14:32:23 OCA PAD AMENDMENT - PROJECT HEADER INFORMATION 06/07/91

Active

Project #: E-21-582 Cost share #: Rev #: 4
Center # : P5075-0A0 Center shr #: OCA file #:
Work type : INST
Contract#: NGT-50526 Mod #: SUPPLEMENT 2 Document : GRANT
Prime #: Contract entity: GTRC

Subprojects ? : N CFDA: N/A
Main project #: PE #: N/A

Project unit: ELEC ENGR Unit code: 02.010.118
Project director(s):
RODRIGUE G P ELEC ENGR (404)894-2944

Sponsor/division names: NASA / MARSHALL SPACE FLT CTR, AL
Sponsor/division codes: 105 / 005

Award period: 890622 to 920621 (performance) 920621 (reports)

Sponsor amount	New this change	Total to date
Contract value	22,000.00	61,200.00
Funded	22,000.00	61,200.00
Cost sharing amount		0.00

Does subcontracting plan apply ?: N

Title: HIGH TEMPERATURE SUPERCONDUCTOR PHASE SHIFTERS

PROJECT ADMINISTRATION DATA

OCA contact: Ina R. Lashley 894-4820

Sponsor technical contact	Sponsor issuing office
EUGENE URBAN/MAIL CODE ES63	ROBERT KOLB/CODE HWC-1
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GEORGE C MARSHALL SPACE FLIGHT CTR	CONTRACTS & GRANTS DIVISION
MARSHALL SPACE FLIGHT CENTER	WASHINGTON, DC 20546
ALABAMA 35812	

Security class (U,C,S,TS) : U ONR resident rep. is ACO (Y/N): N
Defense priority rating : N/A N/A supplemental sheet
Equipment title vests with: Sponsor GIT
"USE OF FUNDS FOR PURCHASE OF EQUIPMENT IS NOT PERMITTED."
Administrative comments -
SUPPLEMENT 2 AUTHORIZES 3RD YEAR FUNDS ($22,000) AND EXTENDS GRANT ONE YEAR.

Dr-459

GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION

NOTICE OF PROJECT CLOSEOUT

Closeout Notice Date 12/11/92

Project No. E-21-582 Center No. P5075-0A0

Project Director RODRIGUE G P School/Lab ELEC ENGR

Sponsor NASA/MARSHALL SPACE FLT CTR, AL

Contract/Grant No. NGT-50526 Contract Entity GTRC

Prime Contract No.

Title HIGH TEMPERATURE SUPERCONDUCTOR PHASE SHIFTERS

Effective Completion Date 920621 (Performance) 920621 (Reports)

Closeout Actions Required:	Y/N	Date Submitted
Final Invoice or Copy of Final Invoice	N	
Final Report of Inventions and/or Subcontracts	Y	
Government Property Inventory & Related Certificate	N	
Classified Material Certificate	N	
Release and Assignment	N	
Other	N	

CommentsLETTER OF CREDIT APPLIES. EFFECTIVE DATE 6-22-89. CONTRACT VALUE $61,200.

Subproject Under Main Project No.

Continues Project No.

Distribution Required:

Project Director	Y
Administrative Network Representative	Y
GTRI Accounting/Grants and Contracts	Y
Procurement/Supply Services	Y
Research Property Managment	Y
Research Security Services	N
Reports Coordinator (OCA)	Y
GTRC	Y
Project File	Y
Other HARRY VANN-FMD	Y
FRED CAIN-OOD	Y

NOTE: Final Patent Questionnaire sent to PDPI.

E-21-582

1 Theoretical Accomplishments

High frequency delay lines are important components in signal processing applications. Presently, methods of delay incorporate surface acoustic waves, magnetostatic waves, and ferrite devices. However, these passive devices suffer from limitations of bandwidth, and signal-to-noise ratios. Superconducting delay lines promise low loss, low dispersion, high integrated device density, and the possibility of externally controlling the phase velocity.

The application of superconducting transmission lines to phase shifters relies on controlling the inductance of the transmission line in a repeatable manner. The relationship between inductance and wave velocity is

$$v_p = \frac{1}{\sqrt{LC}} ,$$

where C is the distributed capacitance of the transmission line. Consider the superconducting transmission line shown in Figure 1. Ignoring fringing fields, the

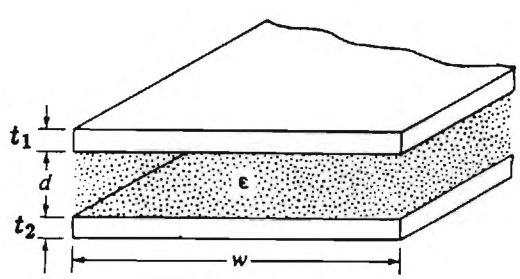

Figure 1: Superconducting thin strip over a ground plane. After T. Van Duzer.

inductance of this structure is proportional to

$$L \propto \left[1 + \frac{\lambda_1}{d}\coth(t_1/\lambda_1) + \frac{\lambda_2}{d}\coth(t_2/\lambda_2)\right] , \tag{1}$$

where the subscripts 1 and 2 refer to the strip and ground plane respectively, λ is the penetration depth of the superconductor of thickness t, while d refers to the thickness of the dielectric. In Equation (1) the first term on the right is associated with the usual geometric inductance due to flux linkage, while the second and third terms correspond to the kinetic inductance of the superconducting films. This kinetic inductance is due to the inertial mass of the current carriers in the conductor. In normal conductors, the kinetic inductance is usually masked by the resistance of the conductor, whereas in a superconductor the resistance can be much smaller than the kinetic inductance. Inspection of Equation (1) shows that the transmission line will have a significant kinetic inductance provided that thin superconductors ($t < \lambda$) are sputtered onto thin dielectrics ($d < \lambda$). In this regime, the inductance of the transmission line may be modulated by adjusting the penetration depth of the superconductor given as

$$\lambda = \sqrt{\frac{m^*}{\mu_o \eta_s (e^*)^2}} \ .$$

In this relation, m^*, and e^* are the effective mass and charge of an electron pair, and η_s is the number density of superconducting electrons. For thin films of niobium, a typical value of the penetration depth is $\lambda(T/T_c = 0.5) \approx 86$ nm. Studies of the new high temperature ceramics show a typical value for $YBa_2Cu_3O_{7-\delta}$ of $\lambda(T/T_c = 0.5) \approx 260$ nm, with different values reported for differently processed films.

Control of λ is accomplished by changing the density of superelectron pairs. For instance, increasing the ambient temperature will decrease the population of superconducting electrons and increase the penetration depth. The control of η_s has been realized by temperature variation, and may also be realized by any depairing mechanism such as magnetic field, quasiparticle injection, or even optical irradiation. In the past, several authors have investigated the possibility of controlling phase velocity of superconducting transmission lines as a function of temperature. However temperature control results in a slow response due to the time required for heat to flow between a heating element and the transmission line. In this work, a novel approach to controlling the penetration depth via magnetic field is investigated. In particular, the Ginzburg- Landau (G-L) theory is used to derive a relation between η_s and an applied magnetic field for thin superconducting films.

It is well known that the state of any system in equilibrium is that state with the lowest free energy. In the early 1950's Ginzburg and Landau applied this concept by formulating a free energy equation of the superconductor. In this theory, G-L postulated the existence of a superconducting order parameter Ψ representing the condensation of electrons from the normal to the superconducting state. In other words, $|\Psi|^2 = \eta_s/\eta$ where η represents all electrons available for conduction. Therefore, $|\Psi|^2$ is normalized between the values of 0 and 1.

By applying the free energy concept, G-L deduced an expression for the free energy density of materials in the superconducting state. This expression includes the effects of applied magnetic fields, temperature, spatial variation of Ψ, and the kinetic energy of the electrons. By applying variational calculus, G-L minimized the free energy with respect to the magnetic vector potential $\vec{A}$ and order parameter Ψ. This resulted in two linked differential equations known as the Ginzburg-Landau equations. Solutions of these equations with the proper boundary conditions will correspond to a state of minimum free energy of the material. Originally, G-L restricted their theory to temperatures near T_c. However, subsequent work has extended the temperature range.

For thin films, Ψ is spatially rigid. Applying this assumption with the proper boundary conditions results in an equation relating Ψ(or η_s) to the applied field H_o:

$$\left(\frac{H_o}{H_{cb}}\right)^2 = \frac{4\Phi_o^2(\Phi_o^2 - 1)\cosh^2(\Phi_o t/2\lambda_L)}{1 - (\lambda_L/\Phi_o t)\sinh(\Phi_o t/\lambda_L)} , \tag{2}$$

where

$$\Phi_o = \frac{\Psi(H)}{\Psi(0)} ,$$

H_{cb} is the bulk critical field, t is the thickness of the superconducting film, and λ_L is the temperature dependent (field independent) London penetration depth $(\lambda_L(0,T))$. In Equation (2), H can vary from 0 to H_c, where H_c is the critical field of the thin film. An interesting result of the Ginzburg-Landau theory is that for films thinner than $\sqrt{5}\lambda_L$, the order parameter Ψ goes smoothly towards zero as the field is increased to H_c. However, for films thicker than this value, Ψ has a minimum value greater than zero, resulting in a discontinuous jump in Ψ at $H = H_c$. Therefore, for maximum velocity control, one should design the device with $t < \sqrt{5}\lambda_L$.

The phase velocity of the superconducting parallel-plate transmission line shown in Figure 1 is given by

$$v_p/c = \frac{1}{\sqrt{\epsilon_{re}}} \frac{1}{\sqrt{1 + (2\lambda(H)/d)\coth(t/\lambda(H))}} \tag{3}$$

where it is assumed that both films are of the same thickness. By inspection of Equation (2), it is apparent that the penetration depth can be controlled by the application of a static magnetic field where

$$\lambda(H) = \frac{\lambda_L}{\Phi_o} \ .$$

Hence, by increasing H_o, Φ_o decreases and increases $\lambda(H)$. A computed plot of phase velocity vs. applied field is shown in Figure 2.

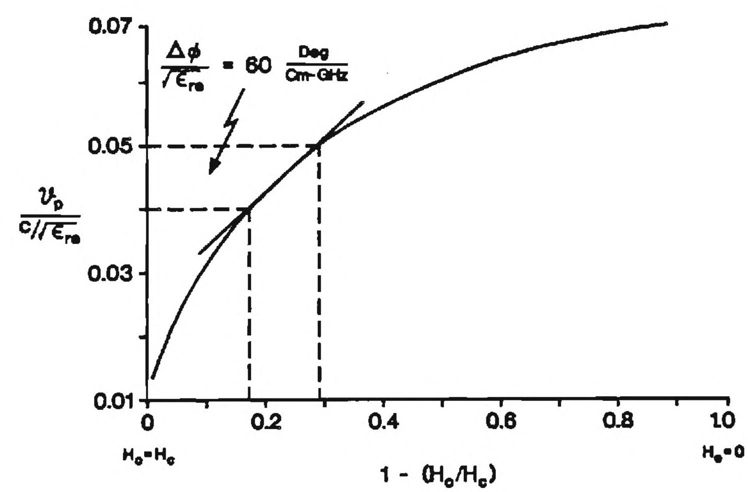

Figure 2: Phase velocity vs. applied field for $d/\lambda_L = 0.1$ and $t/\lambda_L = 0.1$. After R.E. Troxler.

The phase shift of this device can be calculated assuming the usual propagation constant $\beta = \omega/v_p$. This results in a phase difference of

$$\text{Phase Difference} = (\beta_2 - \beta_1)l \ ,$$

where l is the length of the transmission line. Thus the maximum phase difference $\Delta\Theta$ is given as

$$\Delta\Theta = \omega l \left(\frac{1}{v_p(H_c)} - \frac{1}{v_p(0)} \right) \ .$$

This equation can be converted to units of Deg/(cm-GHz) given as

$$\frac{\Delta\Theta}{\sqrt{\epsilon_{re}}} = \frac{360 \times 10^7}{3 \times 10^8} \left(\sqrt{1 + \frac{2\lambda_L}{d\Phi_c} \coth\left(\frac{t\Phi_c}{\lambda_L}\right)} - \sqrt{1 + \frac{2\lambda_L}{d} \coth\left(\frac{t}{\lambda_L}\right)} \right) .$$

By applying this result to the example of Figure 2, phase shifts of about 300 Deg/(cm-GHz) are predicted. However, these calculations do not consider the practical aspects of this device such as loss. These loss mechanisms will limit the performance of this device.

The effects of conductor loss can be modeled by the two-fluid theory, and the effects of dielectric loss are given by

$$\alpha_d = (\omega/2v_p)\,(\epsilon''/\epsilon') .$$

Another important loss mechanism results from the radiation of power or 'leaky modes'. As a consequence of these losses, the relative permittivity (ϵ_{re}) of the transmission line is less than ϵ_r.

2 Experimental Accomplishments

Current research at Georgia Tech also includes an experimental setup to measure the microwave surface resistance of superconductors. This system uses an HP-8510 network analyzer to measure the quality factor of a circular cavity operating in the TE_{011} mode at 16GHz. The following work has been implemented:

- Designed and machined a copper TE_{011} resonant cavity with replaceable end plates
- Designed a coupling system to excite the proper mode in the cavity
- Formulated the equations to extract surface resistance from bandwidth and resonant frequency measurements
- Verified equations by running tests at room temperature with copper end plates

- Designed a 43 $\times$ 2 inch ($L \times D$) pyrex glass vacuum tube with air valves and electrical connections. The resonant cavity is inserted into this tube and the entire assembly is inserted into a super-insulated dewar. The glass tube is filled with an exchange gas of helium, and the dewar is filled with liquid nitrogen (or helium).
- Devised a calibration scheme for the cavity measurements
- Set up necessary hardware allowing a computer to read the temperature of the cavity (K)
- Implemented software to fully automate the measurement process
- Tested entire system from 77K to 300K using copper end plates.

3 Future Experimental Research

More work needs to be performed in the calibration area. This includes hardware adjustments such as the extension of the reference line on the HP-8510. Some software implementation may also be needed. Surface resistance measurements of the new high- temperature superconductors will begin when these materials become available.

4 Future Theoretical Research

- Electromagnetic Analysis including the following effects:
    1. Conductor loss
    2. Dielectric loss
    3. Radiation loss
- Propagation constant and loss mechanisms as functions of:
    1. Temperature

2. Applied magnetic field
3. Transmitted power

- Design of a delay line

1. Dimensions
2. Materials (dielectric, substrate, superconductor)

- Validity of Ginzburg Landau theory

1. Thin film limit
2. Magnetic field limit
3. Temperature limit

- Overall assessment of all assumptions used in theory and design.

The design of a delay line will begin after the electromagnetic analysis has been completed.

E21-582

Georgia Tech

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December 1, 1992

M E M O R A N D U M

TO: NASA Headquarters
Office of External Relations
Educational Affairs Division
Attn: Elaine Schwartz
Code XEU
Washington, DC 20545

NASA Headquarters
Contracts and Grants Division
Attn: Grants Specialist
Code HWC-1
Washington, DC 20545

FROM: G. P. Rodrigue

The attached Administrative Report is being sent in accordance with the provisions of NASA Training Grant Number **NGT-50526.**

GPR:sr
Encls

cc: (1) Frank Six
University Affairs Officer
George C. Marshall Space Flight Center
MSFC< AL 35812

(2) Mary Wolfe
OCA
Georgia Tech

Administrative Report

Submitted to

National Aeronautics and Space Administration

for

Training Grant Number

NGT-50526

To

Georgia Tech Research Corporation

for Support of

Robert E. Troxler

Under the
Graduate Student Researchers Program

Robert E. Troxler was supported by the Training Grant number NGT-50526 over a three year period from July 1989 to June 1992.

Nine months into the program (April 1990) he formally proposed to the School of Electrical Engineering that his Ph.D. Dissertation topic be "Magnetic Control of Superconducting Phase Shifters". This proposal was reviewed by a faculty committee and approved on June 5th, 1990.

Mr. Troxler pursued his research both at Georgia Tech and at Marshall Space Flight Center, Huntsville, Alabama, He received laboratory facility support through Dr. Palmer Peters, of The Space Science Laboratory, and spent some 14 months on experimental work directly in Dr. Peters' laboratory.

By January 1992 he had completed his experimental work at MSFC, and returned to Georgia Tech. Between January 1992 and June 1992, he analyzed his results obtained at MSFC, and using facilities at Georgia Tech. Both computational and experimental facilities were used to investugate the quality of the films. In September of 1992 he submitted a draft of his thesis to a committee of faculty from the School of Electrical Engineering at Georgia Tech. This committee was chaired by his advisor, Dr. G. P. Rodrigue, and included Dr. Glenn Smith and Dr. Albin Gasiewski.

He successfully defended his Ph.D. Dissertation on November 13, 1992 before a Final Examination Committee consisting of the above named faculty from the School of Electrical Engineering with the addition of Dr. W. Brent Carter, Materials Engineering, Georgia Tech, and Dr. Palmer Peters, Marshall Space Flight Center, Huntsville, Alabama. A copy of his Dissertation has been sent to Dr. Frank Six's office, University Affairs Officer, in Huntsville.

His Ph.D. degree will be officially conferred at commencement ceremonies on December 12th, 1992.

Dr. Troxler plans are to pursue a career in industrial research. He will be employed by Troxler Electronic Laboratories, Inc., located in the Research Triangle Park, Raleigh, North Carolina.