REPORT DOCUMENTATION PAGE

AFRL-SR-AR-TR-03-

0096

1. AGENCY USE ONLY *(Leave blank)*	**2. REPORT DATE**	**3. REPORT TYPE AND DATES COVERED** 1 Jun 96 - 30 Nov 99 FINAL

4. TITLE AND SUBTITLE
Depscor-95 Agile Optical Phased Arrays for Microspacecraft

5. FUNDING NUMBERS
61103D
3484/BS

6. AUTHOR(S)
Dr Fork

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
UNIVERSITY OF ALABAMA
301 SPARKMAN DRIVE
HUNTSVILLE AL 35899

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AFOSR/NE
4015 WILSON BLVD
SUITE 713
ARLINGTON VA 22203

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
F49620-96-1-0206

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION AVAILABILITY STATEMENT
APPROVED FOR PUBLIC RELEASE, DISTRIBUTION UNLIMITED

20030508 109

13. ABSTRACT *(Maximum 200 words)*

The introduction of ultrafast technology into space offers novel opportunities. Agile optical phased arrays that allow rapid forming and redirection of high average power beams with little or no mechanical movement are especially interesting. Recent advances in semiconductor and optical fiber lasers suggest lightweight compact optical phased arrays suitable for microspacecraft are feasible. Double clad fiber offers an opportunity to provide average powers of order ten watts in single mode fibers. Modelocked laser technology we are now addressing provides means for combining these high average power single mode lasers into phased arrays. Related photonic band gap research we are pursuing identifies an approach we believe will provide opto-electronically controlled true time delays for the array elements. We propose to develop this technology and test the results in space missions. Agile optical phased arrays with the average power, spatial resolution, and high data rate suitable for an advanced global information network based on microsatellites would have an extraordinary impact on military capability. We combine our ongoing work on ultrafast technology with an earlier DEPSCoR funded program in microsatellites, both at the University of Alabama in Huntsville, to explore this possibility We leverage this effort with existing investments, relationships with strong research partners, and the favorable location of the University of Alabama in Huntsville. We are consequently able to offer a program of national significance for relatively modest cost.

14. SUBJECT TERMS

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	**18. SECURITY CLASSIFICATION OF THIS PAGE**	**19. SECURITY CLASSIFICATION OF ABSTRACT**	**20. LIMITATION OF ABSTRACT**
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

Agile Optical Phased Arrays for Microspacecraft

Richard L. Fork
Department of Electrical and Computer Engineering
University of Alabama in Huntsville

Abstract

The introduction of ultrafast technology into space offers novel opportunities. Agile optical phased arrays that allow rapid forming and redirection of high average power beams with little or no mechanical movement are especially interesting. Recent advances in semiconductor and optical fiber lasers suggest lightweight compact optical phased arrays suitable for microspacecraft are feasible. Double clad fiber offers an opportunity to provide average powers of order ten watts in single mode fibers. Modelocked laser technology we are now addressing provides means for combining these high average power single mode lasers into phased arrays. Related photonic band gap research we are pursuing identifies an approach we believe will provide opto-electronically controlled true time delays for the array elements. We propose to develop this technology and test the results in space missions. Agile optical phased arrays with the average power, spatial resolution, and high data rate suitable for an advanced global information network based on microsatellites would have an extraordinary impact on military capability. We combine our ongoing work on ultrafast technology with an earlier DEPSCoR funded program in microsatellites, both at the University of Alabama in Huntsville, to explore this possibility. We leverage this effort with existing investments, relationships with strong research partners, and the favorable location of the University of Alabama in Huntsville. We are consequently able to offer a program of national significance for relatively modest cost.

Table of Contents

12. Nature of Expected Results

Agile Optical Phased Arrays for Microspacecraft

Richard L. Fork

1. Introduction

Double clad optical fiber provides a breakthrough technology that has already demonstrated orders of magnitude increase in the average power deliverable from single mode optical fiber lasers. We propose to combine our current work on synchronization, and phase locking of ultrashort single mode fiber lasers with this improved capacity for high average power. We propose to do this with means suitable for microspacecraft and to test that technology in actual demonstrations. We anticipate this work will facilitate realization of high average power agile optical phased arrays suitable for microspacecraft.

Agile high average power optical phased arrays having the efficiency and low mass suitable for microspacecraft appear directly applicable to a variety of DoD missions. The capacity to occupy low earth orbit while retaining contact with multiple targets in rapid relative motion and also operate at high data rate addresses key DoD interests. The current decision to emphasize missile defense is one such effort. Providing agile optical phased arrays with minimum perturbation of the sending platform at reasonable cost per satellite will enhance secure communications, improve remote sensing, and, in general, contribute to a broad array of DoD goals. The technology also appears to scale in a manner that allows consideration of eventual directed energy applications.

The possibility of developing this technology at this time emerges because of recent advances in several distinct fields. The proposed effort is directed toward an integration of these multiple recent advances. Lightweight diode sources and double clad fiber optical fiber provide the power. Recent advances in modulators, pulse generators, precision electromechanical technology, and harmonically modelocked optical fiber lasers offer means of generating, synchronizing, and phase locking stable trains of short optical pulses. The result we expect to be low mass, high average power, rapid response technology needed for actively stabilized space based sources.

The challenges that hinder realization of this technology appear addressable in a well structured research program. The principal needs are those of obtaining and integrating enhanced precision in electro-optic switching and laser brightness, a simple means of phase stabilizing optical fiber lasers, and means for phase locking multiple harmonically modelocked fiber lasers. Our program attacks these various challenges in an integrated manner. This particular proposal primarily addresses the construction of the stable harmonically modelocked lasers and the amplification of the output pulses in double clad optical fiber. The approach, however, is carefully planned so that the developed technology will integrate with other parts of the optical phased array, such as synchronization and phase locking of the family of sources, in a manner that is designed to facilitate realization of the complete system.

2. Background

Previous work can be viewed as primarily addressing three distinct strategies for realizing optical phased arrays: (1) phase locking of modelocked laser oscillators; (2) a master oscillator multiple power amplifier approach; and (3) use of Talbot-like resonators where multiple transverse modes have some regions of spatial overlap and some regions that are spatially resolved. Each approach has some advantages and disadvantages. We intend to seek the best combination of these strategies for utilizing the currently emerging technology. A novel feature of the fiber approach is an increased opportunity to introduce large temporal delays and additional controls of each individual optical path. These features provide opportunities not previously available and may prove decisive in realizing practical agile arrays.

An additional important problem is the difficulty of obtaining large time delays for optical beams in a simple manner. While not the focus of this particular proposal, we are pursuing separately means of using photonic band gap devices to achieve rapidly adjustable delays suitable for true time delay. This work, more fully described in a related proposal, explores development and use of novel electrically controlled photonic band gap structures to achieve the needed opto-electronically controlled delays. We develop the proposed system in a manner that recognizes the potential of this emerging technology.

In the past investigators of optical phased arrays have not seriously considered modelocked optical fiber lasers as sources. The perceived limitations have been the tendency of the lasers to fluctuate between supermodes, the relatively low output power per laser, and the lack of work on phase locking multiple optical fiber lasers.

We believe these perceived barriers can be overcome. We base this conclusion on our own successful research and on the extraordinary progress in the field of fiber lasers and pumping of fiber lasers. Emerging techniques have been identified that provide a simple means of stabilizing the lasers [1,2,3], the double clad fiber provides high average power [4] and phase locking of multiple lasers was achieved in the dye laser environment in some of our prior work[5]. We believe those solutions can be transferred to the proposed fiber laser environment. We also gain an opportunity to explore the use of solitons in optical phased arrays as these fiber lasers can produce well defined solitons.

As regards location, the University of Alabama in Huntsville (UAH) provides an ideal facility for pursuing this program. The close physical and practical relationship with the Marshall Space Flight Center (MSFC) of NASA, U.S. Army Missile Command (MICOM), U.S. Space and Strategic Defense Command (SSDC), and the world class optics at the Center for Applied Optics (CAO) and the Optics Group of MSFC provide a unique opportunity to pursue this important task of integrating advanced optical and advanced space capability.

The space component of this work is built on an existing program funded by DEPSCoR, NASA, and private industry. A successful 1992 DEPSCoR proposal by the UAH Students for Exploration and Development of Space (SEDS) has resulted in a program supporting a satellite UAH SEDSAT 1 that is manifested to fly on Space Shuttle flight STS 87. The requested space related equipment augments this DEPSCoR initiated effort along lines that will facilitate the space oriented component of this current proposal. Particularly relevant areas are those for optical detection of laser signals, communication over an optical link, processing of optical image oriented information, and tracking and location related to laser originated signals.

The requested funds are to help integrate the laser and microsatellite efforts, with a focus on introducing agile optical phased arrays into microsatellites. The primary resources requested are for the PI's time, for the time of a principal in the earlier DEPSCoR funded satellite project, Mr. Dennis Wingo, for the electronics and optical equipment needed to address a new precision phase locking strategy for modelocked optical fiber lasers, and software and hardware to augment the current DEPSCoR project in ways that support the proposed integration. Significant matching funds beyond the amount requested for DEPSCoR are committed by UAH.

3. The scientific and technical merits of the proposed research.

The proposed research has scientific merit in that it explores the fundamental capabilities of agile optical phased array systems. It allows us to address soliton based approaches, but does not necessarily restrict attention to soliton based systems. We include a practical examination of phase locked ultrashort pulse arrays where nonlinear phase locking of multiple fiber lasers can play a role. This approach lays the basis for exploring a regime of ultrafast coupled nonlinear optical systems at a level of complexity, temporal resolution, and sophisticated control not previously accessed.

The proposed research also has technical merit in that it integrates several emerging technologies to create a novel and potentially powerful source of agilely steered digitized optical radiation. The emergence of double clad fiber increases the average power produced by diode array pumped single mode fiber lasers by several orders of magnitude. The phase locking of these individual high average power lasers has a potential to provide agile steerable optical beams with intensities that can exceed existing lasers by many orders of magnitude. Intensity levels in the terawatt range cannot be ruled out.

The proposed work could have also have commercial applications. For example, the phase locking and true time delay strategies could be useful in conventional microwave radar as a means for optical distributing signals between elements of the microwave system. This phased array strategy may be useful, scaled to smaller dimensions, in applications, such as reading CD ROMS. Attention is restricted in this proposal to the development of agile optical phased arrays for space; however, we intend to maintain awareness of possible directions for alternate uses of the evolving technology.

4. The potential contributions of the proposed research to the defense missions of the sponsoring agencies

Agile phased arrays contribute to many DoD mission related tasks. The compact lightweight character opens the possibility of both applications in space and other missions where portability is important. The optical character offers a novel and powerful degree of agility. The important goals of seamless communications, communication on the move, very high data rate sensing, control, and directed energy are also addressed in various degree. The innovative exploration of practical goals and use of emerging technologies while also training U.S. citizens in applications of interest to DoD provides a clear contribution to the defense missions of the sponsoring agencies.

5. The likelihood of the proposed effort to develop new research capabilities and to broaden the university research base in support of national defense.

The proposed effort promises to develop a number of important new research capabilities. The stabilized harmonically modelocked optical fiber lasers we are developing provide a source of optical pulses at multigigahertz data rates with a degree of stabilization and simplicity not previously available in this country.[4] The technology is directly applicable to high performance communications and data processing research, e.g.. The pulses can also be amplified, spectrally broadened and used for ultrafast measurements of material and device dynamics that would otherwise not be available in Alabama. We also intend to route the pulses over optical fiber on campus and can thus share the technology with a number of other users and educational facilities at our university. Our campus and building facilitate this effort. This work is thus designed to both develop new research capabilities and to provide novel and effective means of sharing the enhanced capability with others.

We note also that this effort is specifically constructed to integrate with an existing DEPSCoR funded effort on satellite construction and launching. This DEPSCoR funded satellite effort has already served as a powerful focal point for students interested in the rapidly growing space industry. We augment that effort and would, in turn, be strengthened by that effort. The combination of the ultrafast optics and the space oriented technology provides an extremely exciting opportunity for students. This combination of efforts also provides a means to draw on the strong space oriented efforts in the Huntsville community and to bring to that community much needed direct access to state of the art work in ultrafast optics and communications.

6. The potential to contribute to the education of future scientists and engineers in disciplines critical to the DoD mission.

We see a high potential to contribute to the education of future scientists and engineers in disciplines critical to the DoD mission. We have more than six undergraduate and graduate students directly involved in our research program. We also make our laboratory available for frequent visits by students, offer seminars on our research, give papers at meetings, and publish in professional journals. We also intend to provide ultrashort optical pulses on fiber, or through free space, to other locations on campus, including the Students for Exploration and Development of Space group that is participating in this proposal. This latter group has participants from a number of engineering and science departments on campus. The disciplines we address of communication, high data rate, phased arrays, ultrafast optical phenomena and directed energy, are all critical to the DoD mission.

7. The qualifications, capabilities, experience and past research accomplishments of the proposed principal investigator, team leader and other key personnel who are critical to achieving the objectives of the proposal.

We bring to this effort a unique combination of expertise and experience. The PI currently holds the world record for the shortest optical pulse produced to date.[6] That work was the culmination of some 20 years of work on modelocked lasers beginning with demonstration of the first modelocked laser [7] and included the invention of the colliding pulse laser that produced optical pulses in the femtosecond time domain. All of this work involved phase locking and nonlinear optics that was strongly innovative and technologically demanding. The PI is unusually well qualified to deal with the technology and science of phase locking and ultrashort optical pulses.

We combine this with access to the unique experience of Dennis Wingo and others relevant to microspacecraft (previously funded by DEPSCoR), and the high quality expertise in theoretical and experimental optics in the Huntsville area. We include in our group Michael Scalora who has developed unique capabilities in numerical simulation relevant to this task. We also work closely in cooperation with the Quantum Optics Group at the Redstone Arsenal Missile Command. We have ongoing work with the Photonics Laboratory at Rome Laboratory. The PI has also worked as a Summer Faculty Fellow in the Optics Group at NASA. This latter group is globally recognized for development of space based optics. We also include in our group Senter Reinhardt and Rachel Flynn who, as highly talented and dedicated undergraduates, have played a substantial role in initiation of this effort at UAH. Joseph Haus of RPI provides strong additional calculational and theoretical support. Walter Kaechele and Reinhard Erdmann of the Photonics Laboratory at Griffiss Air Force Base provide an experimental effort at Rome Laboratory.

We have also received an offer of guidance from Dr. Francis C. Wessling. Dr. Wessling is a professor of mechanical engineering at UAH. He has been working on space-related experiments since 1985, and has been at UAH since 1984. Many of the experiments Dr. Wessling has designed have successfully flown on the space shuttle, either in the shuttle payload bay, the shuttle mid-deck, or on sounding rockets. He has also served as project manager of the first three Consort sounding rocket flights and had experiments on all six sounding rocket flights. From 1991 to 1994 he served as the technical monitor for the commercial experiment transporter (COMET) launch system. He is associate director of the Consortium for Materials Development in Space at UAH. He has written more than 70 publications, and has written and contributed to seven successful major research proposals. Curriculum vitae for key personnel are included at the end of this proposal.

8. The proposed involvement and interaction with DoD or other federal laboratories, industry, or other existing research centers of excellence

8.1 Rome Laboratory, Griffiss Air Force Base

We have a continuing interaction with the Photonics Center at Rome Laboratory at GAFB. At this time a graduate student, Walter Kaechele, is funded by AFOSR under an AASERT award and has succeeded in synchronizing two harmonically modelocked lasers under Reinhard Erdmann as part of our effort. The PI has a contract with Rome Laboratory and also helps supervise Mr. Kaechele's work. The PI makes a number of trips to Rome Laboratory each year as part of this effort. The excellent resources of the Photonics Center allow us to explore aspects of the work that could not be otherwise explored.

8.2 Kirtland Air Force Base

We have begun a dialogue with personnel at Kirtland Air Force Base in Albuquerque, NM. We understand there is a substantial interest in phase locked signals propagating in optical fiber arrays. Our initial discussions have been with Cliff Muller. The basic plan is to look for ways that our work can support the effort at KAFB. We anticipate that we will address double clad fiber technology in a manner that increases the average power of high quality ultrashort optical pulse trains useful for tasks of interest to KAFB.

8.3 U.S. Army Missile Command (MICOM), Redstone Arsenal

We have an ongoing interaction with personnel at the Weapons Sciences Directorate at MICOM. The theoretical group led by Dr. Chuck Bowden is performing very high quality theoretical work in the area of optics related to our area of interest. The work on photonic band gaps and on nonlinear propagation of short and ultrashort optical pulses is especially relevant. We intend to work with them as regards incorporating photonic band gap technology in optical phased arrays for achievement of opto-electronically controlled true time delay.

8.4 Marshall Space Flight Center (MSFC) NASA

We have an ongoing interaction with the Optics Division of the Marshall Space Flight Center of NASA. The PI is a Summer Faculty Fellow at MSFC at this time working with the Coherent Lidar Group. This work brings us into contact with some of the principal work in NASA on space related optics. This contact is extremely valuable in helping us to formulate a program for producing technology that will be suitable for microspacecraft. We are currently preparing a technical report on the use of optical amplifiers for coherent lidar.

8.5 US Army Space and Strategic Defense Command (SSDC)

We have ongoing discussions with personnel at SSDC. These discussions are extremely helpful in gaining perspective on the DoD needs in space. One of the graduate students in our group, Esam Gad, is a full time employee of SSDC. He anticipates spending a year of leave with our group during the time period when the funding from DEPSCoR would be in effect. He would benefit directly from the resources in work on his doctoral thesis that is intended to address topics related to this proposal. We are also carrying on discussions with Kevin Dietrick and have talked with Dr. Brian Strickland and Dr. John Johnson regarding the interests of SSDC.

8.6 Optical Fiber Technology Center (OFTC), University of Sydney, Australia

We interact regularly with personnel at OFTC. We received dual core fiber from OFTC for a current project. Future work may involve novel electrically poled optical fiber that could be used for the adjustable optical delay in our proposed optical array system. Key contacts at OFTC are Simon Poole and Graham Atkins. OFTC is a world class optical fiber center and provides us with access to samples and some of the best expertise in the optical fiber related disciplines. OFTC is a potential source of double clad fiber.

8.7 Optoelectronics Research Centre University of Southampton, UK.

We have initiated discussions with personnel at the Optoelectronics Research Centre University of Southampton, UK as regards obtaining double clad fiber. John Minelly is our principal contact at this time. This is an alternate source of double clad fiber that we are exploring.

8.8 University of California at Santa Barbara

We have initiated discussions with Marc Rodwell at the University of California at Santa Barbara. Dr. Rodwell has developed nonlinear transmission lines important to the generation of very short electrical pulses that will assist us in generating the proposed stable trains of ultrashort optical pulses synchronized to a common master oscillator. We understand that it is likely we can obtain some of these devices at low, or no, cost as Dr. Rodwell is working under related AFOSR funding.

8.9 Other

We also have ongoing dialogues with K. Blow of the UK, and H. Avramopoulos of Athens, Greece. These are both major contributors to the optical fiber area. Also the PI has long standing relationships with many personnel in the ultrafast optics area, such as Linn Mollenauer and George Harvey of AT&T, who have been extremely helpful in assisting us with the initiation of our fiber laser program. We also are in contact with the considerable work on fiber optic devices at Lincoln Laboratory in Lexington, MA. Our principal contact at this time at Lincoln Laboratory is R. Bondurant.

9. The realism and reasonableness of cost, cost sharing, and availability of funds.

The cost of the proposed work is very reasonable for the performance offered. We also believe the proposed effort, while adventurous and ambitious, is realistic. The reasons we are able to offer a substantial effort on a high value project for very reasonable cost are: (1) a leveraging of existing funded work in our group at UAH, (2) recognizing a highly favorable opportunity for combining emerging technologies, (3) using to maximum advantage our location in Huntsville and (4) drawing on our relationships with a number of other high quality research organizations. We also provide more cost sharing than required and ask only for a relatively small fraction of the available funds.

One of our specific advantages is two of our graduate students recently won full scholarships with the Marshall Space Flight Center. We also interact on a regular basis with students in the SEDS (Students for the Exploration and Development of Space) program at UAH. We consequently have direct access to high quality information and expertise concerning space oriented technology at essentially no cost to this project.

We also are seeking to obtain the double clad fiber at the most reasonable cost. We are discussing obtaining double clad fiber from optical fiber centers at either the University of Southampton in the UK or the University of Sydney, in Sydney, Australia. We also have a quotation from Spectra Diode Labs as a commercial source. We are assured access to the fiber, but will seek the most favorable use of the awarded funds.

We are also able to explore modulator arrays and photonic band gap materials at minimal cost through our collaborative relationship with the Advanced Weapons Directorate at MICOM. This group provides both a high level of theoretical expertise and access to materials and devices that would otherwise be prohibitively expensive.

Our currently funded effort by AFOSR has enabled us to build up a state of the art laboratory for addressing the proposed research at no cost to this contract. We will use these existing facilities as a foundation for the proposed work. We also have a large and rapidly growing library of numerical simulation programs. This library and a relationship with Dr. Joseph Haus at RPI provide us with essential predicative capability for the proposed systems and technology. We also have access to state of the art electronic pulse shortening technology from Marc Rodwell at University of California at Santa Barbara.

10. Specific Research Program

10.1 Objectives

The objective of this work is to develop technology and science that will enable agile optical phased arrays to be introduced in microspacecraft. The primary focus of this particular proposal is development of the lightweight stable modelocked source laser and associated double clad fiber amplifier, see Fig. 1. This requires a source laser that has the very high stability needed for the eventual phase locked system. This is a much higher stability than normally obtained in modelocked laser work requiring stabilization of the overall laser length to a fraction of a micron. We have already, however, demonstrated such stability in an earlier laser.[1] A spectrum of that laser indicating the well defined stable mode structure is shown in Fig. 2.

The current work will be to develop and demonstrate a simpler stabilization technique [4] appropriate for a space based application that will also allow use of shorter pulses than in the reported previous work. Figure 3 shows, e.g., an autocorrelation trace of a 720 femtosecond pulse obtained with our current laser. The work in this current proposal will be to seek an optimal combination of stability, repetition rate, average power, and pulse duration while at the same time recognizing the special demands of constructing an agile phased array and of introducing that array into a space based application. We intend to maintain close contact with the various DoD agencies so as to include in our work an awareness of specific DoD interests.

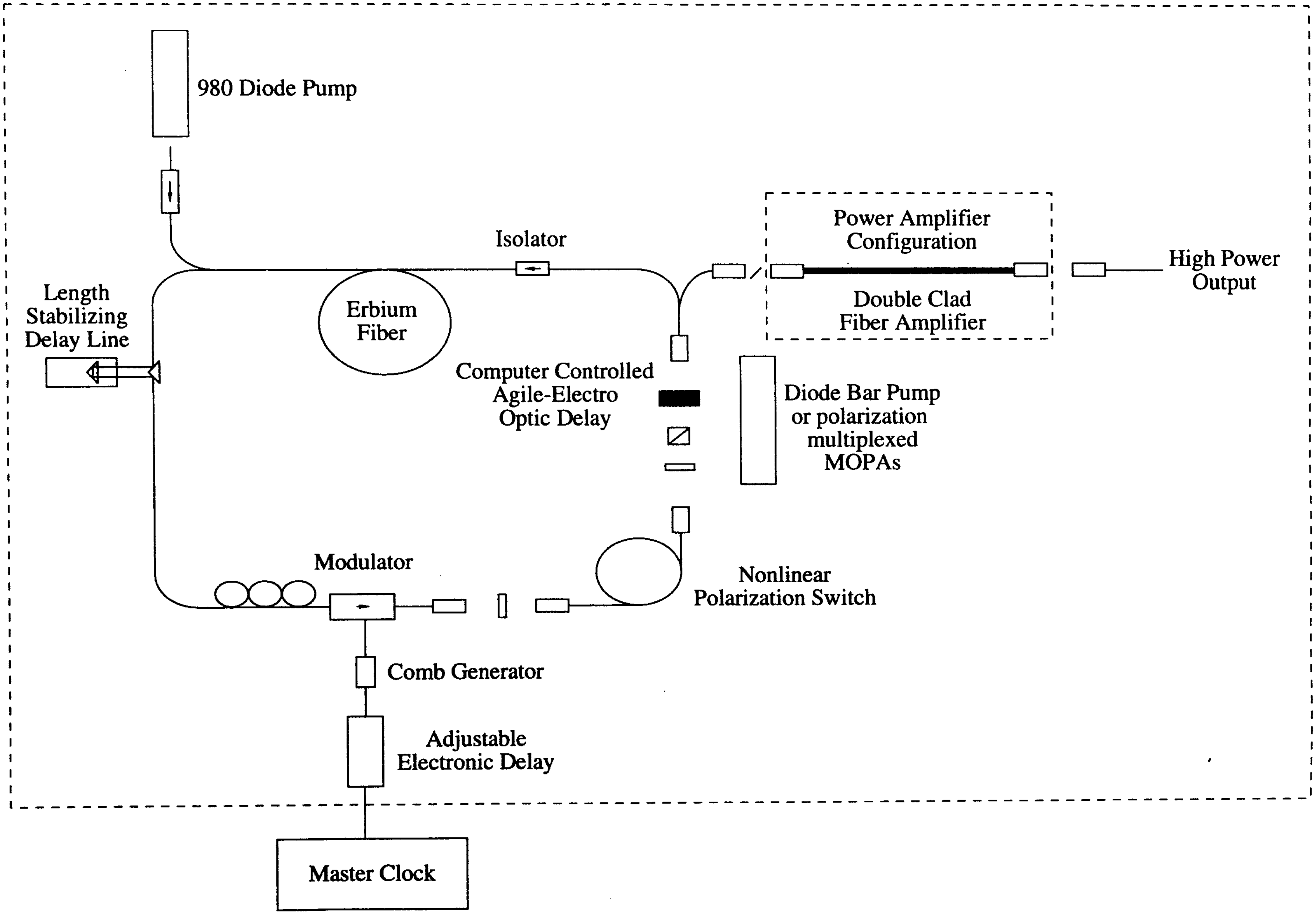
980 Diode Pump
Isolator
Length
Stabilizing
Delay Line
Erbium
Fiber
Power Amplifier
Configuration
Double Clad
Fiber Amplifier
High Power
Output
Computer Controlled
Agile-Electro
Optic Delay
Diode Bar Pump
or polarization
multiplexed
MOPAs
Modulator
Nonlinear
Polarization Switch
Comb Generator
Adjustable
Electronic Delay
Master Clock

Figure 1

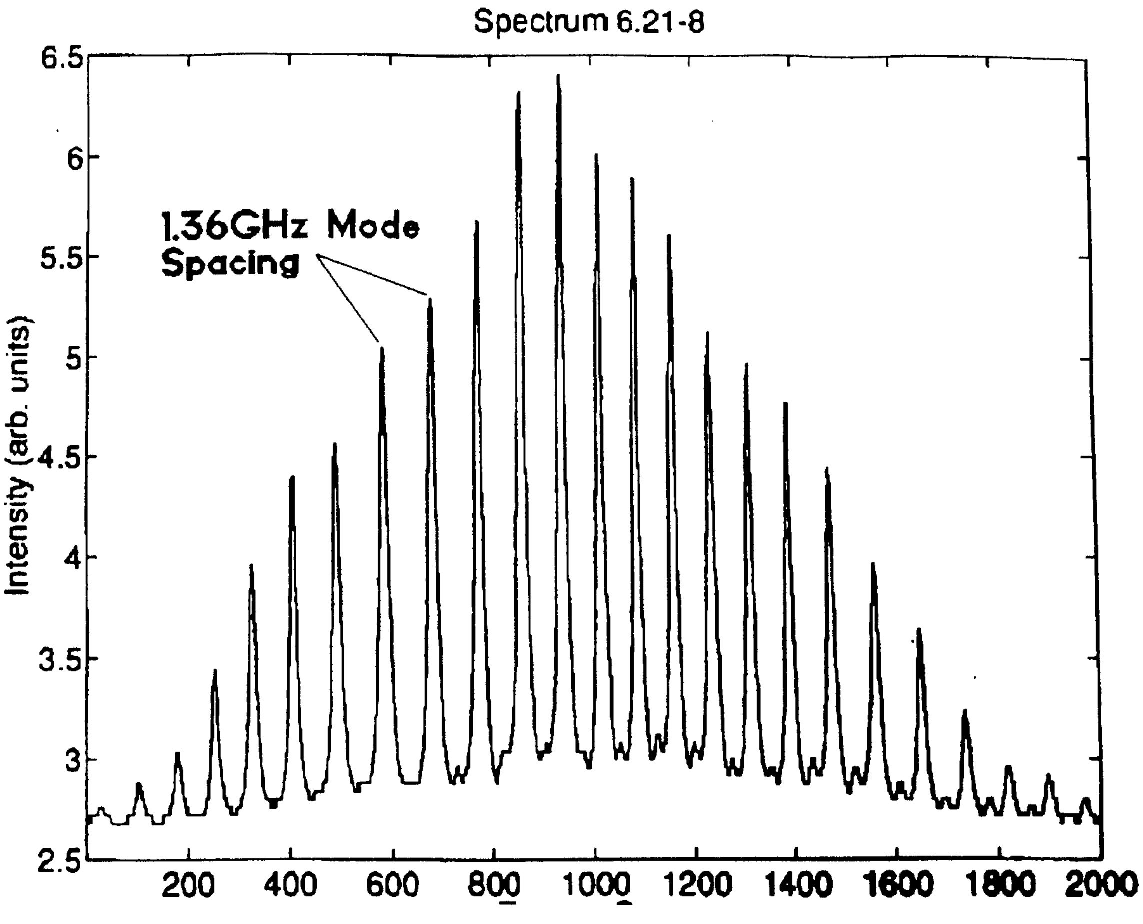

Fig. 2. Spectrum of frequency stabilized harmonically modelocked laser.

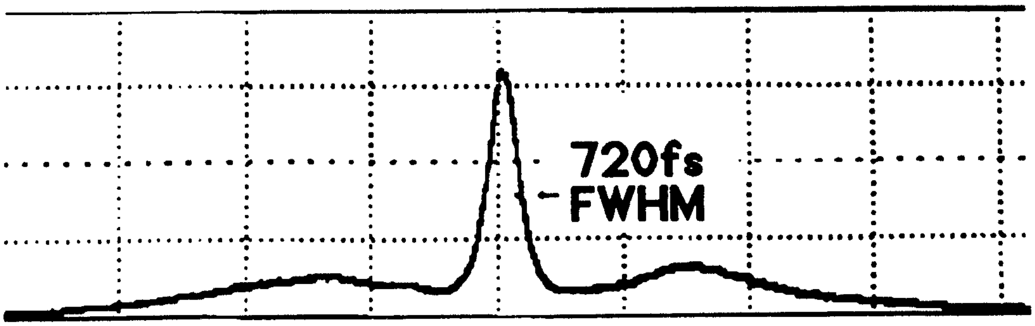

Fig. 3. Autocorrelation trace of harmonically modelocked laser pulse obtained using nonlinear polarization pulse shaping

10.2 Structuring of the Effort

There are clear stages to the overall effort. The first stage is to develop highly stable harmonically modelocked optical fiber lasers suitable for introduction to space. The second is to develop a double clad fiber power amplifier, and possibly intermediate and preamplifier fiber amplifier stages. The objective will be to provide the desired increase in power while still preserving the phase relations and stability of the pulses and the pulse train. The third step will be to phase lock pairs of these stable lasers. The fourth step is build up phased arrays of these pairs of phase locked lasers while maintaining the average power and stability of the individual lasers throughout the complete system. The fifth step is to enable a degree of envelope and phase control that will make possible agile beam formation and steering. In general, we intend to recognize the overall goal at the beginning of the work and develop each stage in a manner consistent with that overall goal. This creates a demanding program, but is expected to provide an extremely valuable end product.

The current proposal relates primarily to the first and second stages of this effort; however, we are also examining details relevant to subsequent stages. We have included a commitment to a space mission as part of this proposal as a means of staying in contact with space based requirements throughout the work. This includes recognizing the traditional safety and launch standards required by NASA, e.g.. Funding for student travel to the required meetings will be sought separately from NASA. The PI is currently working with the Optics Division of NASA at the MSFC as a summer Faculty Fellow. We anticipate interaction with this world class optics group and support for some of the student effort.

10.3 Relevance of Harmonically Modelocked Optical Fiber Lasers

Part of our work is to establish the relevance of harmonically modelocked optical fiber lasers to agile optical phased arrays for space based applications. These lasers have traditionally not been considered for use in optical phased arrays, or for agile optical phased arrays. We believe these lasers, given recent advances in related fields, are excellent candidates for this application. Part of our effort will be to test and verify the premises of the reasoning.

One problem in phase locking semiconductor arrays is the strong coupling of the refractive index of the laser medium and the gain. A second problem is the large parameter space available to both the individual lasers and also to the laser array. These two problems interact to create structures that are difficult to stabilize and operate. In addition, the need for large adjustable true time delays further complicates the problem.

The highly stabilized and controlled optical fiber laser we propose to explore offer solutions to both of these problems. The coupling of refractive index and the gain in fiber lasers is significantly reduced. Also the number of controls in the form of actively controlled lengths, spectral filters, polarization constraint, gain level, pumping rate, actively modulated transmission, and nonlinear pulse shaping and nonlinear coupling provide a rich variety of adjustable controls.

The relatively long length of optical fiber, e.g., some 10 meters in a harmonically modelocked laser, might be considered a drawback. However, any agile optical phased arrays useful in space will require relatively large dimensions for the purpose of obtaining diffraction limited beams that can be targeted efficiently on distant objects. Also the need for rapidly adjustable delays demands an array of delay lines of the order of the dimensions of optical fiber lasers. The long lengths can also ease thermal difficulties. We propose to explore the role of the optical fiber as a positive resource in agile optical phased arrays.

Further economies in optical fiber systems may emerge from an exploration of multicore fibers. We have an existing effort in this area, as well as one of the world's best libraries of numerical simulation programs for multicore fiber systems. We thus feel confident that our group is well qualified to address issues relating to multiple core optical fiber technology. We will maintain an awareness of multicore fiber during the proposed effort and can add effort in this direction should it prove beneficial. Our current work indicates that multicore fiber technology may well become highly valuable, The present demand is one of maintaining the phase relationship of optical beams in the different cores. Our experience in this area should be helpful in judging the relevance of this emerging technology.

10.4 Choice of Strategy for Timing and Phase Locking

One of the basic tasks in attacking the problem of phased arrays is choosing the strategy for achieving the required timing of the various pulse envelopes and also achieving the required well defined phase relation of the multiple optical carrier fields. Earlier approaches have tended to address one of three different types of structure. One approach is that of a master oscillator followed by an array of amplifiers that generate the multiple signals. A second is the use of arrays of coupled laser oscillators. A third is the use of Talbot resonators that permit mixing of individual modes, but also allow spatial separation of those modes in some region.

Our approach is to focus on the nature of the optical fiber systems we are exploring, on the emerging technologies, and on the needs of DoD. The relevant physical laws appear to permit achievement of the proposed goals. The research work will involve examining various trade offs, such as the use of a master electronic clock and active modulation that exploits state of the art electronic pulse sources and high speed modulators. We also will investigate combining optimally active and passive modelocking while performing feedback stabilization of laser length. The use of the most advanced electronic based timing we regard as especially important as a key to the linking of the electronic and optical portions of these sophisticated systems with picosecond and subpicosecond precision. An important part of the funding is to be used for this purpose. In general we will assess state of the art optical and electronic capabilities and seek to optimally integrate these capabilities.

10.5 Stabilization of Harmonically Modelocked Fiber Lasers

A primary objective of the experimental part of the proposed work is the development of highly stable harmonically modelocked lasers with an orientation toward technology suitable for introduction to microspacecraft. We have already stabilized harmonically modelocked lasers.[1] We show in Figure 2 the trace of the output spectrum of one of our harmonically modelocked lasers. The uniform mode pattern is indicative of the stabilized laser. We have successfully used active feedback to stabilize this emission pattern. Work at AT&T Bell Laboratories [2] has successfully demonstrated use of lasers of this type for highly reliable error free transmission over distances of megameters.

A key objective of the proposed work will be to develop the simplest stabilization strategy while also reducing optical pulse duration to the subpicosecond regime. The existing stabilization strategy [2] works well, but is somewhat cumbersome for a space based application. That strategy would also hinder the reduction of pulse duration in ways that would unnecessarily limit an approach to maximum data rates. We note that even with the current system, rates approaching 100 Gbits can be considered. This is consequently not a severe limitation; however, throughout our work we will seek to identify pathways that will minimize any unnecessary limitations.

The improved stabilization scheme we will initially explore is one demonstrated by Takara et al of NTT. [3] In essence the frequency spectrum of the laser emission is monitored up to about 40 kHz and the integrated signal used to introduce a correction in the laser length. This approach requires a highly precise electrically driven optical gate that can be obtained using the equipment we have requested. The precision optical gate is important since it limits the opportunity for the laser to oscillate in alternative supermodes. It is the lack of that constraint that is a key barrier to stable modelocked optical fiber lasers and hence to agile optical phased arrays based on these lasers.

The correction is introduced by varying the optical delay at the point in the laser (see Fig. 1) where an adjustable optical delay is introduced. We will explore various means of introducing the needed delay in a manner compatible with technology for microspacecraft. Some of the possible devices are miniature stepper motors, electrostrictive devices for stretching optical fiber, combinations of the above, photonic band gaps controlled electrically, and poled optical fiber controlled by introduced electrodes. We either have these capabilities, will have them with the requested support, or can access them through our collaborative relationships.

10.6 Double Clad Fiber Lasers

A major part of this effort will be to explore double clad laser amplifiers pumped by semiconductor laser arrays. These double clad fiber lasers are a recent breakthrough that enables efficient pumping of single mode optical fiber lasers. This efficient high power capability allows optical fiber lasers to reach power levels, (e.g., 5-10 Watts average power) that can support very high data rate long distance transmission in space.

The precise means of integrating the double clad fiber as an amplifier will be part of the research. Fig. 1 indicates schematically the introduction of the double clad fiber as a power amplifier. We anticipate that for this part of the system we will need to explore use of chirping, compressing, preamplfication, and possibly intermediate amplifier stages as well as different pump sources and means of coupling pump and signal into the double clad fiber. The proposed effort will seek the best solution consistent with the proposed goals.

We have active ongoing dialogues with The University of Southampton, The University of Sydney and Spectra Diode Laboratories on obtaining the best source of these amplifiers. The price quoted in our budget is our best current estimate based on these discussions. Current work by others is described in reference 8.

10.7 Development of Improved Electro-Optic Modulators and Modulator Arrays

We also have an agreement with United Technologies to explore means of increasing the bandwidth and reducing the required voltage on the modulators they produce. This is important in producing the stable harmonically modelocked lasers. Fast modulators of the kind needed have been developed by Sumitomo, however they are not commercially available at this time in this country. We believe it is important to work with a U.S. based firm to develop this important capability.

Another agreement is with Dr. Paul Ashley of MICOM to evaluate development of arrays of electro-optic modulators and determine what would be needed to extend this capability to the arrays of fiber devices needed to realize agile optical phased arrays. Dr.

Ashley has an existing program addressing key issues. [8] We will use our lasers to evaluate the array structures he is developing and provide feedback concerning their relevance to this important optical phased array task.

The improved electro-optic modulators are important to obtaining the stable harmonically modelocked lasers and also the short duration pulses that will allow high data rate communications. We show in Fig. 3 an autocorrelation trace of the pulses obtained at 1.36 GHz using our current laser. We have added polarization shaping to the active modelocking so as to obtain pulses with durations, as shown by the autocorrelation trace, of 720 femtoseconds. These pulse durations would, in principle, allow data rates up to terabits. The wings on the trace are indicative of instabilities in the current laser output that would be remedied by the addition of the requested equipment.

10.8 Related Efforts

In separately funded efforts, or efforts for which we are currently seeking funding, we are exploring in collaboration with others the introduction of true time delay by electro-optically tunable photonic band gap structures, fabrication of means for holding the optical fibers in stable position suitable for a phased array, means for remote sensing, and means for electro-optic control of the array. The combination of these phase locked arrays of fiber lasers and related capabilities is intended to be carried out so as to develop space capable technology suitable for microspacecraft.

10.9 Terrestrial and Space Based Tests of the Technology

We plan to send signals from our Ultrafast Photonics Research Laboratory to the SEDSAT Lab as a terrestrial test of the transmission technology. We also plan a test between our laboratory and a station on nearby Monte Sano. For space based tests we plan to send a signal from a ground station to the SEDSAT satellite, UAH SEDSAT 1, when it is launched in 1997. As a final phase we include preparation for an experiment to be carried on a shuttle mission in a G.A.S. (Get Away Special) enclosure. We believe we can do this at very reasonable cost through the student space organization relationship to NASA.

11. Competing Technologies

11.1 Ultrafast Technology in Space

At this time there is essentially no ultrafast technology in space. We propose to carry out some of the initial experiments introducing ultrafast technology into space. Ultrafast optics can be of great value in space because of the opportunity for long distance high data rate communication with rapid switching and redirection of the optical beams. The realization of agile optical phased arrays attacks the problem of agile tracking of multiple moving targets (or other satellites) that is of great importance, but difficult of realization. It is possible that the quieter environment in space will facilitate phase locking. We intend to evaluate such issues.

11.2 Semiconductor Laser Sources for Space Communications

At this time various sources are being explored for laser communications in space. Dr. John Johnson of SSDC is supervising a program based on use of GaAs laser diodes for communications. [9] This is an important step in communication systems for space. We plan to stay in close contact with Dr. Johnson's effort as a way of evaluating the merit of our program. At this time the SSDC program is not addressing the issue of agile optical phased arrays, but rather achieves orientation of the beams by moving mirrors mechanically. We will include an evaluation of the relative merits of the system currently under development and our longer term proposed system.

12. Nature of Expected Results:

12.1 Stable and Compact Short Pulse Harmonically Modelocked Lasers

We expect to: (1) obtain highly phase stable individual modelocked fiber lasers using the fast electro-optical stabilization strategy, (2) provide amplification of high average power in double clad fiber, and (3) identify problems and novel solutions for those problems as regards construction of the large arrays of these phase locked lasers that will be needed for high average power space based communication systems.

Coincident with this phase locking work, we expect to be developing, under separate funding, photonic band gap technology for true time delay and purely electro optical beam forming and directing. Part of this effort will involve using the phase locked and stabilized lasers as sources to measure and evaluate the performance of the devices to be used to obtain true time delay, such as photonic band gap structures. This stage of the effort is critical because the photonic band gap structures must be precisely constructed and tuned to match the optical spectrum of the phase locked lasers.

The ring fiber lasers we use provide a natural optical delay line. We will explore the feasibility of using these fiber rings as natural "fast cache" adjustable delay lines that could provide the agile, but stable, adjustment of relative timing of pulses needed for true time delay agile phased arrays. A report will be issued addressing the attractiveness of this particular approach to achieving agile true time delay.

12.2 Terrestrial and Space Based Tests

We expect to carry out tests to provide a measure of the data rates that can be accessed, the difficulties to be encountered in sensing and tracking the laser beams, and the degree of agility required for a given rate of beam reorientation and forming. The terrestrial and space based tests will also require attention to hardware issues, weight of components and issues of the robustness of the components. The annual reports will detail progress along these lines.

13. Facilities Available For Performing the Proposed Research

The PI currently is supervising the Ultrafast Photonics Research Laboratory at UAH. This laboratory includes the necessary equipment, aside from that requested in the proposal, needed to pursue the proposed work. The laboratory includes a state of the art fusion splicer that can splice polarization maintaining fiber, MOPA semiconductor diode pump lasers, an optical table, fast oscilloscopes, a spectrum analyzer, an autocorrelator, couplers, precision hardware, optical fiber, and other components needed for modelocked optical fiber laser research.

The SEDSAT laboratory at UAH includes the resources needed for microsatellite assembly and preparation for launch. The laboratory includes resources obtained through earlier DEPSCoR support. Specialty hardware include a Panoramic Annular Lens, an ARPA supplied SCC 100 parallel processor, and a SEASIS telephoto imaging system. Pointing and tracking capabilities as well as extensive image analysis capabilities are also available. Substantial expertise is available in the UAH student population participating in the SEDSAT organization.

We also note that expertise in space related work abounds at UAH. In particular, we have already had very favorable experience in working with the on campus machine shop headed by Greg Tyler. Mr. Tyler has had extensive experience in preparing equipment for shuttle launch. We anticipate calling on his shop for fabrication of components related to our proposed space based tests.

14. Rationale For Each Item of Equipment in Budget

14.1 Optics Components

14.1.1 - 83711A HP Signal generator. This is a state of the art cw signal generator needed to generate the narrow time window electrical pulse at gigahertz rates. This provides a high quality stable source.

14.1.2 - 83006 HP amplifier. We need this unit to increase the signal from the pulse generator to provide adequate drive for the electronic pulse generator.

14.1.3 - MZM-1.5-18-T-1-1 UTP Modulators. These are the state of the art modulators needed for the precise pulse control.

14.1.4 - 6205C Dual Channel Power Supply. These are needed for the modulator bias.

14.1.5 - MOPA laser diode. This is needed for pumping double clad fiber.

14.1.6 - LDC 3900 ILX Controller. Needed for driving the diode MOPA pump.

14.1.7 - N1-S Double clad fiber. This double clad fiber is needed to obtain the required high average power via double clad fiber pumped by a diode bar. This is an estimated price based on discussions with SDL and two university suppliers. We have a quotation for a complete system from Spectra Diode Labs for $60,000. We also have offers of the fiber through other sources. Our budget includes what we believe to be the most reasonable estimate. We will seek the best value approach for this evolving technology.

14.1.8 - 71450A-Opt 2,51,101 This is a spectrum analyzer needed for analysis of the laser system.

14.1.9 - 54750 HP 50 GHz Oscilloscope. Needed for observing the short pulses.

14.1.10. 1011 45 GHz photodetector. Needed for observing the short pulses.

14.2. Space Related Equipment

14.2.1 - Apple Power MacIntosh 9500 & National Instruments Software. This machine is to be used primarily as a high speed image analysis machine for the imagery obtained from the SEDSAT SEASIS instrument. The National Instruments Labview upgrade and new software will form the heart of the analysis suite. Current Labview hardware and software, obtained with DEPSCoR 92 funding and NASA P.O. H-20305D funding, is used with current MacIntosh hardware for the graphical oriented telemetry capture and display system. The Hi-Q numerical analysis software will take data in real time from the satellite's AX.25 data stream and give near real time feedback on image quality. This will supplement the hardware and software on board the satellite which uses an ARPA supplied (MOA) SCC-100 parallel processor that serves as the on board image processing system. The RAM on the MacIntosh will allow for the same level of capability on the ground as is present on the satellite. This will provide a sophisticated analysis of the Hyperspectral

Image information obtained from SEASIS. We will use this equipment to obtain a measure of the needed data handling rates.

14.2.2 Spectra Systems FDDI Fiber Optic Data Card. This is a two card suite and includes software and cables that will form the basis for the phase I laser communications effort. This will be an add-on card for the Power MacIntosh. The utility of this purchase is that we will be able to simultaneously download from the satellite via our existing MacIntosh Quadra computer, transfer the data at high rate to the Power MacIntosh and ship it out to the FDDI net. In addition we will be able to receive data from remote ground stations in the same manner over traditional Internet connections and ship that data out to the FDDI net, effectively forming a gateway between the two networks.

14.2.3 Microway Monoputer. This will be used for a second development system in addition to an existing one supplied to us by our ARPA MOA. We expect this to improve the productivity of the graduate and undergraduate computer science students developing the flight image processing and real time control software for the SEASIS image instrument. The software purchased will compliment the hardware and will provide a full development system for software and hardware.

14.2.4 UAH Open bid for Computer System Components. This request will upgrade the capability of existing 486-50 computers that were purchased under Depscor 92 and those obtained with a $23,000 dollar UAH Foundation grant. The replaced hardware will be used to upgrade older 386 class machines that are used for the PC based ground station.

14.2.5 Saltire Software/Stardyne PC 1000 software. This is an upgrade on our structural analysis software originally purchased for Depscor 92. This software is used for the analysis of the SEDSAT 1 structure in order to comply with NASA Goddard Space Flight Center and NASA Marshall Space Flight Center requirements for flight on the Shuttle. This software will also be used for follow on efforts to build a standardized microsatellite bus that can be used to support our phase III and IV effort for the laser flight experiments.

14.2.6 Techni-tool Equipment. This entire list of equipment is designed to support the research effort by obtaining the equipment necessary to build prototype and protoflight electronics. This test equipment will replace and supplement the resources gathered and depleted over the life of the SEDSAT 1 project as well as support the flight integration into the Shuttle Orbiter of SEDSAT 1 in the spring of 1996. These tools will also be available to support prototyping of hardware for the phased research effort that goes along with and beyond SEDSAT 1.

14.2.7 Hewlett Packard Equipment. These power supplies will be loaded into the power supply mainframe that was purchased for Depscor '92. The mainframe can accept a total of 8 power supplies. Only 2 were purchased previously. This power supply system has been invaluable in giving an assured power supply system that can simulate the satellite power supplies. Also, the ability to accurately set the current and voltage limits is absolutely necessary to reliably power flight components that in some instances are worth hundreds of thousands of dollars.

14.2.8 Hewlett Packard Equipment. This equipment will complete the generic small satellite power supply and load system that was begun with Depscor 92 and carried forward in year 1 and 2 of this proposal. This will allow the total simulation of a small satellite power system, both for loads and for power generation. This will allow software development for future satellites and shuttle experiments relating to the phase III and IV efforts to be carried out with greater efficiency. The combination of this hardware and previously purchased National Instruments Software and data acquisition hardware will be used for the development of the microsatellite systems.

14.2.9 Special items for shuttle experiment

Item 8	Fixed Signal Generator for G.A.S.	$7,000
Item 9	Control System for G.A.S. can	$7,500
Item 10	Experimental Mounting Plate for G.A.S.	$7,500
Item 11	Batteries for G.A.S. experiment	$2,000

The above prices were arrived at after a consultation with Dr. Fran Wessling and Mr. Dennis Wingo from the University of Alabama in Huntsville. Dr. Wessling has been involved with several shuttle missions and experiments including Get Away Specials (G.A.S.). The prices were based on their own experiences with G.A.S. missions. Items 9 and 10 will be made in-house, in UAH's machine shop which is qualified to work on any level of space qualification. Items 8 and 11 will most likely be purchased by an outside vendor and then modified for the specific experiment.

15. Other Parties Who Will Receive the Proposal or Who Will Partially Fund the Proposed Work

This particular proposal is submitted only to DEPSCoR.

We have existing support for related work from AFOSR that will end November 30, 1995 and an AFOSR AASERT for a graduate student and two undergraduate students that will continue until May of 1997 for the graduate student and May of 1996 for the undergraduates. Two graduate students will receive support from NASA beginning September 1995. We intend to submit related proposals dealing with true time delay technology and enhanced detection via correlated spontaneous emission to AFOSR and ARO respectively. One Research Associate, Michael Scalora, is currently funded by MICOM and ARO to do numerical simulation work.

16. References

1. "Harmonically mode-locked laser and applications," R.L. Fork, K. Singh, J. Haus, R.K. Erdmann, S.T. Johns, SPIE Proceedings **2216**, 148-159 (1994).
2. "Harmonically mode-locked fiber ring laser with an internal Fabry-Perot stabilizer for soliton transmission," G.T. Harvey, L.F. Mollenauer, Optics Letters **2**, 107-9 (1993).
3. "Stabilization of a modelocked Er-doped fibre laser by suppressing the relaxation oscillation frequency component," H. Takara, S. Kawanishi, M. Saruwatari, Electronics Letters **4**, 292-6 (1995).
4. "Femtosecond pulse amplification in cladding-pumped fibers", J.D. Minelly, A. Galvanauskas, M.E, Fermann, D. Harter, J.E. Caplen, Z.J. Chen, and D.N. Payne.
5. Song Wu, "The third order nonlinear process in femtosecond time-resolved four-wave mixing and femtosecond lasers", PhD Thesis, Rensselaer Polytechnic Institute, 1993.
6. "Compression of optical pulses to six femtoseconds by using cubic phase compensation," R.L. Fork, C.H. Cruz, P.C. Becker, C.V. Shank, Optics Letters **7**, 483-5 (1987).
7. "Locking of He-Ne laser modes induced by synchronous intracavity modulation," L.E. Hargrove, R.L. Fork, M.A. Pollack, Applied Physics Letters **1**, 4-5 (1964).
8. Paul Ashley, MICOM, private communication.
9. John Johnson, SSDC, private communication.