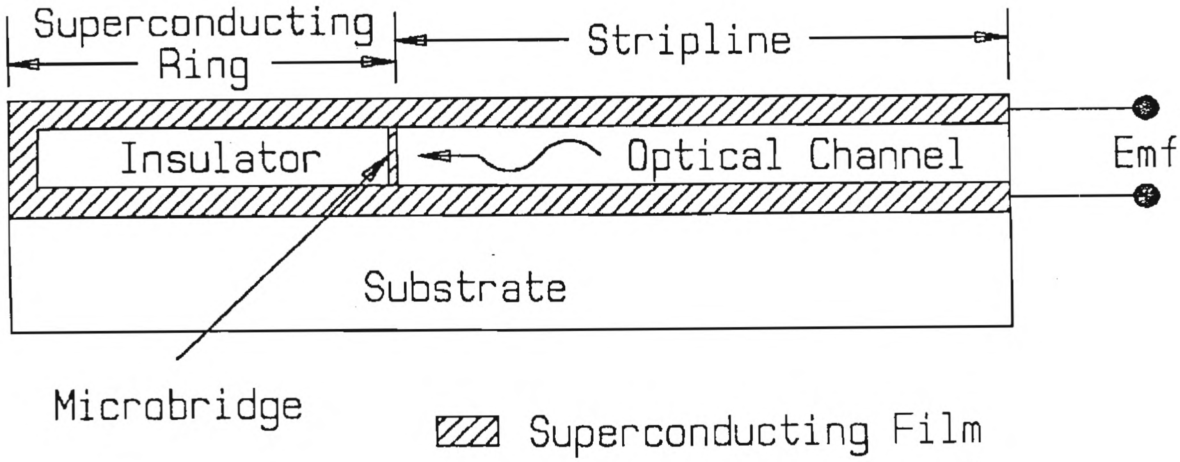

Fig. 7 Optically switched microbridge in superconducting ring in stripline geometry.

completed by depositing an insulator to replace the dielectric that had been milled away beyond the step in the waveguide and then an upper superconducting stripe laid down directly over the waveguide and shorted to the film at the far end to complete the superconducting ring. The strip line geometry might provide more convenient impedance matching to the room temperature amplifier. This geometry has the further advantage of being capable of producing a pickup loop that is very thin in one dimension, and thus capable of very good spatial resolution along that dimension.

A major motiviation for this work has been the desire to have a capability for measuring the magnetic field at many closely spaced points in a plane immediately above a current carrying surface. From measurements of the field the current density distribution in the surface could be deduced. Furthermore, if the device is capable of responding at relatively high frequencies it would be possible to observe time variations of the current density distributions. With a sufficiently fine grained array of magnetic field detectors it should be possible to measure the trapped flux distribution in superconductors or in superconducting thin films and to observe flux motion. A similar device could be used to measure the current density distribution in semiconducting devices with currents dominantly in surface layers.

Optically switched SQUIDs may be particularly useful for such arrays because in contrast to rf SQUIDs there are relatively small circulating currents in the rings and consequently much less disturbance from rf coupling between adjacent rings.

VIII. Conclusion

The design described in this report appears to offer a relatively simple scheme for studying optical switching in thin film bridges that can be expected to yield useful information for applications of these switches in superconducting circuits for magnetometry.

References

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4. F.J. Rachford, S.A. Wolf, J.K. Hirvonen, J. Kennedy and M. Nisenoff, IEEE Trans. Mag. MAG-13, 875 (1977).