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Submitted by A.E. Siegman on behalf
of the faculty and staff of the
Edward L. Ginzton Laboratory

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I. INTRODUCTION

SUMMARY AND OVERVIEW

This annual report covers work done by the Edward L. Ginzton Laboratory JSEP Program at Stanford University, under Contract N00014-75-C-0632, for the period 1 April 1980 to 31 March 1981. Significant progress is reported in high-temperature superconducting Josephson junctions, programmable acoustic wave imaging and signal-processing devices, fiber directional couplers and fiber optic signal processing, acoustic wave processes in new acoustic materials, and measurement methods for ultrafast optical phenomena. The significant accomplishments in each of these five JSEP Work Units are briefly summarized in a "Review of Significant Accomplishments," section at the front of this report, followed by a more detailed annual progress report for each of the six projects.

The reader of this report will note some common features of all six of these projects, as of other research activities in this Laboratory, including

- an emphasis on new physical concepts and interactions, and on the basic physical understanding of those interactions, coupled with
- a strong orientation toward new devices and toward finding practical device applications for these basic physical phenomena, coupled with
- an emphasis on developing new technology, new techniques and processes, for achieving these goals.

The emphasis on basic physics in this work means a heavily scientific orientation toward finding, understanding and explaining new physical
phenomena, using all the tools of fundamental physics, quantum theory and other sophisticated scientific theories where these are needed. The device orientation means that, although new basic scientific information is valued for its own sake, there is also a strong drive to identify potential new device applications for this knowledge, and to develop these device capabilities at least to the point of feasibility demonstration. The researchers are heavily motivated to carry new basic scientific ideas far enough to see them exploited.

The emphasis on technology means such things as sophisticated new thin film preparation techniques, preparation of new materials, growth of crystals in novel fiber forms, construction of new lasers; all of these done in our own Laboratory (or associated Stanford facilities) with our own tools. The crucial materials or samples or instruments in the majority of our projects in fact are made or prepared in-house, not purchased outside, often by novel techniques developed here and not yet available anywhere else. These techniques, as they are developed and their importance shown, are then distributed to industry and elsewhere by publications, by visitors to our Laboratory, and of course most of all by our graduating students.

This emphasis on new technology also means, of course, a constant struggle to maintain the facilities and capability of our Laboratory research facilities. The problem is not so much in buying the latest and most sophisticated instruments as instruments. It is rather in acquiring and supporting the laboratory and scientific shop tools and facilities—and maintaining the laboratory personnel skills—which will enable us to build for ourselves still newer instruments, devices and techniques. This
capability is vital for continued progress at the frontiers, but is also a continual struggle to maintain and develop.

Four of the Work Units summarized in this report are being continued under JSEP support. The research under Work Unit #5, Measurements of Ultrafast Physical Phenomena (A.E. Siegman), is being redirected, with the previous work being continued under other support, while this Work Unit proceeds along a new direction (Picosecond Raman Spectroscopy of Electronic Solids). Work Unit #3, Research on Fiber Optic Interactions with Application to High Speed Signal Processing (H.J. Shaw) has been terminated, since the outstanding work on single mode fibers in this group is now being supported by other government and industrial sources.

Five journal publications were published under JSEP support during the period being reported, with four other manuscripts submitted or in press. At least half a dozen conference presentations and talks also reported on various aspects of the work.
II. REVIEW OF SIGNIFICANT ACCOMPLISHMENTS

A brief review of significant accomplishments during the past year for each of the current Work Units is given in this section. More details on each of these projects will be found in the longer Annual Progress Reports for each of the Work Units, which follow this section.

Work Unit #1: HIGH-\(T_c\) SUPERCONDUCTING WEAK-LINK JOSEPHSON JUNCTIONS AND CIRCUITS, Professor M.R. Beasley

During the past year we produced the first successful superconducting Josephson junction capable of operating reliably at temperatures up to 16.5 K (where cheap, small-scale cryogenic refrigerators are available) and in fact with good performance over a temperature range of 2 K to 16.5 K. All previous high-temperature Josephson devices have been highly idiosyncratic, restricted in their operation to a narrow temperature range near the transition temperature \(T_c\), and have typically exhibited only feeble and strongly temperature-dependent Josephson behavior.

The present devices are SNS (superconductor-normal-superconductor) \(\text{Nb}_3\text{Sn/Cu/Nb}_3\text{Sn}\) Josephson microbridges fabricated in our laboratory using a new variant of "step-edge patterning." They exhibit well-developed Josephson behavior of \(2 \, \text{K} < T < 16.5 \, \text{K}\). The fabrication technique employed is a generic one and should be extendable to any high-temperature superconductor. The electrical characteristics of our new devices appear similar but generally superior to our earlier, lower temperature \(\text{Nb/Au/Nb}\) SNS bridges for which we have developed good theoretical models. These theoretical models should help give us the theoretical foundation for further progress in these devices.
Work Unit #2: ACOUSTIC SURFACE WAVE SCANNING OF OPTICAL IMAGES,
Professor G.S. Kino

During the past year we have demonstrated a novel active and programmable surface acoustic wave device using zinc oxide (ZnO) acoustic waveguides on a semiconducting silicon substrate. Surface acoustic wave (SAW) devices which perform nonlinear functions such as convolution and correlation between two simultaneous rf acoustic signals are now in widespread use, based in large part on earlier work in this Laboratory. Our new device permits simultaneous convolution and correlation of two such signal which can be read into the device at different times. This accomplishment (and extensions of it which we are now developing) are heavily dependent on ZnO film technology developed in our group. We have also developed theoretical explanations, and a new design for focusing acoustic wave couplers.

Work Unit #3: RESEARCH ON FIBER OPTIC INTERACTIONS WITH APPLICATION TO HIGH SPEED SIGNAL PROCESSING, Professor H.J. Shaw

A fiber optic delay line memory has been demonstrated. The delay line utilizes single mode fiber allowing very large bandwidth. The delay line is a solid-state device, constructed entirely of single-mode fiber components. It is thus not only small and rugged, but has much lower insertion loss than comparable systems using classical bulk optical components for closing the recirculating fiber path and for injecting and extracting signals. This device was made possible by the use of efficient single mode fiber directional couplers developed previously under this project.
Work Unit #4: NONLINEAR INTERACTIONS OF ACOUSTIC WAVES WITH DOMAINS IN FERROIC MATERIALS, Professor B.A. Auld

This project is studying the basic nonlinear acoustic properties of novel "ferroic" materials (i.e., ferroelectric-cum-ferroelastic materials) with potential applications in acoustic waveguiding, steering, and signal processing devices. During the past year ten boules of one such material, gadolinium molybdate (GMO), were grown, together with several preliminary fiber samples of this material. A novel technique using laser probing for measuring the nonlinear acoustic resonances of ferroic acoustic resonators was also demonstrated, and will now become a useful research tool for studying further materials properties.

Work Unit #5: MEASUREMENTS OF ULTRAFAST PHYSICAL PHENOMENA
Professor A.E. Siegman

During the past year the optical apparatus for this work unit, including three separately tunable dye lasers pumped by a common Nd:YAG laser, was completed and put into full operation. Laser-induced transient gratings were produced and diffracted probe signals observed in test samples. Full experimentation with the system can now begin. Several publications on related developments in pulsed laser technology were also completed and published.
During the past year we completed (in collaboration with Professor Robert Feigelson of the Stanford Center for Materials Research) and Professor John Shaw, Ginzton Laboratory, a novel apparatus using a CO$_2$ laser for growing single crystal optical fibers of novel and useful materials. So far we have grown and evaluated fibers in diameters from 35 to 500 microns and lengths up to 15 cm, of two orientations of LiNbO$_3$, three orientations of Nd:YAG, and two orientations of sapphire. The physics of single crystal growth in fiber form is extremely interesting, and the device possibilities for optical (and acoustic) waves trapped in fibers of these widely used optical materials are equally interesting.

Studies of the unique domain characteristics, poling properties, and other optical properties of many of these fibers, especially the LiNbO$_3$ fibers, are now under way. Random fluctuations in fiber diameter have also been identified as a major problem with present fibers. Improved growing techniques (using actually a smaller CO$_2$ laser for the fiber growth process) are now being implemented.
III. JSEP Sponsored

Publications and Papers

A.E. Siegman, "Laser Induced Grating Techniques for Picosecond Spectroscopy," Report of Workshop on Picosecond Spectroscopy (sponsored by DARPA), La Jolla Institute, La Jolla, California, May 7-8, 1980. (Partially supported by AFOSR.)


* Totally or partially

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IV. INDIVIDUAL WORK UNIT RESEARCH PROGRESS

Unit 1

HIGH-T<sub>c</sub> SUPERCONDUCTING WEAK-LINK JOSEPHSON JUNCTIONS AND CIRCUITS

M. R. Beasley
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A. Research Plan and Objectives

The underlying, long term objective of this program is to explore the feasibility of high-T<sub>c</sub> and/or hard Josephson junction superconducting thin-film circuits; to establish the relevant physics, fabrication procedures, and operating characteristics of such devices; and hopefully to lay the groundwork for a superconducting integrated circuit technology based on these materials. This objective requires the development of practical high-T<sub>c</sub> and/or hard Josephson devices and also the passive circuits elements necessary for a complete circuit technology. Success in this program would lead to devices capable of operating at substantially higher temperatures (~ 10-15 K) and/or more rugged circuits resistant to damage due to thermal cycling, handling, and hostile field environments.

Toward this general objective we have been developing superconducting weak-link (i.e., non-tunneling) Josephson junctions using refractory and high-T<sub>c</sub> superconducting materials and by necessity thin-film deposition, microlithography, and processing technologies suitable for such materials. Specifically we have been concentrating our efforts on the A15-type superconductors, for example Nb<sub>3</sub>Sn (T<sub>c</sub> = 18 K) with related work on elemental Nb(T<sub>c</sub> = 9 K) in order to more easily test some of our fabrication techniques.
From the theoretical point of view when considering refractory and high-$T_c$ superconducting materials the most attractive type of weak-link Josephson junctions appear to be planar SNS (superconductor/normal metal/superconductor) or SSemiS (superconductor/semiconductor/superconductor) bridges, although it must be noted that granular superconducting weak links have recently shown interesting performance.\textsuperscript{1,2} A satisfactory theory of such devices has not yet been developed, however, so it is hard to assess their relative advantages and disadvantages. In this program we are focusing on SNS bridges. These bridges are like the usual SSS superconducting microbridges but where the bridge region itself is a normal metal while the banks are superconductors. The rationale for such devices is that by making the bridge region itself from a normal metal (e.g., Cu, Au, or Ag) one can circumvent the extremely small ($< 100 \, \AA$) bridge dimensions theoretically required to obtain ideal Josephson behavior in a totally superconducting high-$T_c$ bridge. In such SNS bridges the dimensions need only be submicron and ideal Josephson behavior should be available over the entire temperature range $0 < T < T_c$.

To achieve such structures in practice we have been using electron-beam evaporation to make suitable thin-film bilayers (e.g., Nb$_3$Sn or Nb on top of Cu or vice versa) out of which the desired submicron planar SNS (e.g., Nb$_3$Sn/Cu/Nb$_3$Sn) bridges are formed.

\textsuperscript{1,2}K. K. Likharev, Rev. of Mod. Phys. 51, 102 (1979).

\textsuperscript{1,2}See for example, J. H. Claassen, Appl. Phys. Lett. 36, 771 (1980).
The fabrication procedures are then appropriately modified in light of the observed electrical properties of the junctions. More specifically the problem is to fabricate a short (≤1 μm) normal metal bridge connecting two superconducting banks while ensuring good contact at the S/N interfaces and not degrading the superconductivity (e.g., reducing $T_c$) of the banks through damage in the fabrication process. At the same time we have been developing theoretical models for such devices based on the Usadel, Ginzburg-Landau and Time-Dependent-Ginzburg-Landau Theories of superconductivity.

B. Progress and Accomplishments

In the earlier phases of this project we explored various techniques for actually forming the desired submicron bridge structures and mastered the necessary lithography and etching procedures. Key to this work was our demonstration that plasma etching was an ideal processing technique. Specifically that it not only provided the desired spatial resolution and material selective properties but also that it did not damage the superconducting materials involved leading to a reduced transition temperature. With this technology we successfully produced Nb/Cu/Nb and Nb/Au/Nb bridges that exhibited good SNS behavior over the entire temperature range $0 < T < T_c$ > 9 K. These devices were the best SNS Josephson devices made to date. The proved the refractory SNS device concept and allowed us to critically test the theory of such devices.
During the past year we have completed our theoretical analysis of these devices and proceeded aggressively toward our original goal of a high-$T_c$ SNS devices. Both have been successful. On the theoretical side we have found that the usual idealized theory of SNS devices developed by Likharev does not properly account for the specific geometry and S/N interfacial properties encountered in real bridges. By suitably modifying this theory we have developed an improved theory that phenomenologically accounts very well for the observed electrical properties of these devices, specifically the magnitude and temperature dependence of the $I_R$ product and the $I-V$ characteristics. Two papers describing the experimental and theoretical aspects of this work have been submitted for publication.\textsuperscript{1,3} A microscopic justification for our phenomenological approach will require further study.

On the experimental side we have finally succeeded in our original objective of making high-$T_c$ SNS microbridges. The crucial new element required was the introduction of so-called "step-edge patterning" in our processing to define the bridge length. The idea here is to use a vertical step in the substrate (See figure) and the shadowing effect of off-normal-indicence angles of deposition to deposit the two superconducting banks with a small gap (down to $\approx 500 \, \AA$) between them, followed by deposition of the normal metal out of which the bridge can be formed by conventional methods.

Fig. 1 Schematic of the Nb₃Sn/Cu/Nb₃Sn microbridges. a) Cross section. The film thicknesses for the bridges reported here are: Cu: 100nm, Nb₃Sn: 100nm and Si: 126nm. The directions of evaporation are shown by the arrows on top. b) The width of the bridge is approx. 3mm.
lithography. The use of step-edge patterning has solved two important problems. First it allows the fabrication of very short bridges in a controllable way. Second, since the bridge length is defined without etching, it permits one to put the normal metal on top where it can be deposited on the more favorable (upper) surface of the superconductor and avoids the deterioration of the normal metal film experienced previously when it was necessary to heat the film to high temperatures in order to deposit a good superconducting film on top. The resulting $\text{Nb}_3\text{Sn}/\text{Cu}/\text{Nb}_3\text{Sn}$ SNS microbridges have exhibited well-defined and robust Josephson behavior from 2 K up to 16.5 K. Occasional bridges have exhibited resistances up to $1 \, \Omega$ and $I_c R_N$ products up to 1 mV which is outstanding performance for such devices.

C. Publications (under this JSEP Program)

Previously Reported


Impending Publications


A. Introduction

At the present time our work focuses on developing acoustic surface wave devices, utilizing the interaction between surface acoustic waves and charge carriers in a semiconductor. Most of our device designs involve the use of piezoelectric zinc oxide which is rf sputtered onto a silicon substrate. Due to the piezoelectric nature of the zinc oxide, electric fields are generated by the acoustic surface waves propagating along the device. These electric fields penetrate into the silicon substrate and interact with the charge carriers near the silicon surface.

Our work now centers around two types of devices:

(1) A programmable active delay line in which signals can be read into the device by means of a charge transfer device (CTD) on the silicon substrate underneath or adjacent to the ZnO layer. After programming the device in this way, we could then use the device in a wide variety of signal processing applications including, but in no way restricted to, adaptive and inverse filtering. This device is an excellent example of the uses to which sophisticated LSI technology can be put in sophisticated real-time applications involving real-time analog and digital signal processing.

(2) An acoustic surface wave waveguide storage correlator.
B. Progress and Accomplishments

We feel that a basic building block for surface wave correlators and programmable delay lines is a narrow, waveguided acoustic surface wave device. Narrow beamwidth devices possess an inherent advantage over wider beamwidth devices since the acoustic power density in the propagation path is proportionally higher, resulting in a more efficient device operation. Additionally, narrow beamwidth devices offer the advantage of high fabrication densities, which offer the potential of constructing two-dimensional devices for imaging and signal processing applications. The device which we have recently investigated is a $\Delta v/v$ waveguided monolithic ZnO on Si storage correlator. A device such as this offers the advantage of high efficiency and straightforward fabrication utilizing the techniques well familiar to those involved in standard IC processing.

The waveguide storage correlator, illustrated in Fig. 1, employs a piezoelectric ZnO layer deposited on Si. Interdigital transducers are used at each end of the device to inject or receive acoustic surface wave signals. In the central region, a row of p-n diodes is fabricated in the silicon underneath the acoustic beam path and metal films (top plate electrode and waveguide metallizations) are deposited on top of the zinc oxide. Since the acoustic surface wave velocity is slightly lowered in the presence of the gold film, the surface wave tends to propagate only in the region defined by the gold films; therefore the waveguiding effect is achieved.

In order to understand the operation of this device, consider what happens when a short pulse of voltage $V$ is applied to the top plate. The
Figure 1

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pulse "turns on" each diode so that the capacity between the top plate and an individual diode becomes charged to a potential close to $V$. After the pulse is turned off, the capacity remains charged. Clearly then the device can store an analog signal. If at the same time an acoustic surface wave signal is passing under the plate when the diode is turned on, the signal stored in the capacitor consists of the sum of the acoustic surface wave signal and the applied pulse. A spatial pattern of charge corresponding to the surface wave signal is stored along the length of the device. At a later time, a further "reading" pulse applied to the "top plate" turns on the diodes once more, but the potential at which they turn on depends on the signal stored in the capacitors. Thus, a spatially varying signal is excited along the length of the device which, in turn, excites acoustic surface waves which can be received on either interdigital transducer. If a more general form of reading signal is applied, the correlation of this signal with the original signal read into the device is obtained as an output from one transducer, and the convolution of the two signals is obtained from the other transducer.

The device itself has been operated in several different modes, but basically it functions as a highly flexible signal processing device which correlates signals either read into it at the same time or read into it at different times.

The results obtained from a waveguided correlator of this type have been extremely encouraging and showed a correlation efficiency $F_T^{corr} = -53$ dBm where $F_T^{corr}$ is defined as

$$F_T^{corr} = 10 \log \left( \frac{P_3}{P_1 P_2} \right)$$
$P_{e1}$, $P_{e2}$, and $P_{e3}$ are, respectively, the input acoustic power, the read-out power applied to the top-plate electrode, and the output power, all expressed in mW. This terminal correlation efficiency $F_{T}^{\text{corr}} = -53$ dBm is 13 dB better than that reported for any other Rayleigh wave ZnO on Si storage correlator. A paper on this device has been published in the Journal of Applied Physics.¹

At the present time we are attempting to further improve the bandwidth and efficiency of the waveguided correlator by development of a new interdigital transducer design. This involves using a curved transducer approximately 1 mm wide to focus an acoustic surface wave beam into one end of the narrow waveguide (see Fig. 2). It has been necessary to develop a new theory for the design of a curved transducer which takes account of focusing in an anisotropic medium. Our design theory, presented at the 1980 Ultrasonics Symposium in Boston, Massachusetts, predicts to second order that the effective focal length of the curved transducer will shift in relation to the amount of parabolic anisotropy present in the medium of surface wave propagation.² Figure 3 shows most graphically the effect that the material anisotropy has on the focusing properties of the curved transducer by comparing the transducer SAW beam profiles both at the transducer's center of curvature (expected focal spot) and at the true focal plane. The parameter $b$ is a measure of the material anisotropy and is defined by the parabolic approximation to the slowness curve:

$$k = k_0(1 + b \theta^2)$$
TOP VIEW OF FOCUSED IDT WAVEGUIDE CORRELATOR
TRANSVERSE RESPONSE AT CENTER OF CURVATURE
OF FOCUSED TRANSDUCER

\[ b = 0.36 \]
\[ \lambda = 32 \mu \]
\[ R = 5 \text{ mm} \]

TRANSVERSE RESPONSE AT FOCAL PLANE

\[ b = 0.36 \]
\[ \lambda = 32 \mu \]
\[ R = 5 \text{ mm} \]

Fig. 3.
Figure 4 shows the radiated power contours for the same transducer design as in Fig. 3.

We have fabricated a LiNbO$_3$ elastic convolver using this focused transducer concept and have obtained very encouraging results. The convolver showed a convolution efficiency $F_{\text{CON}} = -73$ dBm with an insertion loss of -20 dB. This higher than usual insertion loss is believed to be caused by inefficient waveguide excitation by the focused interdigital transducers.

In order that we may more accurately understand the mechanisms of loss in our surface acoustic wave convolvers and correlators, we have set up a laser system to probe our devices and provide us with a map of surface wave amplitude and phase at any point in the propagation path. The system is based on a Michelson interferometer where one arm of the interferometer has its optical length modulated by the surface undulations of the device under scrutiny. The optical beams in both arms of the interferometer are modulated using a Bragg cell in order to provide stability against spurious path length variations.

Programmable SAW-CTD Storage Device

The programmable delay line concept involves constructing an adaptable monolithic SAW filter which can be programmed from an external source. To do this, we intend to combine the features of the acoustic surface wave storage correlator and a charge transfer device (CTD) on one silicon substrate and therefore avoid the pitfalls of hybrid technologies which limit the number of taps which can be realistically employed.
RADIATED POWER CONTOURS FOR A FOCUSED TRANSDUCER

RADIUS OF CURVATURE $R = 5 \text{mm}$
ANGULAR APERTURE $\alpha = 0.2 \text{ rad}$
$\lambda = 32 \mu\text{m}$

$\theta = 0.36 [(11\bar{1}) \text{ PROPAGATION ON } (111)\text{ Si}]$

Fig. 4.
The basic principles of operation of this device follow directly from that of the storage correlator. Figure 5 shows a simplified view of the device. We see here that it is very similar to the storage correlator except for the important difference that each diode is connected to a MOSFET, the drains of all the individual MOSFETS being connected to a common input-output line. The gates of the MOSFETS themselves are controlled by a shift register. We see that this device employs far more sophisticated semiconductor techniques than just the diffusion of simple diodes. It is capable of processing high-frequency signals (from the surface acoustic waves), while controlling the processing with relative low-frequency signals (by way of the shift register/multiplexer arrangement). It is also possible to use such a configuration as a system for reading in and processing a signal at high speed using surface acoustic waves and reading out the processed signal at low speeds using the CTD portion of the device.

At the present time, photo-sensitive devices have been developed which read out the charge produced by light incident on a row of diodes from an illuminating source, such as one line of a TV image. Thus, the basic devices exist which can switch from an input-output line to any one of a row of diodes.

One such commercial device which we experimented with is made by Reticon Corporation. This device (RL 512 S) is a solid state line scanner in which a series of 512 FET switches are used to connect individual diodes to an input-output line. These switches are addressed one after the other by a controlling signal inserted into a tapped shift register with one tap per switch. The beauty of using this sophisticated device lies in the fact that
Figure 29

Schematic of SAW/FET device

**INTERDIGITAL SAW TRANSDUCER**

**700 ELEMENT DIODE ARRAY**

**INTERDIGITAL SAW TRANSDUCER**

CLOCK \( (f_c) \) → **SHIFT REGISTER**

\[ f_{saw} \gg f_c \]

READ-OUT OF DIODE CHARGES OR INPUT CHARGE PATTERN TO DIODE ARRAY

**SCHEMATIC OF SAW/FET DEVICE**
in order to convert it to an adaptable SAW filter, we need, in principle, only to deposit a zinc oxide layer with a metal film laid on top of it (with associated surface wave transducers) on top of the diode array. Thus, we are not only able to read a signal into (or out of) the diodes at the surface wave frequency (64 MHz) but also address the diodes slowly at the frequency of the CTD multiplexer (less than 2 MHz).

As one simple example, we might read in a coded signal through the CTD into the diodes. This forms a set of taps with variable weighting on the acoustic surface wave delay line. Therefore, if a signal is read into the acoustic surface wave delay line and read out of the top plate on the high-frequency terminal, the device acts as a programmable tapped delay line. Thus, we should be able to make programmable filters, variable delay devices, etc. by reading a low-frequency analog signal into the device. As this low-frequency analog signal can in turn be controlled from a shift register or RAM through a D-to-A converter, we now have the possibility of constructing a range of coded surface wave devices whose codes are obtainable from a digital memory.

A major difficulty in using the Reticon device has occurred in our ability to deposit high-quality zinc oxide over the diode array. During the last year our zinc oxide technology has progressed to the point where we can reliably deposit extremely high-quality zinc oxide over thermally grown silicon dioxide, but we have experienced considerable difficulty in performing the zinc oxide deposition on top of the chemical vapor deposited (CVD) silicon dioxide as is found over the diode array on the Reticon device. This is due to the more irregular structure of the CVD silicon dioxide as compared to
thermally grown silicon dioxide. In order to surmount this unyielding problem with the Reticon device, we decided that it was in our best interest to pursue the development of our own, custom-made multiplexed FET arrays. With the invaluable aid of the Stanford Integrated Circuits Laboratory, we have developed an array that is much more suited to our previously established goals. By doing this we have accomplished several objectives:

(1) The Stanford device design has 700 taps as compared to the 512 tap Reticon device. An increase in the number of taps makes the device a more powerful signal processor;

(2) The tap spacing in the Stanford device has been reduced as compared to the Reticon device, thus allowing higher frequency (100 MHz) surface acoustic wave propagation.

(3) The Stanford device is fabricated in a way to insure complete compatibility with the acoustic surface wave concept. In other words, the topography of the device is well suited for the rf sputter deposition of a ZnO layer.

At the present time we feel that we are quite close to obtaining a fully operational SAW/FET. We have evaluated our zinc oxide films grown on the Stanford device design by way of x-ray diffraction scans and interdigital transducer impedance curves. The results of both of these diagnostic techniques lead us to believe that the Stanford SAW/FET is topographically compatible with the deposition of reasonably high-quality ZnO films.

Recently we have discovered that the ZnO sputter deposition lowers by approximately one volt the threshold voltage of the MOSFET's present in the shift registers of the SAW/FET. Although this has the effect of changing
enhancement mode transistors into depletion mode FET's, proper device 
operation can still be achieved by the application of a suitable offset to the 
substrate potential. We have in fact fabricated a SAW/FET complete with zinc 
oxide that has shown to work as a simple shift register, albeit only with 
strangely offset clock voltages. We feel though that this minor problem might 
be easily rectified by an improved silicon nitride passivation of the device 
 prior to the zinc oxide deposition. Based on the above results, we feel very 
confident that we will have a completely operational device in a short period 
of time.

We believe that these concepts are merely the first of a wide range of 
devices which could be constructed with entirely new configurations and system 
arbitrage if the necessary LSI and VLSI silicon technology were available. We have described here, for instance, only a device controlled 
from a shift register input; a still more flexible valuable time delay signal 
processing device could be made if the control were directly made from a RAM 
input rather than the shift register. Yet other possibilities arise by using 
amplifiers in the acoustic analog system rather than passive diodes. Thus, 
with a sophisticated VLSI technology available, a new signal processing 
technique can be devised to carry out analog or digital signal processing in 
real time at relatively high frequencies (in the UHF range).

C. Publications and Papers Citing JSEP Sponsorship

1. J. B. Green, B. T. Khuri-Yakub, "A New Narrow-Bandwidth High Efficiency 
Zinc Oxide on Silicon Storage Correlator," J. Appl. Phys. 52 (1), 

A. Introduction

The aim of this project has been the study of optical fiber systems for high speed signal processing. Our approach has been to work toward the development of recirculating delay lines, and the key fiber optic components that make these delay lines possible.

Systems of this kind (Fig. 1) have been developed using closed loops of coaxial cable or waveguide as recirculating delay lines for the storage of signals modulated onto microwave rf carriers. Such systems are used for temporary storage and retrieval of broadband microwave signals in ECM applications. Analogous systems using surface acoustic wave delay lines at UHF frequencies have been developed, and have been applied here earlier, under a JSEP project, to signal processing operations. Systems using bulk acoustic wave delay lines have also been developed as transient memory stores for digital signal processing. In our present approach, the microwave coax or waveguide delay line is replaced with a fiber optic waveguide, with prospects for much larger bandwidth and delay time per circulation.

Fig. 1--Schematic of recirculating delay line.
B. Approach

The approach is to use long, single mode optical fibers, taking advantage of the low attenuation available in such fibers (fractional dB per kilometer) for storing long signal trains. Fibers can be coiled with very large numbers of turns to provide a long propagation path occupying small volume and having very high information capacity and processing speed. Even with the existing attenuation one can get storage times of many microseconds. One hundred microseconds, for example, would correspond to perhaps 15 dB. With the use of optical amplifiers for recirculation of the signal, one can obviously do much better. Another project being conducted here under other sponsorship is concerned with developing optical amplifiers. However, even in the absence of an amplifier one can still get very interesting performance. Also, the exceptionally low dispersion per unit time delay in single-mode fibers means that extremely high data rates can be transmitted via single mode fiber. As a result, delay line devices that use single-mode fiber can have time-bandwidth products that greatly exceed those achievable in similar devices that use conventional technologies.

A key component required is a directional coupler suitable for single mode fibers, which can inject or extract a propagating signal in a fiber without breaking into the fiber. Such a coupler for fiber-to-fiber coupling, with controllable coupling and very low insertion loss, was developed earlier under the present contract.

C. Single Mode Fiber Recirculating Delay Line

The experimental delay line consisted of a single strand of single mode fiber of 200 meter length, which provides a delay of 1 µs per transit. The

directional couplers indicated in Fig. 1 are of the type demonstrated earlier under this program, and which is now being further developed under another program in the laboratory. Basically, this device consists of two quartz substrates whose flat surfaces are mated face-to-face through a layer of oil. Each substrate carries a length of single mode fiber, a portion of whose cladding has been removed by mechanical polishing, exposing the evanescent fields of the fiber cores. Coupling between the two parallel and adjacent fibers takes place over a distance of approximately 1 mm, and is adjusted to any desired value by translating one substrate with respect to the other in the direction perpendicular to the fibers. Coupler loss is only a few percent.

The delay loop was closed upon itself by carefully cleaving the fiber ends, butting them together and using a drop of index matching oil to eliminate any discontinuity at the splice. The completed system is shown schematically in Fig. 2.

In order to test the system an electro-optic cell was used to pulse modulate a low power He-Ne laser (633 nm). The resulting short pulses (~ 2 ns width) were injected into the loop via the input coupler. The couplers are adjusted for a relatively low coupling which maximizes the number of circulations. Thus a large fraction of the input power is discarded at the input coupling point. However, that light which is coupled into the loop tends to remain there, subject to the losses encountered during each circulation: coupling and insertion loss at each coupler, coupling loss at the splice, and propagation loss around the loop. The output coupler samples the signal on each pass and guides it to the detector.
Fig. 2--Schematic single mode fiber recirculating delay line.
This system shows a large improvement over the earlier hybrid system, giving the same number of observable recirculations, namely six, with a reduction in laser output power by a factor of 50. Furthermore, in the present system the limitation on circulations is not associated with the fiber circuitry, but with the laser source and detector system available when the measurement were made.

D. Conclusions

The use of integrated fiber optic circuitry has significantly improved the performance of the recirculating delay line, and forms the basis for future developments being carried out here under other support. More efficient detection and processing of the output signal are to be applied. Also, a significant amount of loss occurs at the fiber splice. The development of less lossy and more permanent methods of fiber splicing will greatly enhance the performance of this system as well as others that use single mode fibers. The injected input power for a given source could be greatly increased if the input coupler were switchable on a time scale that is short compared to the transit time around the loop. Such a switchable coupler is presently under study in this laboratory. The inclusion of an amplifier in the circuit to compensate for loop losses would greatly increase the circulation times and the utility of the device. Such a fiber amplifier is presently being developed in this laboratory under another program.

E. Publications and Papers Citing JSEP Sponsorship

A. Introduction

Ferroic materials (ferromagnetic, ferroelectric and ferroelastic) have the unique property of exhibiting switchable configurational states with distinct macroscopic material properties. These states are not only switchable but also have a latching property, or memory. That is to say, once the material is switched it remains in the switched state until further addressed by an electric or mechanical signal. Furthermore, different regions of a single specimen of ferroic material may be in different configurational states. These regions of distinctly different configurational states, called domains exhibit distinct physical properties and the boundaries between domains, or domain walls, are therefore surfaces of abrupt change in material properties. The existence of switchable and latching boundaries of this nature provide a basis for a variety of optical and acoustical devices such as diffraction and phase matching gratings, directional couplers, filters and memory stores. The goal of this project is to study the nonlinear interaction of acoustic waves with domains (primarily in ferroelastics and ferroelectric-ferroelastics) with a view of gaining a better understanding of the physics involved and then evaluating the potential of such materials for new device applications.
The general research plan focuses on (1) the nonlinear acoustic properties of ferroic materials, particularly the influence of domain walls on these nonlinearities, (2) the influence of domain wall structure on acoustic parametric processes and harmonic generation and, (3) the interaction between a domain wall and the static forces generated by nonlinear elastic "rectification" of an acoustic wave. We are concentrating our efforts on two materials - gadolinium molybdate (GMO), a ferroelectric-ferroelastic, and neodymium penta- or ultra-phosphate (NPP), a pure ferroelastic. The latter material, which is currently arousing great interest with regard to miniature infrared laser applications but is not commercially available, is being furnished to us in a cooperative effort by Dr. W. Zwicker of Phillips Laboratories. Another related activity at Stanford is being developed by the Crystal Technology Group in the Stanford Center for Materials Research. This concerns a new technique for growing thin single crystal fibers of ferroelectric and ferroelastic materials and studying the properties of domains in these fibers. We are currently continuing to interact closely with this group.

With regard to potential device applications of the materials and phenomena under study, these all involve the use of periodic arrays of grating, created and aligned by either the nonlinear acoustic methods referred to above or electrical poling techniques above the Curie temperature. Specifically of interest are acousto-optic diffraction gratings for signal processing, phase matching for collinear phase


matched optical harmonic generation and gratings for distributed feedback lasers. The latter aspect of the potential is of particular interest in connection with the miniature NPP lasers noted above.

B. Progress and Accomplishments

In last years progress report it was noted that experiments on domain wall motion induced by a nonlinearly generated static elastic stress had not met with success. Three areas of basic investigation were proposed to explain and overcome these negative results: (1) a study of reasons why the threshold for domain wall motion might be higher than expected - i.e., because of material imperfections, edge cracks, and the fact that nonlinear stresses generated in the resonators used for the experiment are spatially nonuniform; (2) a detailed examination of the nonlinear elastic properties of ferroelastic materials in order to base predictions of the intensity of the rectified elastic field on measured rather than estimated third order elastic constants; (3) reconsideration of the nature of the interaction of domain walls with the nonlinear elastic field.

During the reporting period March 1980 to March 1981, attention has been focused on item (2) above, on preparing our own samples of GMO in both boule and fiber form, and on improving our technology of resonator fabrication. With regard to items (1) and (3) and also to advancing basic physical knowledge of nonlinear elasticity in ferroelastics, it has been arranged for a visiting scientist specializing in ferroic materials, P. Toledano of the University of Picardie, to spend six months at Stanford (July through December 1981). As a guide to future experiments, he will perform fundamental calculations on third order...
elastic constants and domain wall motion in ferroelastics.

(i) Third Order Elastic Constants in Ferroelastic Materials

The reason for expecting unusual nonlinear elastic effects in a ferroelastic material is very simple. It is based on consideration of the free energy as a function of the strains. Since the elastic constants are equal to the various second derivatives of the free energy with respect to the strains, the level of elastic nonlinearity can be quickly estimated from the shape of the free energy curves. In particular, a purely parabolic curve has constant second derivatives and, therefore, strain-independent elastic constants. The free energy function of a ferroelastic has a double minimum, corresponding to its two equilibrium states, and should therefore be strongly nonlinear. These elementary considerations are complicated by the fact that a ferroelastic may be either proper or improper, depending on the nature of the order parameter of the ferroic transition (i.e. mechanical or electrical). Furthermore, even in a proper ferroelastic (such as NPP), the order parameter may be an internal optical mode displacement rather than elastic strain and this should have a substantial effect on the degree of elastic nonlinearity. These questions have been discussed with Prof. G.R. Barsch of The Pennsylvania State University, who has studied nonlinear elasticity both theoretically and experimentally in some of the intermetallic ferroelastics. It is verified by his work that these particular ferroelastics do exhibit unusually large third order elastic constants. As yet, no corresponding studies have been made of ferroelastic insulators (such as NPP, a proper ferroelastic, and GMO, an improper ferroelastic).
Pending the arrival of Prof. Toledano, a purely experimental study of the nonlinear elastic properties of GMO and NPP has been initiated. Basic measurement methods for determining third order elastic constants are observation of changes in the second order constants as a function of hydrostatic pressure, and observation of acoustic wave second harmonic generation (SHG). The second approach, followed here, uses either the standard traveling wave method or a resonator method developed under this program. In the traveling wave technique an acoustic delay line is fabricated from the material under study, with the fundamental and second harmonic outputs detected by means of a capacitive pickup. The newly developed resonator technique has two advantages from our point of view: (1) it is more sensitive because of resonance build up of the second harmonic signal, and (2) it measures nonlinearity in the presence of sample boundaries, as required for domain wall interaction experiments.

Several acoustic SHG experiments have been performed during the past year. Two resonators were fabrication in order to test the resonant SHG concept - a face-shear mode quartz resonator and an extensional mode PZT (lead zirconate titanate ceramic) resonator. In the first case no second harmonic was observed because the electrode design provided insufficient coupling to the second harmonic resonance. The PZT resonator, on the other hand, showed a strong harmonic output. Subsequent to this work, during the stay of a visiting scientist Dr. D. Hauden from one of the National Research Center Laboratories in France, the idea was conceived of using a laser probe to measure directly the fundamental and second harmonic acoustic displacements at the surface of the sample. This is a modification of the capacitive pickup technique mentioned
above, but with a number of practical advantages. It does not require
critical mechanical assembly, it is adaptable to any traveling wave or
resonant sample geometry, and it allows remote probing of a sample
placed in an oven or cryostat - an important feature for the study of
materials with a ferroelastic phase transition. Attempts to realize
this new experimental method led to the invention of a novel phase-
heterodyning technique for isolating the second harmonic signal
generated acoustically in the crystal. In essence, the optical probe
technique is based on phase modulation of a laser beam reflected from
the vibrating acoustic sample. Since phase modulation is a nonlinear
process, harmonics of the acoustic drive frequency are generated by the
modulation process, as well as by elastic nonlinearity in the sample.
The method developed for separating these contributions involves secon-
dary phase modulation of the light beam by a "local oscillator" fre-
quency, using an electro-optic modulator. This produces mixed frequency
side bands of the desired signal, which can be separated by the follow-
ing electrons. (In June 1981 the method was successfully realized with
the PZT resonator referred to above and is the subject of a publication
submitted to Electronics Letters.)

(ii) Composite Resonator Design and Fabrication

Observation of nonlinear domain-wave interactions in a
ferroelastic resonator requires choice of a geometry favoring both
domain wall motion and simple standing wave resonances. This choice is
complicated by the fact that ferroelastics have low order crystal sym-
metries and, consequently, complicated elastic behavior. Since domain
walls are most easily injected and displaced in thin plate samples, this
geometry was selected for study, with the elastic vibration spectrum analyzed by Mindlin theory. Figure 1 shows a mode spectrum for NPP. This is typical of plate resonator spectra for other materials and illustrate the three types of resonance modes encountered:
(1) Extensional E, (2) Flexure F, and (3) Width Shear. The two mode-types of interest are flexure and width shear, since only these have a shear strain component that interacts strongly with the domain wall. Earlier work on this program was directed toward use of the width shear mode for domain-wave interactions. It is clear from the figure, however, that the flexure family has much cleaner behavior, and the resonators currently under study are all of this type. Since NPP is a nonpiezoelectric crystal, it can be used only in a composite resonator structure - with some suitable piezoelectric driver attached to it. This has been realized by bonding a thin elongated plate Lithium Niobate (LN) resonator to the NPP resonator, Fig. 1, thereby effecting a coupling between the modes of the two plates. Figure 2 illustrate this coupling by comparing the resonance frequency of the uncoupled LN plate with that of the LN-NPP composite. It is seen that the coupled NPP resonances are clearly visible.

(iii) Crystal Growth

Crystals of NPP used in this work are provided to us in a cooperative effort with Dr. W. Zwicker of Phillips Laboratories. During the past year we have embarked, in collaboration with Dr. R. Feigelson of the Stanford Center for Materials Research, on a program of growing our own GMO. This latter activity has two parts; one the growth of

Fig. 1—Theoretical frequency spectrum of extensional, flexure, and width shear modes in a thin plate NIP resonator.
Fig. 2(a)--Measured frequency spectrum of a Lithium Niobate (LN) thin plate resonator in the configuration of Fig. 1 with \(c/b = 1\).
Fig. 2(b) -- Measured frequency spectrum of an NPP resonator with c/b = 5 bonded to the LN driver resonator of Fig. 2(a). Comparison of the two curves shows NPP resonances superposed on Fig. 2(a).
boules by the standard Czochralski method and the other the growth of single crystal fibers by a laser melting and pulling technique. During the year, ten GMO boules were grown, attempting to reproduce and adapt to our laboratory the procedure described by Brixner\textsuperscript{4,4} Quality improved generally but the process is not yet under control with respect to simultaneous control of the problem areas: diameter control, interface shape, cellular growth, and precipitates.

The GMO fiber growth activity, related to a general program on single crystal fibers at Stanford, is motivated by a desire to avoid some of the difficulties in Czochralski growth and also, by directly preparing samples in small cylindrical geometries, to avoid some of the difficult subsequent steps required in preparing small ferroelastic devices. Since GMO is electro-optic, as well as ferroelastic, it has the additional attraction of being a candidate for optical fiber devices. Several fibers have been pulled from a GMO seed but examination showed that they were highly nonuniform. This was found to be due to noncongruent melting, with the molybdenum evaporating rapidly in the laser heating. Several techniques have been tried for maintaining excess molybdenum, including fabrication of a seed with a solid molybdenum core. None of these has been successful and a solution will be looked for by using a hot-pressed powder seed with molybdenum enrichment. It should be noted that these difficulties are not unexpected, as GMO is the first noncongruently melting crystal attempted under this fiber growth activity.

C. Publication and Papers

Impending Publications


A. Introduction

The general objective of this group is to develop and apply new laser methods for the measurement of ultrafast physical, chemical and biological processes – an area which has come to be known as picosecond spectroscopy. The particular objective of this project is to demonstrate and make use of a novel technique we recently proposed which should permit the measurement of subpicosecond physical phenomena using a tunable laser-induced grating method.

Over the past few years our group has successfully measured several ultrafast processes (partially under JSEP support) using picosecond laser pulses in a transient laser-induced grating technique.\(^2\)\(^-\)\(^7\) In this pulsed technique two picosecond pulses from the same laser arrive at an experimental sample at the same time, but from two different directions, creating a transient interference pattern and producing a transient hologram or grating of excited states in the sample. The diffraction of


a separate variable-delay probing pulse by this grating is then measured as a function of the delay between excitation and probe pulses. By observing the diffracted intensity versus delay time in this manner, we have measured both fast relaxation times and orientational rotation times \(10^{-8}\) to \(10^{-11}\) sec) in organic dye molecules,\(^2,3\) and also fast transport or diffusion processes of excited electronic states in organic molecular crystals.\(^4,5\) Very interesting microwave acoustooptic effects have also been observed.\(^6\)

Many important physical processes have characteristic times in the subpicosecond range. In the tunable laser-induced grating technique being developed under this project the excitation beams are cw (or long-pulse) lasers which have an adjustable frequency difference \(f_d\) between them, with \(f_d\) in the 0.1 - 100 cm\(^{-1}\) range. These two beams produce a moving interference pattern, whose fringes sweep through the sample at the frequency \(f_d\). The excited-state pattern induced in the sample then follows or does not follow these moving fringes, depending upon whether the excited state response time \(\tau\) is short or long compared


to the frequency $f_d$. In particular, for $f_d > 1/\tau$ the excited states will
not be able to follow the moving fringes. The grating pattern will
then be washed out, and the probe diffraction will disappear. The
"break frequency" in a plot of diffracted probe intensity versus difference
frequency $f_d$ between the excitation beams should yield the time constant
$\tau$. For simple cases the relation between lifetime and break frequency is

$$f_d (\text{cm}^{-1}) \tau (\text{psec}) = 5.3.$$  

Thus, a time constant of 0.1 psec (100 femtoseconds) corresponds to
50 cm$^{-1}$ of tuning, which is easily achieved with modern dye lasers.
This technique should become most useful just where conventional pico-
second or subpicosecond pulse techniques become impossibly difficult.\footnote{A.E. Siegman, "Grating Spectroscopy," Invited paper, Conference on
Dynamical Processes of Excited States in Solids, Madison, Wisconsin,
June 18-20, 1979.}

B. Progress To Date: Theory

We are planning to apply the tunable laser-induced grating method
eventually to a wide variety of physical systems, including:

-- rotational and fluorescent lifetimes in organic dye
  solutions and in large molecular complexes.
-- excited-state and carrier lifetimes in semiconductors.
-- exciton diffusion processes in one-dimensional organic
  crystals.
-- vibrational relaxation processes in liquids.
-- lifetime measurements in dyes used for laser Q-switches
  mode-lockers, and optical Kerr cells.
We have reviewed the literature on subpicosecond phenomena in these systems. Of particular interest to us initially are organic dye solutions and semiconductors. We thus plan to do our initial experiments with a dye solution and then focus on obtaining important results relevant to semiconductor physics.

An advantage of the tunable laser induced grating method over similar recently proposed methods is its inherent flexibility: three separate lasers of different wavelengths produce the excitation and probe beams while other techniques provide for only two separate wavelengths. As a result many beam geometries are possible. The most commonly used and best understood beam geometry in grating experiments - involving all nearly copropagating beams (see Fig. 1a) - proved problematic in our preliminary experiments because of obscuration of the weak signal beam radiation by Rayleigh-scattered pump beam light. We have performed an in-depth theoretical analysis of all possible beam geometries that result in phasematched

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5.11 Rick Trebino, James P. Roller, and A.E. Siegman, "Beam Geometries in Four-Wave Mixing and Induced Grating Experiments," to be published. (This work was also partially supported by the Air Force Office of Scientific Research).
Fig. 1: Beam geometries in four-wave mixing and induced-grating experiments. Exl and ex2 refer to excitation beams that form the grating. The probe beam diffracts off this grating to produce the signal beam. Each figure is representative of a class of geometries.
interactions in four-wave mixing and induced-grating experiments. We have found the appealing geometry (see Fig. 1b) that employs nearly copropagating excitation beams to form a grating which is probed by a nearly counterpropagating probe beam (used effectively in transient grating studies\textsuperscript{2-7} to reduce scattered excitation beam light) to be inappropriate for our technique due to probe beam Bragg-angle variation by a large amount as the excitation beam frequency difference is scanned, a phenomenon we have termed "Bragg angle instability." Our analysis has further revealed that a class of geometries employing nearly counterpropagating excitation beams (see Fig. 1c) offers many advantages over the previously mentioned geometries with respect to the problems of scattered light, Bragg angle instability, and alignment difficulty. An additional problematic effect, the formation of thermal gratings,\textsuperscript{12} can result in enhanced signal intensity for stationary gratings and, possibly, to spurious results. The above class of geometries allows very closely spaced grating fringes so that thermal diffusion can significantly reduce the contribution to the signal intensity of thermal gratings (particularly in solids) yielding more easily interpreted results.

C. Progress To Date: Experiment

Dye Laser Development

Three YAG-pumped pulsed dye lasers employing a design developed at Rice University (see Fig. 2), which uses a reflective beam

Fig. 2: Schematic diagram of the Cassegrain dye laser
expander and a grating in the Littrow configuration, were first built but found to be inadequate for our purposes due to several unforeseen design flaws. These flaws, many of which were observed during high power operation (required for our experiments), included the need to replace optics during wavelength scans, a diffraction grating damage mechanism during alignment, and all drawbacks of the Hänisch design including alignment difficulty, the presence of much amplified spontaneous emission, and inefficiency due to long cavity length.

We have since set up several pulsed dye laser designs in our laboratory for the purposes of comparison on more than a dozen performance parameters. A resulting publication reviews the state-of-the-art of pulsed dye laser engineering and indicates that the best overall design is the recent achromatic-prism-beam-expander design of Klauminzer, while the inexpensive and easy-to-align grazing-incidence design offers extremely narrow linewidth at a cost in efficiency. We have found that a slightly less oblique grating incidence angle results in significantly improved efficiency in the grazing-incidence design with, for our purposes, a tolerable increase in linewidth. In addition, the use of holographic gratings with skewed-gaussian groove


shape developed recently by Jobin-Yvon has further improved the performance of the grazing incidence design, and therefore we have converted back to it with these modifications.

**Grating Experiments**

We have now performed preliminary grating experiments in the liquid samples \( \text{CS}_2 \) and the organic dyes DODCI and Rhodamine 6G. Stationary gratings have been induced and probed with .5 mJ of tunable dye laser radiation in the range 560-590 nm and also with 10mJ of fixed-frequency radiation at 532 nm. Signal beams were detected, and diffraction efficiencies on the order of \( 10^{-4} \) were observed with 532 nm excitation radiation and \( 10^{-5} \) with the less intense 560-590 nm excitation radiation. Gratings induced with one color have been successfully probed with another distinct color. We are at present attempting to detect much weaker diffracted signals from moving gratings formed by excitation beams from two separate dye lasers as required by the technique in order to measure ultrashort lifetimes.

**D. Additional Work: Second-Harmonic-Generation Rings**

and Refractive Index Measurement

The non-collinear phasematching requirement in the four-wave mixing/induced grating interaction is similar to interactions in second-harmonic-generation (SHG) in which non-collinear three-wave mixing occurs. The most common example of such mixing in SHG involves the \( k \)-vector of the main (unfocused) fundamental beam mixing vectorially with a (scattered) off-axis fundamental wave to yield, in a phasematched manner, a relatively strong second harmonic wave. Many scattered wave directions yielding phase-matched SHG usually exist giving rise to interesting ring-shaped patterns near the spot of the main beam on an observation screen. In a type II SHG
crystal, as many as three off-center rings can be observed simultaneously (see Fig. 3).

These rings have been understood since 1962 when Giordmaine\textsuperscript{18} treated a simple special case. We have catalogued and derived simple expressions for the ring centers and radii for all of the non-collinear ring-producing processes for both positively and negatively birefringent uniaxial SHG crystals.\textsuperscript{19} We have also observed that measurements of these parameters for various values of the crystal tilt angle will yield extremely accurate relative values (better than one part in $10^6$) for the four relevant crystal indices of refraction. The important quantity, the temperature derivative of the difference between ordinary and extraordinary indices of refraction of a crystal is particularly easy to obtain with great accuracy using ring parameter measurements.


Fig. 3: Two of the three SHG rings produced in a Type II KD*P doubling crystal. (Third ring is larger and dimmer than these two rings). Fundamental radiation wavelength used for these photographs is 1.064 \( \mu \text{m} \) and the wavelength of the second harmonic is 532 nm. The sequence illustrates the ring evolution as the crystal is tilted by a few degrees through the phasematching angle. Below each

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photograph, the theoretically predicted ring patterns are illustrated. The angle between the laser propagation direction and the crystal c-axis is denoted by $\theta_o$ and $\Delta n = \frac{1}{2} [n_o(1.06\mu) + n_e(1.06\mu, \theta_o)] - n_e(532 \text{ nm}, \theta_o)$ is the "index mismatch" of the process.
E. Publications and Papers

1. A.E. Siegman, "Laser Induced Grating Techniques for Picosecond Spectroscopy," Report of Workshop on Picosecond Spectroscopy (sponsored by DARPA), La Jolla Institute, La Jolla, California, May 7-8, 1980. (Partially supported by AFOSR).


INTRODUCTION

This project is concerned with the growth of single crystal fibers, the evaluation of their linear and nonlinear optical properties, and the development of optical and nonlinear optical fiber devices. The unique combination of single crystal material properties and fiber geometry offers intriguing capabilities in a variety of optical devices. Three materials successfully grown at Stanford this year typify the broad range of potential applications. The large nonlinear coefficients of LiNbO$_3$ suggest a number of modulators, signal processors and parametric sources. Miniature lasers made from Nd:YAG fibers$^1$ have been known for several years. They might also be used as in-line amplifiers in conjunction with conventional glass fiber systems. Sapphire's high melting point, mechanical strength, resistance to chemical attack and favorable optical and thermal properties make it an excellent candidate for monitoring temperature or optical radiation in hostile environments and for guiding high power optical beams.

The efficient realization of these sorts of devices, particularly those involving parametric processes, require the growth of fibers with good optical and structural uniformity and the ability to launch and preserve low order propagation modes. Our efforts this year have been oriented toward achieving these goals.

CURRENT PROGRESS

A. Fiber Growth

The first generation constructed under non-JSEP support was completed in autumn 1980. The crystal growth research group directed by Dr. R.S. Feigelson, Center for Materials Research, Stanford University, has succeeded in growing several materials in addition to the three mentioned in the Introduction, including one, calcium scandate, that had not previously been obtained in single crystal form, using this station.

Fibers have been grown with diameters ranging from 500 microns down to 35 microns in lengths up to 15 cm. Growth rates are typically 1 - 10 mm/min, though faster rates are currently being investigated. Oriented fibers have been grown, including [111], [110], [100] Nd:YAG, [100], [001] LiNbO$_3$; and [100], [001] sapphire. The fibers tend to exhibit cross sections similar to those of Czolchralski grown bulk boules, e.g., [111] Nd:YAG has a hexagonal cross section, [100] LiNbO$_3$ is elliptical. Preliminary optical and X-ray investigations indicate that the fibers are single crystal, though photomicrographs show larger diameter Nd:YAG fibers have core defects similar to those in bulk grown boules.
The major problem with the current system is growth instability which leads to fibers with diameters varying by 5% over 5 mm lengths and 10% or more over larger lengths. Scanning electron micrographs have shown that the diameter variations have a broad spectrum ranging from millimeter periods down to submicron. Estimates based on coupled mode theory suggest that these random diameter fluctuations will have to be reduced by at least an order of magnitude if tolerable levels of mode conversion, loss and phase matching are to be achieved.

A number of components of the current fiber growth system and process are implicated in the diameter control problem. Figure 1 is a schematic of the current system. A 1 mm square rod, chucked to a lead screw, is fed into the common focus of the two beams from a 50 watt CO\textsubscript{2} laser. A seed crystal, chucked to another lead screw, is dipped into the molten bead formed on the rod, then withdrawn at a constant rate to pull the fiber. The diameter reduction from rod to fiber is determined by the ratio of feed to pull speeds. Typically, a diameter reduction of 2-5 is feasible. Thus 3-5 regrowth cycles yield a fiber in the 50-100 \textmu m range.

A primary cause of the diameter fluctuations is the square feed rod used in the initial growth cycle. It is necessary to rotate the square rod to maintain a uniform melt. Since it is impossible to make the rod rotate precisely concentrically with the seed, a "candy cane" spiral appears on the fiber surface. Ideally, the initial feed rod would be circular with a 0.5 mm or smaller diameter, with an accurately maintained cross-section along its entire length. After an extended search we located several Swiss manufacturers of watch bearing grinding machines capable
of producing the necessary rods; we are in the process of obtaining formal price quotations. We have also located a local shop which may be able to grind the feed rods. In addition, improved beam alignment and focusing mechanisms intended to improve thermal symmetry in the melt have been designed and assembled, and will be installed in the system.

The higher frequency diameter variations are probably associated with laser power fluctuations, particularly when the laser is operated near threshold during small diameter fiber growth. The theoretical analysis of the fiber system thermal response indicates time constants of $0.1 - 0.01$ second can be expected, which is consistent with the periodicity of the observed diameter variations. We have incorporated a feedback system to stabilize the laser power, but it is limited by the slow time constant of the thermal detector used to monitor the laser output. To eliminate this problem, we have assembled a detector based on a commercial pyroelectric element and an 8 kHz resonant scanner, which, combined with suitable demodulation electronics provides a bandwidth in excess of 1 kHz. This detector will be incorporated into the growth system within the next several months. In addition, we have designed an attenuator system with three fixed levels and minimal beam walk and beam steering that will allow well above threshold operation of the laser for all fiber diameters.

In the present system configuration, the growth zone is not fully isolated from ambient conditions. This exposes the fiber to the perturbative influence of drafts and convective air currents. The CNR group is designing a controlled atmosphere chamber which should alleviate these problems, and also permit growth in inert atmospheres, oxygen, or vacuum.

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We hope that the aggregate effect of these modifications will be a substantial improvement in the open loop growth stability of the fiber diameter. Once this goal is achieved, it would be useful to incorporate feedback to the laser power based on an error signal derived from the fiber diameter. To this end we have assembled a prototype diameter measurement system with a resolution of ~ 0.75 micron and a measurement rate of 1 kHz, based on a similar system published by Smithgall. 2 The optics used in this system would be considerably complicated by the long working distance entailed by the controlled atmosphere chamber. We are therefore studying improved signal processing methods which would relax constraints on the optical system, and perhaps yield a considerable increase in sensitivity. If this method is successful, it could be of value as a commercial device. Consideration is also being given to the purchase of a commercial diameter measurement system, but none has appeared optimal thus far.

While we expect these modifications will considerably improve fiber quality, a more comprehensive solution entails construction of a new growth station. The new system will utilize the same basic growth technique as the first generation station, but will incorporate refinements in many of the subsystems. A 20 watt waveguide CO2 laser with active thermal and output power stabilization is more compact than the laser currently in use and should provide better power and beam pointing stability.

We have designed a novel optical system for focusing the 10.6 micron radiation onto the fiber in a 360° symmetric distribution. This is an improvement over the two-beam, rotating periscope, or ellipsoidal focussing systems previously used in laser drawn fiber stations. The diffraction limited f/2 optics will allow focussed spot size as small as 20 micron, important for well controlled growth of small diameter fibers. The symmetric energy distribution will alleviate the problem of coldspots in the growth zone, a potential source of instability.

The feed rod and fiber will be translated with a capstan and pinch roller design that offers several advantages over the lead screws used previously:

1. Maximum fiber length is no longer limited by the length of the lead screw.
2. The controlled atmosphere chamber no longer requires mechanical feedthroughs.
3. The DC motors driving the capstans are encoded and phaselocked to a crystal controlled oscillator, allowing stable and convenient adjustment of the growth rate.
4. Post growth annealing is easily accomplished.

All the components for this system were ordered this summer. We expect to have it operational this fall. Funds for construction of the system were from the current JSEP program and from AFOSR support.

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Figure 1.
B. Fiber Characterization and Preparation

As higher quality fibers become available, it will become important to characterize their properties. We have begun to assemble the instrumentation necessary for these measurements.

A fiber diameter measurement system has already been described in connection with use in feedback control of the growth process. In addition to this use, a statistical record of diameter variations will be useful as a diagnosis for understanding growth perturbations, and for the prediction of mode conversion and loss phenomena. The scanning electron microscope at the Center for Material Research has been used for the characterization of surface flaws below the resolution of the current diameter measurement system.

An important parameter for ferroelectric fibers like LiNbO₃ is the distribution of domains of spontaneous polarization. We have assembled a device based on the measurement of the pyroelectric coefficient which is capable of resolving domain distribution both along the fiber axis and across its endface, with 20 micron resolution. A determination of the domain distribution in an a-axis LiNbO₃ fiber showed an interesting configuration. The domains were layered transversely to the c-axis rather than parallel to the c-axis as is generally the case in bulk crystals. The explanation for this behavior is not yet clear, though it is probably related to the large surface area to volume ratio of the fiber geometry.

Nonlinear interactions do not proceed efficiently in randomly poled materials, so it will be necessary to pole the LiNbO$_3$ fibers before using them in any nonlinear device. The second generation growth station will be equipped with platinum electrodes so that electric fields can be applied to the fiber immediately after crystallization or in a post-growth reheating.

It is also important to know the radial and axial variations of the index of refraction. Ideally there would be no axial variations, as these represent inhomogeneities in the fiber. The radial variation is of course critical in establishing the modal propagation properties of the fiber. Nonuniform radial distribution of nonstoichiometric constituents, e.g., Nd in Nd:YAG, could be determined by an index profile measurement. In cooperation with the Shaw group, we have assembled a system similar to that described by Eickhoff$^7$ which can measure index variations of five parts in ten thousand with several micron resolution.

The index profiling method is based on an accurate measurement of Fresnel reflectivity, so it is necessary to prepare very flat faces on the fiber. Selective launching of low order modes also requires accurately flat fiber ends, so we are attempting to master fiber polishing techniques. We have acquired a commercial fiber polishing unit, and retrofitted a metallurgical microscope to permit interferometric determination of fiber end quality. Our initial polishing efforts have led to fibers with insufficiently flat ends. The rounding appears to be associated with difficulties in rigidly mounting the fibers, which is, in turn, aggravated by the

nonconstant diameter of the fiber. We are currently investigating several potential solutions to this problem.

DEVICES

A. Experiment

Because of the inadequate diameter control thus far obtained, we have not devoted much effort to experimental investigation of fiber devices. We have succeeded in launching and preserving low order modes in commercial multimode glass fiber, and had some encouraging preliminary results with mode launching in a LiNbO$_3$ fiber.

One simple but interesting proof of principle device we assembled was a remote temperature sensor based on a sapphire fiber. Radiation from a hot filament was focussed onto a 10 cm long fiber, whose output was fed into a grating monochrometer. The ratios of the intensity of two wavelengths gave temperature measurements that agreed to within 2K with an optical pyrometer.

B. Theory

An important topic is the effect of diameter perturbations on mode mixing and radiation loss. This subject is treated extensively in the literature, but generally under the assumption of small core-cladding index differences. Since this assumption will not be applicable to our fibers until we develop suitable cladding techniques, we have extended standard coupled mode theory to include the case of low order modes in fibers with large index differences. In addition to providing the diameter tolerance limits mentioned in the fiber growth section, this

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coupled mode theory suggests a technique with extremely interesting device potential. If our growth process advances to the point where it would be possible to introduce periodic diameter variations into a fiber by modulating the CO$_2$ laser output, distributed feedback devices of the type now used in integrated optics could be introduced into optical fibers.

We have also developed a fairly general theory of nonlinear interactions in fibers. In the absence of linear coupling the nonlinear problem is easy to solve. Under this assumption we have estimated the efficiency of various nonlinear devices, with results presented in Table 1. If our techniques for poling LiNbO$_3$ prove to be sufficiently controllable, it should be possible to periodically pole a fiber in order to take advantage of the large $d_{33}$ coefficient. Efficiencies for this case are also listed in the table.

Solutions for the case of simultaneous linear coupling and nonlinear interaction are more difficult to obtain, but will be pursued in the coming contract period. We also intend to investigate the effect of strong anisotropy on fiber modes.

OBJECTIVES FOR THE COMING PERIOD

In the coming year we will continue our close cooperation with the Shaw and CM1R group in upgrading the first generation growth station. We will also finish assembling the second generation growth station. Open loop growth characteristics will be determined and a suitable closed loop diameter control system designed.

Using the instrumentation developed this past year, it should be possible to rapidly evaluate the properties of the fibers which will
<table>
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<tr>
<th>TABLE 1. Efficiencies of Nonlinear Processes in LiNbO₃ Fiber (2%/m)</th>
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<tr>
<td>Bulk 5 cm Multimode Fiber 5 cm Length</td>
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<tr>
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<tr>
<td>SHG 1.06 μm + 0.532 μm</td>
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<tr>
<td>Frequency Mixing 0.58 μm + 0.75 μm + 2.56 μm</td>
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<td>d₂1, d₂3</td>
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aid in the growth of improved fibers.

Once fibers of sufficient quality become available, we intend to try some basic nonlinear interactions, in particular electrooptic modulation and doubling 1060 nm + 532 nm.

Longer term goals include the construction of more sophisticated nonlinear devices, e.g., a CW parametric oscillator, development of cladding techniques for better mode control, and investigation of periodic poling and periodic diameter variations. We will focus our attention on LiNbO₃ nonlinear optical devices and sapphire devices.
V. LABORATORY CONTRACT AND GRANT SUPPORT

(Edward L. Ginzton Laboratory)

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### VI. REPORTS AND PUBLICATIONS

**EDWARD L. GINZTON LABORATORY FACULTY AND STAFF**

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<td>Fesler, &quot;PVF Transducers,&quot; Reprint from 1980 Ultrasonics Symposium Proceedings,</td>
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<td>pp. 927-940.</td>
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| 9. PERFORMING ORG. NAME AND ADDRESS | Edward L. Ginzton Laboratory Stanford University Stanford, CA 94305 |

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| 12. REPORT DATE | April 1981 |

| 14. MONITORING AGENCY NAME & ADDRESS | Approved for public release; distribution unlimited |

| 19. KEY WORDS | Superconductivity Ultrafast physical phenomena SNS. Step-edge-patterning Acoustics Weak-link Josephson junctions Surface acoustic wave devices Surface waves Nonlinear optical studies High speed signal processing Optical imaging Single mode optical fibers Ferroic-acoustic resonators Fiber optics High Tc superconducting materials Pulsed laser technology |

| 20. ABSTRACT | This report summarizes the research progress and activity on Joint Services Electronics Program Contract N00014-75-C-0632 for the period 1 April 1980 through 31 March 1981. Specific projects are: (1) High Tc Superconducting Weak-link Josephson Junctions and Circuits (M.R. Beasley); (2) Acoustic Surface Wave Scanning of Optical Images (G.S. Kino); (3) Research on Fiber Optic Interactions with Application to High Speed Signal Processing (H.J. Shaw); (4) Nonlinear Interactions of Acoustic Waves with Domains in Ferroic Materials (B.A. Auld); (5) Measurements of Ultrafast Physical Phenomena (A.E. Siegman); (6) Optical and Nonlinear Optical Studies of Single Crystal Fibers (R.L. Byer). |

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