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Robust, Brillouin Active Embedded Fiber-Is-The-Sensor System in Smart Composite Structures

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Annual Progress Report

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INTRODUCTION

Extensive review of our proposed sensing scheme, based mainly on the forward Guided Acoustic Wave Brillouin scattering (GAWBS) with backward stimulated Brillouin scattering (sBs) as an auxiliary scheme for system fault tolerance has been completed during this project period. This preliminary study is conducted foe a number of reasons. The most significant reasons lie in the essential capability of the system to measure temperature and pressure. These two measurands have been proposed to be sensed by sBs in our proposal. Temperature and pressure/strain are important measurands in structural monitoring, so that the effectiveness of sensing by sBs needs to be further examined.

It has been pointed out initially that sBs shift will be dependent on temperature and pressure/strain simultaneously. The shift versus temperature or strain is linear. Now, the question is how can these two measurands be separated when sBs is used to sense an environment, in which both temperature and strain are changing simultaneously. Typical sBs shift plotted versus strain and varying temperature is shown in Fig. 1. As is clear, a fiber initially stressed will relax with rising temperature. This is verified by a displacement to the right with rising temperature of the sBs shift vs strain curves in the figure. A way to circumvent this ambiguity is by employing two fibers, one pre-stressed and the other is a free fiber. The latter will measure temperature and subtracting data in the latter fiber from those of the former will give us net strain readings. This is a laborious approach, since it involves the use of two identical fibers, and this is hard to accomplish, especially when many sensors are needed. Additional multiplexing of the data stream for data subtraction becomes a necessity.

We are in the process of designing a single fiber sBs sensor for separate temperature and strain sensing. We have proposed originally to perform sensing based solely on sBs and GAWBS frequency shifts. No consideration has been given to the sBs and GAWBS signal amplitude. Our new findings point to the significance of the amplitude data in the temperature and strain sensing schemes. Thus, an sBs shift accompanied by sBs amplitude variation indicates a temperature change to the fiber enviroment, while an sBs shift with no significant amplitude variation points to only a strain in the fiber.

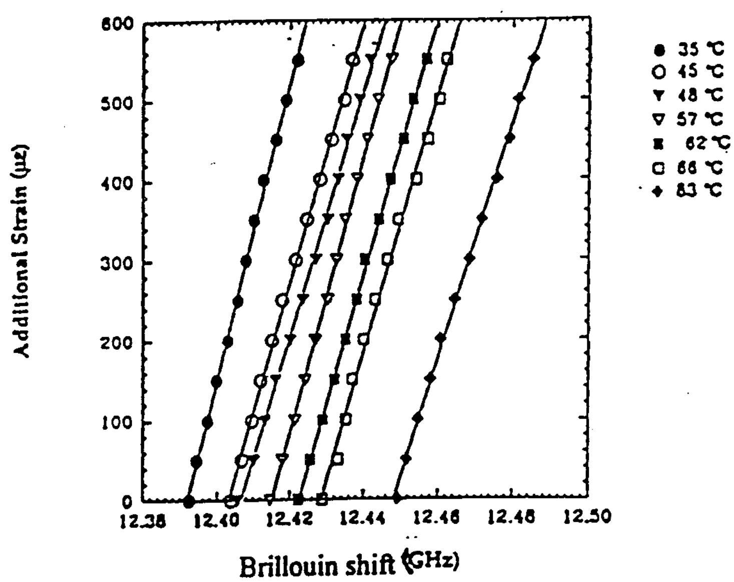


Figure 1. Typical sBs shift Versus strain and varying temperature

I. TEMPERATURE DEPENDENT SCATTERING PROPERTIES OF OPTICAL FIBERS

1.1. Reversible Back Scattering

The total scattering coefficient consists of several contributions, which we can write as:

$$\alpha_s = \alpha_{sr} + \alpha_{sb} + \alpha_{sra} + \alpha_{sf}$$

where α_{sr} is the temperature dependent Rayleigh scattering coefficient, α_{sb} the temperature dependent Brillouin scattering coefficient, α_{sra} is the temperature dependent Raman scattering coefficient, and α_{sf} is the static, "frozen in" Rayleigh scattering coefficient. The scattering coefficient α_{sf} is due to frozen in density and dopant concentration fluctuations which consist of thermodynamic, and nonthermdynamic, process dependent contributions.

The temperature dependent Rayleigh and Brillouin scattering contributions are comparable in size, and the Raman coefficient is about 100 to 1000 times smaller.

The contribution to the scattering coefficient from temperature dependent Rayleigh scattering is given by

$$\alpha_{sr} = \frac{8\pi^3}{3\lambda^4}\left[\frac{k_B T n^8 (p_{11} + p_{12})}{9B} + 4n^2\left(\frac{dn}{dT}\right)^2 \frac{(k_B T)^2}{\rho C_v}\right]$$

The first term is from thermodynamic volume fluctuations and the second tem is from thermodynamic temperature fluctuations. The reversible contribution to the scattering coefficient from temperature dependent Brillouin scattering is given by

$$a_{sb} = \frac{8\pi^3}{3\lambda^4}\frac{k_B T n^8 p_{12}^2}{v_l^2 \rho}$$

The Brillouin scattering coefficient is due to scattering of light by thermally excited longitudinal acoustic waves, and the v-v polarization contribution. The transverse acoustic wave contribution is more than 15 times smaller (GAWBS contribution), but much more easily detected by electronic heterodyning. The parameters are, the refractive index n, absolute temperature T, bulk modulus B, wavelength λ, heat capacity per unit mass C_v, mass density ρ, Boltzmann's constant k_B, photo elastic constants p_{11} and p_{12}, and longitudinal speed of sound v_l.

In the reversible backscatter mode, the temperature dependence of backscatter intensity is essentially linear. The second term in the expression for Rayleigh scattering is less than 1% of the value of the first term. Hence, both the Rayleigh and Brillouin backscattering coefficients are extremely linear in temperature for fused silica fibers. Such linearity is shown below:

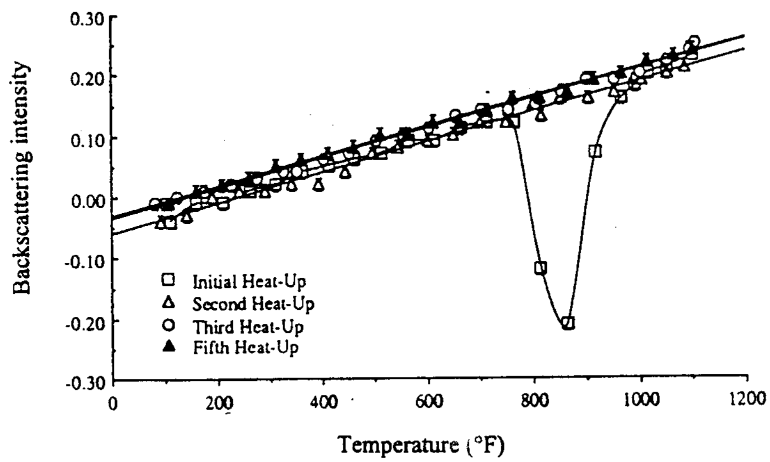


Figure 2. Backscattering intensity vs temperature
Notice the Dip at 800°F in the first heat-up is due to sublimation of the acrylate coating of the fiber

It can thus be predicted that both sBs shift and signal magnitude increase with temperature in the reversible temperature range. On the other hand, strain will only affect the sBs shift, but not its magnitude.

1.2. Temperature Dependence of sBs Threshold

When sBs signal amplitude is to be used as a sensing mechanism, we must first consider the sBs threshold. The sBs threshold is a function of many variables, as the formula indicates:

$$P_{th} = 21\frac{KA_{eff}}{g_0 L_{eff}} \cdot \left(\frac{\Delta\nu_B}{\Delta\nu_{Int}} + \frac{\Delta\nu_L}{\Delta\nu_{Int}} \right)$$

where K and g_0 are the polarization factor (K = 2 for random polarization state) and the Brillouin gain coefficient, respectively. These values are both independent of wavelength. L_{eff} represents the effective interation length, and is defined as $L_{eff} = \{1 - \exp(-\alpha L)\}/\alpha$ where α is the fiber attenuation coefficient and L the fiber length. A_{eff} is the effective core area. $\Delta\nu_L$ is the laser linewidth. $\Delta\nu_{Int}$ is the intrinsic Brillouin gain bandwidth (= 35 MHz for silica based fiber at 1.55 μm), which is the local bandwidth of Brillouin gain. $\Delta\nu_B$ is the Brillouin bandwidth of the fiber, which expresses the bandwidth of the Brillouin gain accumulated along the fiber length. The $\Delta\nu_B$ values of the conventional fiber with a uniform Brillouin frequency shift coincide with the intrinsic Brillouin gain bandwidth $\Delta\nu_{Int}$. On the other hand, for a fiber with a nonuniform Brillouin frequency shift along its length, $\Delta\nu_B$ is larger than $\Delta\nu_{Int}$. Thus, the threshold power can be increased by broadening the Brillouin bandwidth $\Delta\nu_B$ of the fiber compared with the intrinsic Brillouin gain bandwidth $\Delta\nu_{Int}$. $\Delta\nu_B$ is broadened by introducing a variation in Brillouin frequency shift ν_B along the fiber length. If this variation is greater than $\Delta\nu_{Int}$, the sBs threshold increases. Such broadening is possible and likely when the temperature along the fiber is nonuniform, as demonstrated in the experiment below.

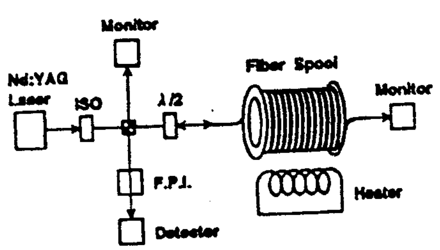


Figure 3. Experimental arrangement for measuring dependence of sBs on temperature distribution in fibers

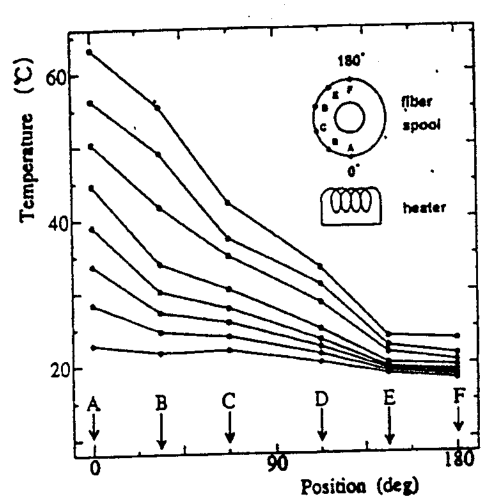
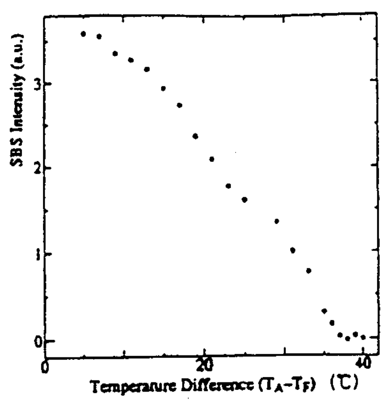


Figure 4. Temperature distribution of heated fiber spool at different maximum temperature difference. Inset indicates positions where temperature is measured



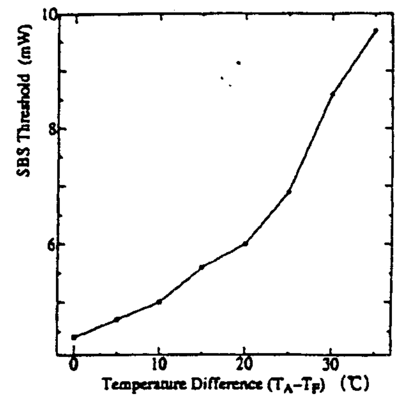


Figure 5. SBs intensity as a function of temperature difference in fiber

Figure 6. SBs threshold as a function of temperature difference in fiber

As a matter of fact, it has been suggested that the scheme is applicable to the evaluation of the temperature difference along the fiber by measuring the sBs threshold ot the sBs intensity.

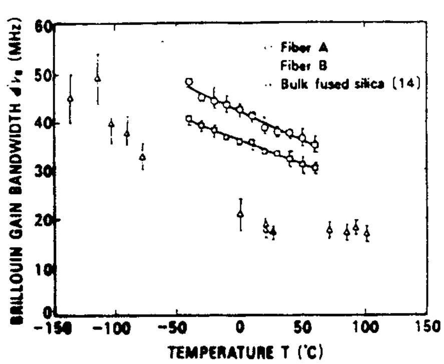


Figure 7. Temperature dependence of the Brillouin gain bandwidth

It is found that the temperature dependence of Brillouin gain bandwidth for single-mode fibers has the same behavior as that in bulk-fused silica glass, and Brillouin gain bandwidth for single-mode fibers decreases linearly with temperature in the -40 °C ~ +60°C range. This temperature behavior may be explained by an anharmonic acoustic damping mechanism involving three-phonon interactions. The measured Brillouin gain bandwidth was broader by a factor of two than those of bulk fused silica glass. It is believed that the discrepancy between them is caused by the inhomogeneous refractive index profiles of the optical fibers, variation in dopant concentrations, and residual stress along the fiber lengths.

A_{eff} is the effective core size of the fiber, and is controlled by dopant concentration, which in turn, can be temperature dependent at elevated temperatures by dopant diffusion. Dopant diffusion alters the refractive index profile of the fiber, and this produces a change in thte mode field radius (A_{eff}) of the optical field in the fiber.

Previous work on the production of tapers by the thermal diffusion of dopants has been confined to germanium doped fibers. But the low diffsion constant of germanium in silica means that diffusion times are too long for most pratical applications. A taper has been made by heating a section of fluorine doped fiber which has a pure silica core and a fluorine doped cladding, the presence of the fluorine decreasing the refractive index of the cladding below that of silica. Fluorine diffuses much more readily than germanium, considerably reducing the heating times required to produce tapers.

We must note that in our GAWBS work, the spectrum is extremely sensitive to dopant type and concentration or refractive indices between the core and the cladding. If dopant concentration varies with temperature, then GAWBS sensing should be highly sensitive to it.

1.3. Irreversible Backscattering

It leads to lower backscattering due to lower backscattering trapping factor and lower scattering coefficient.

1.3a. Structural relaxation

These processes are primarily structural relaxation of the amorphous material, and fiber dopant diffusion processes. The scattering from frozen in density fluctuations associated with the liquid state is responsible for the majority of the attenuation in silica optical fibers. Thermodynamic considerations predict a value for the density fluctuations. It is possible to have density fluctuations in excess of thermodynamic values by rapid cooling of the optical fibers during their manufacture, which is process dependent. Relaxation of the density fluctuations towards smaller values predicted by thermodynamics can be achieved by annealing at high temperatures. The annealing point of bulk fused silica is approximately 1140°C (2084°F), as compared to a strain point of 1070°C, and a softening point of 1665°C. However, stress relief annealing and structural relaxation is expected to take place at somewhat lower temperatures in fused silica optical fibers, since the material has not been consolidated in the same manner as bulk fused silica.

1.3b. Dopant Diffusion

The diffusion coefficients of dopants in solids are strongly temperature dependent, and it is known that significant diffusion of germanium in fused silica occurs in a few hours at 1200°C. Since dopant concentrations are considered proprietary, it could not be determined with certainty the degree to which dopants were responsible for the irreversible change. From estimates of core diffusion times based on published diffusion constants, it is believed that the diffusion of dopants, some with larger diffusion coefficient than germanium, plays a major role in the decreased level of backscattering.

The refractive index profile and waveguiding properties of optical fibers are controlled by suitable dopants in the core and cladding regions of the fiber. Commonly used dopants are GeO_2 (to raise the refractive index of the core region), Fluorine (to lower the refractive index of the cladding), and additional dopants such as Chlorine (to remove OH during fabrication), Boron, and Phosphorus. Each of these dopants makes a contribution to the refractive index profile and scattering coefficient of the fiber. The various dopants have differing diffusion coefficients at elevated temperature, and thus, depending on the fiber composition, different behaviors will occur in regard to altering the fiber numerical aperture (and thus trapping factor S), and scattering coefficient due to concentration fluctuations.

The (irreversible) diffusion of dopant atoms can be described by the diffusion equation

$$\frac{\partial C}{\partial t} = D\nabla^2 C$$

where D is the diffusion coefficient of the dopant of interest (in SiO_2) and C is the mole concentration of the dopant. In a binary system such as GeO_2-SiO_2, the relation between the dopant concentration profile and the refractive index profile can by described by the equation

$$n^2(r,t) = n_S^2 + C(r,t)(n_G^2 - n_S^2)$$

where $n_S = 1.458$ and $n_G = 1.603$ are the refractive indices of pure fused SiO_2 and GeO_2 respectively, and r is the radial distance from the center of the fiber. Note that the refractive index profile mirrors the shape of the dopant concentration profile. The on axis (r = 0) solution to the diffusion equation for an initial parabolic concentration profile (graded index fiber) is

$$C(0,t) = C_0(1-(t/\tau_C)(1-e^{-(\tau_C/t)}))$$

where C_0 is the initial value of the on axis concentration and the core diffusion time is given by

$$\tau_C = \frac{a^2}{4D}$$

where 2a is the initial core diameter of the fiber. Note that unusual time dependence in the exponent. The fiber numerical aperture, which is proportional to the back scatter trapping factor, can by written as

$$NA(t)^2 = C(0,t)(n_G^2 - n_S^2)$$

Thus we see that the back scattering trapping factor S is directly proportional to the on axis dopant concentration.

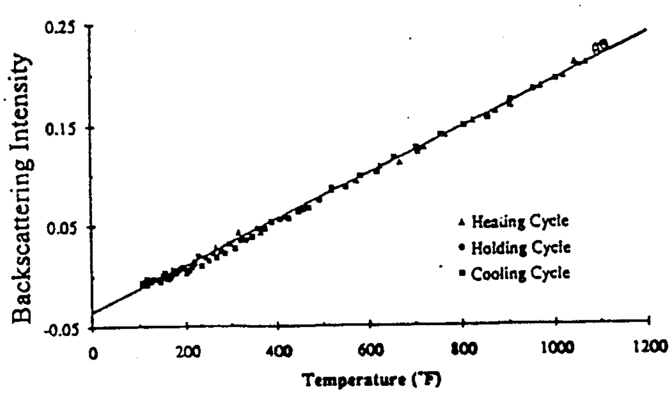


Figure 8. Temperature dependent response of 50/125/185 μm gopld coated, graded index optical fiber showing reversible behavior.

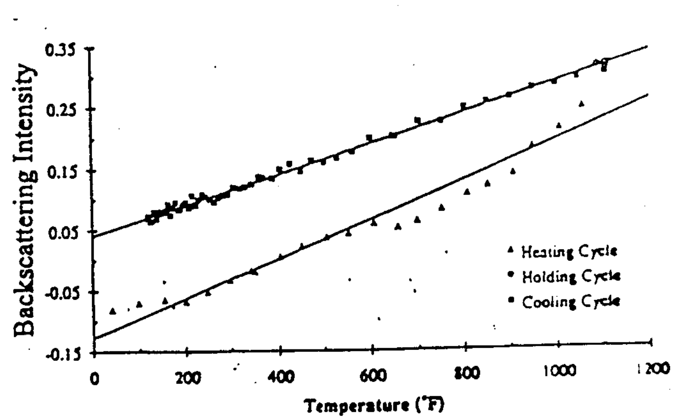


Figure 9. Temperature dependent response of 50/125/175 μm aluminum coated, graded index optical fiber showing irreversible behavior, initial heating and cooling cycle

II. STATUS OF WORK

2.a. Some preliminary sBs experiments have been conducted. The backscattered signal was substantial such that optical feedback into the laser head was not blocked even with the use of optical circulator and isolator. The laser head was thus sent to the manufacturer for inspection and the installation of an additional isolator inside the laser head. With the original isolator, this would effectively provide us with 120 dB isolation. The laser head is being reassembled and will be in operation by the end of this month.

2.b. Since we have altered our research direction by concentrating on sBs as the main sensing mechanism and GAWBS as the auxiliary mechanism, our previous work on GAWBS is quite sufficient at this time. Our main thrust is to prepare the laboratory for sBs work.

2.c. It appears temperature and strain are the key measurands, so that much preparatory work has gone into understanding the fiber in the context of sensing. We have so far utilized only commercially available fibers for our sensor work, even though these fibers are fabricated mainly for communication. We have thus realized that sensor fibers may have to be different in mechanical and chemical properties, and that these have to be designed by us. We have so far concentrated on the following: fiber design for optimum temperature sensing; fiber design for optimum strain sensing; fiber design for harsh environment.

2.d. Fiber characterization

In fiber communication, in order to transmit more optical power in the fiber core, the acoustic properties of the core and cladding of SMF (single mode fiber) should be arranged in such a way that the acoustic guidance in the fiber core is minimized. Making v_S and v_L of the core higher than those of the cladding is one approach. As the velocity difference increases, the threshold of sBs increases and the sBs gain decreases. This approach can be verified by the experimentally observed high threshold of sBs in a fiber with pure FS as core and B_2O_3-doped FS as cladding, and this fiber does not guide acoustic waves well. However, in sensor applications where high efficiency GAWBS and sBs is desirable, then good acoustic wave guidance is necessary.

2.e. Effect of dopants on sound velocities

Fiber parameters and estimated sound velocities

F concentration wt%	Index difference %	Diameter μm	$a(V_S/V_L)$	Sound velocity V_S(m/s)	V_L(m/s)
1.01	0.29	126.4	0.63	3669	5824
1.04	0.30	126.4	0.63	3661	5811
1.22	0.35	126.9	0.64	3632	5675
1.55	0.44	126.5	0.63	3615	5738

Measured elastic parameters and estimated shear wave velocities

F concentration wt%	Density g/cm^3	Young's Modulus 10^9 Pa	Poisson's Ratio	Shear wave velocity m/s
0	2.204	71.9	0.160	3750
0.30	2.200	70.8	0.163	3720
0.75	2.198	69.0	0.164	3672
1.08	2.196	67.7	0.169	3631
1.40	2.194	66.5	0.175	3591
1.83	2.191	64.4	0.174	3538

Properties of several glass

composition	ρ(Kg/m$_3$)	v_L(m/s)	v_S(m/s)	index	wavelength(nm)
100% SiO_2	2202	5933	3764	1.4580	0.60
95% SiO_2 5% B_2O_3	2187	5605	3601	1.4546	0.5145
85% SiO_2 15% B_2O_3	2169	5164	3099	1.4547	0.5145
97% SiO2 3% GeO_2	2244	5806	3677	1.4624	0.5145
92.5% SiO_2 7.5% TiO_2	2213	5736	3625	1.4834	0.589

It is seen that if 3% GeO_2 doped and pure fused silica are chosen as the core and cladding materials respectively, this particular fiber can be used as both acoustic and optical fiber waveguide. If pure and 5% B_2O doped fused silicon are selected as the core and cladding materials respectively, the fiber can be used only as optical fiber, but not as an acoustic fiber.

2.f. Fiber type, core and cladding sizes, doping, length and possible ring configurations must be explored to establish optimum multimeasurand sensing characteristics. Various fiber types must be used to perform different sensing functions. Thus, to sense temperature, longitudinal strain, sBs based fibers must be used, while for transverse fiber variations and chemical sensing, such as corrosion, GAWBS can play the major role. sBs is a stimulated process, to reduce required threshold, efforts must be made to maximize sBs by maximizing acoustic wave guiding. On the other hand, GAWBS is a resonantly enhanced spontaneous scattering process, so that shorter fibers will suffice, as demonstrated with minimum detection in fibers as short as 1 m. Further sensing sensitivity enhancement is possible by resorting to fiber rings. Preliminary work has shown that GAWBS and sBs efficiency will be increased. GAWBS mode peaks can also be selectively enhanced in a fiber ring by choice of ring parameters, such as the type of coupler used and the length of the fiber forming the ring. It has been theoretically predicted and experimentally observed that bare fibers produce narrower GAWBS mode linewidth. This leads to enhanced resolution of mode lines. In the case of remote sensing, where the sensor portion is located remotely from the light source, GAWBS generated in the long lead fiber to the sensor must be removed. This has been found to be conveniently accomplished by interfacing the long lead to a short polarizing fiber segment before connection to the sensor fiber. The polarizing fiber will filter out any GAWBS components due to the long lead.

2.g. sBs and GAWBS phenomena in fiber rings

Preliminary studies have indicated lowering of the sBs threshold and selective enhancement of GAWBS mode peaks in a fiber ring. Further study is necessary to arrive at optimum ring parameters for dual sBs and GAWBS sensing applications.

III. PLANNED WORK FOR YEAR II

3.a. Fundamental Fiber Studies

Our laboratory is furnished with most of the equipment to accomplish all test and measurements. A system has been set up to implement dual sensing of sBs and GAWBS. This system consists of full line of fiber based components, such as waveplate, polarizers, detectors, polarizing fiber, fiber rings, and an assortment of specialty fibers of different core and cladding dopants. Both sBs and GAWBS have been observed in our laboratory regularly.

3a.1 New fiber will be designed and acquired for optimum temperature and pressure/strain sensing separately and with maximum sensitivity with the harsh ambient conditions in mind: composite curing 120 - 300 °C; ceramic testing up to 1500 °C.

3a.2 The installation of a temperature chamber for high temperature fiber testing. Additional resources will be accessed through partners, such as the Boeing Environmental Testing facilities. Prior understanding exists for us to ship the fibers to those facilities for testing without charge.

3a.3. Reversible and irreversible fiber testing will be implemented so as to study the effectiveness of using GAWBS for fiber health monitoring. Such effects will also be studied for sBs.

3a.4. **Testing of sBs threshold as function of temperature, dopant types and concentration, using specially designed fibers of varying lengths and fiber parameters.**

3a.5. **sBs threshold studies for its supppression and enhancement for various specially designed fibers..**

IV. In-Situ Testing During Composite Manufacture

4.1. Embedded fiber in-situ sensing during composite curing

Techniques must be established to protect fiber pigtails from the flow of the excess resin during composite curing process by coating key areas with silicone RTV sealant. The cured RTV sealant can also provide stress relief at the ingress and egress points. During the curing process, residual stresses develop in composite structures due to mismatch in the thermal expansion coefficients of various piles. These stresses lead to microbending of optical fiber sensors.

4.2. Robustness of embedded fiber sensors

Embedding of fiber may affect the structural integrity of composite and integrity of the sensor. These effects may include both static, such as tensile and compressive stiffness and strain, and dynamic, such as damage tolerance to impact and fatigue. Embedding may also affect the mechanical and optical properties of the fiber. The severe temperature and pressure changes required for curing of composite materials (120-300 C) reduce the resiliency of the fiber sensor by degradation. This may lower the robustness of the embedded sensor and may cause attenuation. Residual stresses developed during the curing cycle in most laminates may also lead to additional optical attenuation, stemming from microbending of the fiber sensor. Embedded fibers have been found to experience a more than 10-fold increase in attenuation.

4.3. Correlation between fiber sensor output and composite structure parameters

It must ultimately be established the existence of correlation between the sensor output and the parameters to be measured: in this case, deformation of the composite structure. Such correlation can be established through tests with standard loads. For instance, sensor response must be measured when composite structure is under uniform uniaxial stress due to tension and compression, uniform shear stress due to torsion, linearly varying stress fields due to cantilever bending, abrupt stress discontinuities due to three-point bending, multiple abrupt stress discontinuities such as four-point bending, and dynamic loading, such as vibration, fatigue and impact.

NASA Technical Memorandum 108527

Institute Study Report

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February 1997

INSTITUTE STUDY REPORT

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1.0 INTRODUCTION

In early 1995, the NASA Centers began investigating the establishment of science institutes with the Agency's science workforce following the recommendations of the Zero Base Review. The NASA Chief Scientist expressed the goals of these institutes as: (1) strengthening the quality of science, (2) binding NASA scientists more effectively to the external community, and (3) coupling the external community to NASA's immense engineering and technical resources more effectively. In response to this activity, the Headquarters Office of Life and Microgravity Science and Applications(OLMSA) took the lead in developing a concept for an International Orbital Research Institute for Science and Technology to support the Space Station. Later, the program did not pursue this concept.

The specific Zero Base Review charge to MSFC was to study institutes in three areas - Global Hydrology, Space Sciences, and Microgravity. In response, MSFC formed an institute working group to research existing institutes, evaluate the OLMSA concept and to develop an institute concept(s) relevant to MSFC science. As the institute planning process proceeded, the focus of the MSFC committee became one of studying existing institutes, and identifying lessons learned for application to developing institute concept(s) for the specified discipline of microgravity science at MSFC. The microgravity institute was studied first because of its extensive involvement with the MSFC engineering workforce.

The initial step in the process of defining a MSFC institute model was the gathering of data on existing institutes thereby creating a benchmark data base. Having established this baseline set of data one could then make application of best practices and previous lessons learned toward the development of the MSFC model. To facilitate collection of this data, a questionnaire(included as Appendix I) was developed to collect information regarding existing institutes' organizational and financial structures as well as to identify the various strengths and weaknesses of those structures. It was further desired to identify research methodologies, interactive relationships with other agencies and various metrics utilized to evaluate their effectiveness.

aid the local economy since their presence encourages industry to locate nearby. Most institutes were formed with a university association to provide the open, academic environment that promotes creativity, the interchange of ideas, and teamwork. Being associated with a large, well-known university was seen as a key element in attracting nationally known researchers, as well as industrial interests to an institute.

The mission emphasis of the institutes which were studied ranged over the continuum from applied to basic research. Basic science institutes, as their name implies, tended to concentrate on research while maintaining a wide external collaboration with the scientific community to sustain cutting-edge research and credibility with that community. Applied research institutes tended to aim their research toward commercial products and thus have more industrial partners. Institutes were involved not only in research and technology development but promoted education and training as well. They usually had a strong, visible presence in the community.

The mission of an institute determined the way it did business, its structure and the evolutionary path undertaken. Basic research institutes were closely tied to the university community, whereas the more product-oriented institutes tended to expand, weaken their university connections, and then become "research for hire" organizations. In some cases where an institute had produced a "product line", it spun off a separate center to concentrate on production leaving the institute itself essentially unchanged.

The evolution of an institute and its mission was observed to be closely tied to the reliability of its core funding, the independence it exercised, and the vision of its Director. In those cases where core funding ceased, the institute changed its mission in order to survive. For example, an astronomy institute whose major funding disappears might increase its emphasis in associated areas of high demand, such as optical coatings development.

1.2.2 THE INSTITUTE DIRECTOR

One factor that was frequently cited as absolutely critical to the success of a research institute, particularly in the early years of its existence, was the selection of the right individual to head the institute. Many of the institute representatives stated that selecting an individual, who was well respected for their work in the field of research pursued by the institute, was essential. However, equally important was, what some described as "entrepreneurial spirit". The ability and the drive to recruit a top-level staff, negotiate for office and laboratory space, acquire equipment and funding, and attract business to the institute, while keeping an eye on the bottom line, were generally acknowledged as being "must have" qualifications for an institute director.

An effective institute director was provided with the power to hire, promote, fire, and to set salaries with minimal restrictions. Also, they had the authority to allocate financial resources where needed. These two factors were often stated as being crucial to the effectiveness of an institute director.

1.2.3 BOARD OF DIRECTORS/ADVISORS

The institutes structured by universities varied a great deal in the degree of independence which they had in their relationship to their parent university. Those with close ties to the university had directors who reported to the university's Vice President for Research. Typically, the more independent the institute, the greater the likelihood that the head of the institute would report to a board of directors. The board of directors was traditionally drawn from groups who had a vested interest in the institute. All institutes had advisory boards, and some large institutes had multiple advisory bodies, whose mission was to provide advice on different aspects of the institute's operation. Members of these advisory boards and panels were consistently drawn from outside the institute itself and occasionally represented groups or entities which had a stake in the success of the institute. Views on the value of such advisory boards were mixed.

Representatives of the institutes which were studied stated that great scientific work required proper facilities and equipment. This was helped by having an atmosphere where ideas could be exchanged freely with the "best" minds in the field. People would compete for the opportunity to work in such an environment even when it meant passing up more lucrative positions at institutions which had less to offer intellectually.

1.3 RESEARCH ARRANGEMENTS

1.3.1 AGREEMENTS

The institutes surveyed utilized a number of different agreements to conduct their research. The type of agreement which was employed depended, in part, on the entity executing the understanding with the institute, the intent of the research, and intellectual property considerations.

In the performance of efforts for the Federal Government, institutes used grants; cooperative agreements; Cooperative Research and Development Agreements(CRADAs); cost reimbursement contracts; Space Act Agreements; cost share contracts and Federal facility operations contracts. In one instance, a Federally Funded Research and Development Center contract(FFRDC) was in place.

Usually, if the government was purchasing services or a product then a contract was appropriate. If research did not require substantial involvement by the government, a grant was used. If there was to be substantial government involvement, a cooperative agreement was utilized. A Memorandum of Understanding was used where the parties did not intend to create legally enforceable rights. This was the least formal of the arrangements. Space Act Agreements were used when no funds were to be exchanged but assets and capabilities were brought to the table by each party to accomplish the research. Sometimes, CRADA's were used similarly but instead of the authority being the Space Act, the Stevenson Wydler Act was used. The FFRDC was used to bring an organization into existence at the initiative of the government to meet a special R&D need which could not be met as effectively by existing in-house or contractor resources.

In another, the customer had a "first right of refusal" to the intellectual property rights.

The institutes did not have problems with the government prescribed intellectual property clauses in the various types of agreements used by the government. In essence, the institutes were willing and capable of negotiating intellectual property rights that accommodated the particular circumstances of the research and the desires of their customers.

1.4 BUSINESS

1.4.1 MANAGEMENT

There was a number of factors that significantly influenced the way that institutes structured their business management operations. The size of the institute budget and number of personnel, the institute's status as a government or non-government entity, the participation of civil servants, and the extent of industrial involvement were all significant considerations. Institutes that did not have civil servant participation, tended to model their business management approach along the lines of a small-to-midsize company with centralized business functions that were the focal points for accounting, budgeting and purchasing. Some included personnel and facility operations as well. The larger the institute, the more likely it was to have a separate human resources department and separate facility operations department. Further, the larger institutes recognized the importance of the business management function and had established vice-president positions to manage this area.

The presence of government employees in the institute complicated the single business approach because of the significantly different and specialized rules imposed by government regulations on personnel practices, travel, etc. The simplest approach to this matter was to maintain segregated business and personnel management functions. Effectively then, the institute was scientifically integrated but administratively divided except for a common Director. Several of the institutes studied were sovereign entities of the state government. To reduce the complications in contracting, one of the state entities established a private corporation to handle the funding arrangements to and from the institute.

1.5 METRICS

What constitutes a successful institute? That it exists at all, may be one measure. That it continues to thrive after two years may be another reasonable gauge, particularly since it appears that institutes undergo "reinvention" every two to five years. Some institutes failed for a variety of reasons - unrealistic expectations of its board of directors; loss of core funding; incompatibility of director and institute mission; cultural and work ethic differences. Clearly, an institute must thrive to survive.

Judging the success of an institute depends not only upon static measurements used to assess the achievement of its goals and mission, but in examining its capacity to alter its purpose and nature. The ability of an institute to reinvent itself, to be forward-thinking, flexible and creative enough to survive dynamic challenges is difficult to quantify.

Most science institutes measured performance by the number of refereed papers published, the number of citations in published papers, and awards granted against submitted proposals. University-based institutes also included the number and quality of graduate students supported, doctorates produced, faculty awards earned and educational seminars hosted in their criteria for success. Independent institutes tended to be more focused on business metrics, using revenue goals, customer feedback, project performance, budget, and schedule measurements to assess their level of success. Applied research institutes added the number and nature of technology transfer transactions, product developments, and industry alliances to their list of performance measurements.

Appendix I

RESEARCH INSTITUTE QUESTIONNAIRE

1. How is your institute organized? (Please include an organization chart.) If you could begin with a clean slate, what changes would you recommend?

2. Describe your institution's personnel and facilities.

3. In your judgment, what are your institutions key strengths as far as organization?

4. What major problems have you encountered over the years? What suggestions do you have for reducing/dealing with these problems? (Lessons learned)

5. How is your research institute funded (Federal, state, industry, other)? How do you attract customers, i.e., academia, industry, and government, to your institution?

6. How do you interact with the industrial research community? What mechanisms do you use? (Co-operative agreements, contracts, formal versus informal agreements)?

7. How do you circulate, distribute, or promote the findings or results of the institute's research? How do you maintain the proprietary data, avoid conflict of interest, and protect the interests of the organizations that sponsor and/or fund the research?

8. Identify opportunities and limitations for a combined research institute, i.e., academia, government, and industry. (Funding level required by each partner both money and in-kind? Any special arrangements required with industry)?

9. How much are personnel from various sectors involved in carrying out the mission of the Institute (i.e., from the Institute, Government, industry, and other academic or research organizations)?

10. What is the ratio of basic to applied research at your institute?

11. What modes of communication are used to promote teamwork from people working away from the Institute?

12. What metrics are used by the Institute, by Government, and by industry to evaluate effectiveness of operations?

APPROVAL

Institute Study Report

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The Information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

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