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Structures Sensing and Control

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Structures Sensing and Control

John Breakwell
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INTRODUCTION

A two-day conference on Structures Sensing and Control was the theme of technical conference 1489 of the SPIE OE/Aerospace Sensing symposium held in Orlando, Florida, 2-3 April 1991. The conference was divided into two subtopics: Smart Skins and Structures, and Controls for Optical Systems.

In the smart skins area, papers were presented on structures with embedded antennas, unidirectional shutters for antenna arrays, optical fiber sensors, frequency-selective surfaces, and ceramic phaseshifters for electronically steerable antennas. The remaining papers dealt with piezoelectric sensors, acoustic coatings for silencing, vibration control, drag reduction, and flow visualization.

The final two sessions addressed controls for optical systems. Now in its second year, this topic again drew interesting papers from both industry and academia, which resulted in a nearly full auditorium. Papers covered new control and identification schemes and new twists on the old ones, active and passive structural control techniques, discrete and distributed sensing, and a number of other interesting subjects. This unique forum has been instrumental in bringing together the disparate disciplines of optics and controls, narrowing the gap that for years has stood in the path of meaningful progress in this arena.

The conference was well attended and marked by lively discussions and interchange between the speakers and the audience. It is clear that much research and development is needed in this fast-growing field, which requires investment of funds from government and industry and the close cooperation of scientists in universities, industries, and government laboratories. Although "smart materials" and "smart skins" are becoming buzz words, it is hoped that materials and structures will develop into truly smart entities that incorporate sensing, analysis, and the required response to a given input, all in near real time. Only then will we have true control of structures. Conferences like this one provide avenues for critical discussions and publications.

The Editors

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STRUCTURES SENSING AND CONTROL

Volume 1489

SESSION 1

Smart Skins and Structures I

Chair

Vijay K. Varadan

The Pennsylvania State University

A wideband, embedded/conformal, antenna subsystem concept

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ABSTRACT

The concept for a wideband, embedded/conformal antenna subsystem is presented. A multilayer radome not only protects the antenna from hostile environments, but is also designed to sustain aircraft dynamic loading. The radiating element consists of a planar, dual-flared slot capable of high-performance, multioctave operation. Advanced materials are currently being developed to enhance the low profile and efficient, wideband performance of the radiating element.

2. INTRODUCTION

Future manned aircraft will require 4π steradian coverage to insure overall situational awareness, such as communication, navigation, terrain avoidance, near-object detection and missile threats. To provide this coverage, a discrete number of wideband, multifunction, conformal, shared apertures will need to be located strategically across the aircraft surface and to be coordinated functionally.

Figure 1 presents the logical flow from threat and Tri-Service, thrust-driven, operational needs into specific avionics and antenna systems technology needs to satisfy embedded/conformal aperture requirements for future smart-skins aircraft.

Anticipated service aviation thrusts and their operational needs are summarized in Figure 2. These needs in turn drive avionics and antenna systems requirements to which architectures, designs and enabling technologies must be responsive.

Figure 3 shows airborne functions versus frequency bands and suggests selected bands over which multifunction, shared apertures could be particularly effective.

An example of a structurally integratable, conformal aperture is illustrated by Figure 4.

This aperture configuration, being skin mounted, must be designed to operate and function to specified performance levels while exposed to severe environments. The structurally integrated aperture must also be capable of:

- Sustaining high-velocity impact from hail, rocks and bird strikes;
- Exposure to corrosive solvents, fuels and lubricants:
- Sustaining low-energy impact due to collisions or dropped tools.

Figure 5 illustrates some of the requirements for integrated, airframe/avionics as a function of vehicle, flight and mission.

The derivation of enabling technology from operational needs can be summarized in three imperatives:

- Reduced observability;
- Enhanced avionics suite performance in all environments with reduced interference among functions to be performed;
- Increased availability, reliability and maintainability for reduced life-cycle costs.

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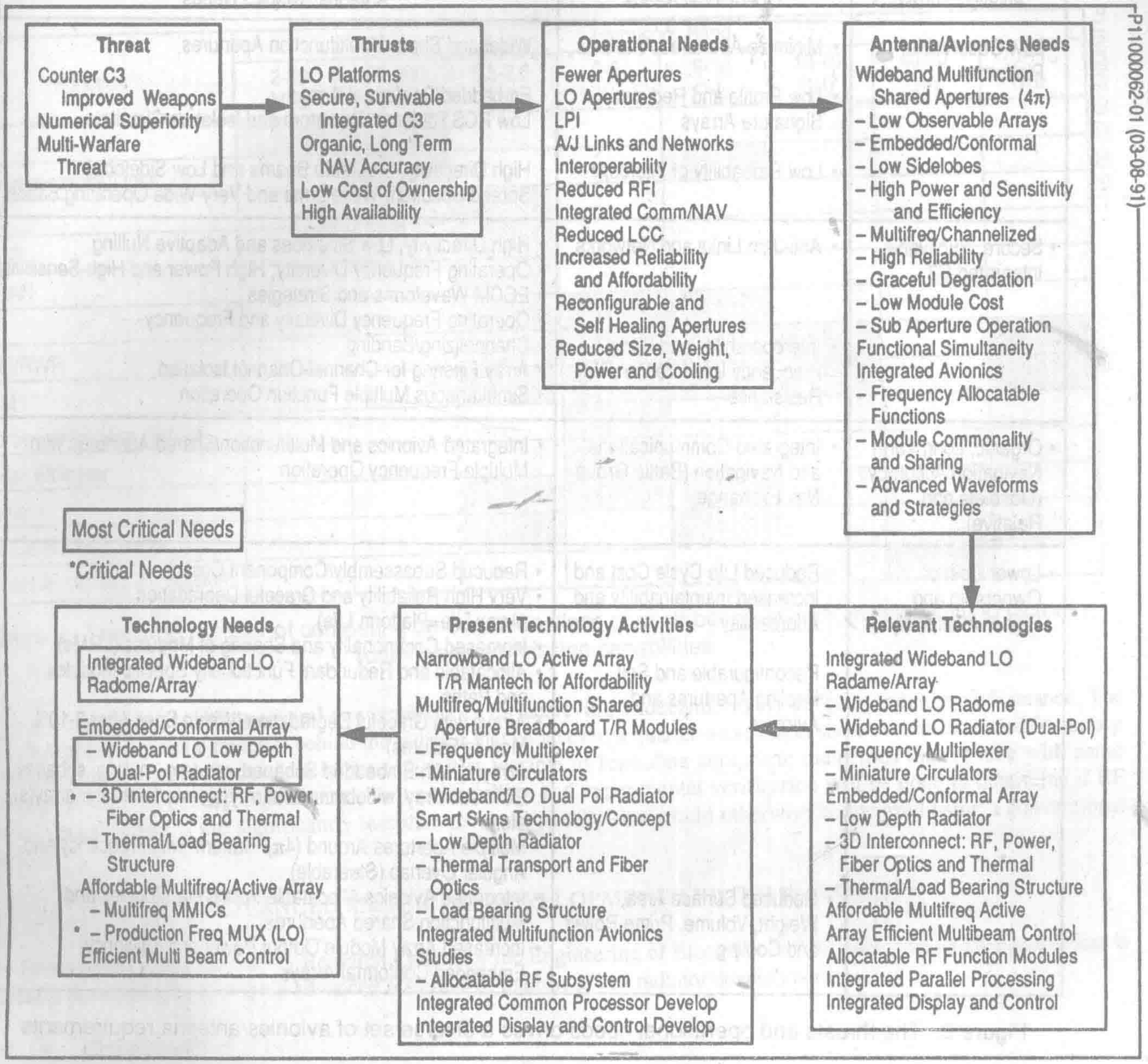

Figure 1. Smart skins antenna requirements/deficiencies flowdown leads logically from threat and thrusts through antenna/avionics needs to the most critically needed technologies

3. TECHNICAL APPROACH

The structurally integratable, embedded/conformal aperture concept, shown in Figure 4, will be designed to sustain aircraft dynamic loading. The fault-tolerant architecture will include enough redundancy to provide enhanced reliability and reduced maintenance through graceful performance degradation.

Hughes is currently developing a wideband, embedded/conformal, RF radiating element known as the dual-flared slot[1] for application to integrated, multifunctional, avionic structures. The key requirements for these applications are wide operating bandwidths, tight (<λ/2) lattice arrays, thin (<1.0 inch) profile for conformal embedment, polarization agility (vertical, horizontal, right-hand and left-hand circular polarization) and the capability to carry structural loads.

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Aviation Thrusts	Operational Needs	Antenna/Avionics Needs
• Low Observable Platforms	• Minimize Apertures Antennas • Low Profile and Reduced Signature Arrays • Low Probability of Intercept	• Wideband Shared/Multifunction Apertures • Embedded/Conformal Arrays • Low RCS Radome, Radiators and Isolators/Circuits • High Directivity, Steerable Beams and Low Sidelobes • Spread Spectrum Waveforms and Very Wide Operating Bands
• Secure, Survivable Integrated C3	• Anti-Jam Links and Networks • Interoperability and Radio Frequency Interference (RFI) Resistance	• High Directivity, Low Sidelobes and Adaptive Nulling • Operating Frequency Diversity, High Power and High Sensitivity • ECCM Waveforms and Strategies • Operating Frequency Diversity and Frequency Channelizing/Banding • Array Filtering for Channel-Channel Isolation • Simultaneous Multiple Function Operation
• Organic, Long Term Navigation Accuracy (Obsolete and Relative)	• Integrated Communications and Navigation (Battle Group Nav Exchange)	• Integrated Avionics and Multifunction/Shared Apertures with Multiple Frequency Operation
• Lower Cost of Ownership and Higher Availability	• Reduced Life Cycle Cost and Increased maintainability and Affordability • Reconfigurable and Self Healing Apertures and Avionics • Reduced Surface Area, Weight, Volume, Prime Power and Cooling	• Reduced Subassembly/Component Cost • Very High Reliability and Graceful Degradation (Array Life=Platform Life) • Increased Commonality and Sharing of Modules (LRMs) • Allocatable and Redundant Functionally Specific Modules and Paths • Arrays with Graceful Degradation (Within Spec After 8-10% Module Failures) • Array(s) with Embedded Subapertures (e.g., nulling, subarray, ECM subarray, widebeam subarray(s), interferometer array(s), etc.) • Multiple Apertures Around (4π) Platform with Frequency and Angular Overlap (Steerable) • Integrated Avionics Allocatable Functional Modules and Multifunction Shared Apertures • Increased Array Module Output Power and Efficiency • Embedded/Conformal Arrays

Figure 2. The thrusts and operational needs drives a diverse set of avionics/antenna requirements

A planar version of the popular flared-notch radiator, known as the dual-flared slot radiator, was selected for developm based primarily on its wideband capability, thin profile and potential for printed-circuit construction. The radiator fabricated on a dielectric substrate initially metalized on both sides. The dual-flared slots, with broadband open circu one-quarter wavelength from the feed points, are etched from one of the metalized surfaces using standard photolithograp processes. The metalization remaining on the near side serves as groundplane for the microstrip-to-slotline transitions that formed by etching the metalization on the far side.

The dual-flared slot radiator, shown in Figure 6, normally radiates in both the forward and reverse directions. In a confor array, the backward radiated signal must either be absorbed or reflected properly phased with the forward radiated sig While placing RF absorber behind the radiator is a simple means to achieve multioctave performance, it is unattractive two-way systems due to the additional transmit/receive loss of 6.0 dB. An efficient, unidirectional design can be realized placing the radiator one-quarter wavelength in front on a reflecting groundplane; however, this limits achievable bandwi to less than one octave.

Function	Frequency Band							
	2-30 MHz	30-500 MHz	0.5-2.0 GHz	2-6 GHz	6-18 GHz	18-40 GHz	40-70 GHz	70-110 GHz
EW	■	■						
Communications/Links		■			■			
GPS			■					
JTIDS			■					
TACAN			■					
IFF			■	■	■			
ESM/RWR			■	■	■	■		■
ECM			■	■	■	■		■
Microwave Landing System				■				
Radar Altimeter				■				
Radar			■	■	■			
Missile Warning Radar			■		■			
Covert Air-Air Communication							■	

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Figure 3. The large number of competing on-board functions plus off-board RFI are a major limiting factor in today's aircraft mission capabilities

Hughes is currently exploring several new approaches for achieving wideband, highly efficient radiator performance. The basic concept is to place a material behind the radiator that behaves as a quarter-wavelength short over an extended frequency band. Preliminary computer models indicate that it is feasible to formulate composite dielectrics that behave with some degree of inverse frequency dependence. Further modelling and experimental verification will be done to determine if RF losses in such materials are significantly less than the 3-dB penalty that would otherwise be incurred using a conventional absorber.

4. ADVANCED MATERIALS DEVELOPMENT AND COMPATIBILITY

The Pennsylvania State University Research Center for the Engineering of Electronic and Acoustic Materials and Devices is currently developing at least three advanced materials of interest to this radiator development:

- Chiral absorbers;
- Low-loss, voltage-controllable dielectrics ($BaSrTiO_3$); and
- Composite dielectrics with inverse frequency dependence.

A chiral absorber is based on the inclusion of microminiature structures or microballoons in a lossy polymeric matrix. Experimental results to date have been made over the frequency range of 5.0 to 40.0 GHz and demonstrate that chiral composite materials can be engineered to have very high RF absorbency over a very wide frequency band. An interesting concept is the use of both chiral and voltage-variable inclusions to form an RF window whose directional properties of transmission, absorption and reflection can be controlled by an applied voltage.

Conceptually, the wideband performance of a planar radiator such as that shown in Figure 6 could be enhanced by placing a frequency independent groundplane approximately one-quarter wavelength behind the radiator. This would require a low-loss material whose relative dielectric constant is proportional to $(1/f)^2$ over the frequency band of interest. Computer modelling

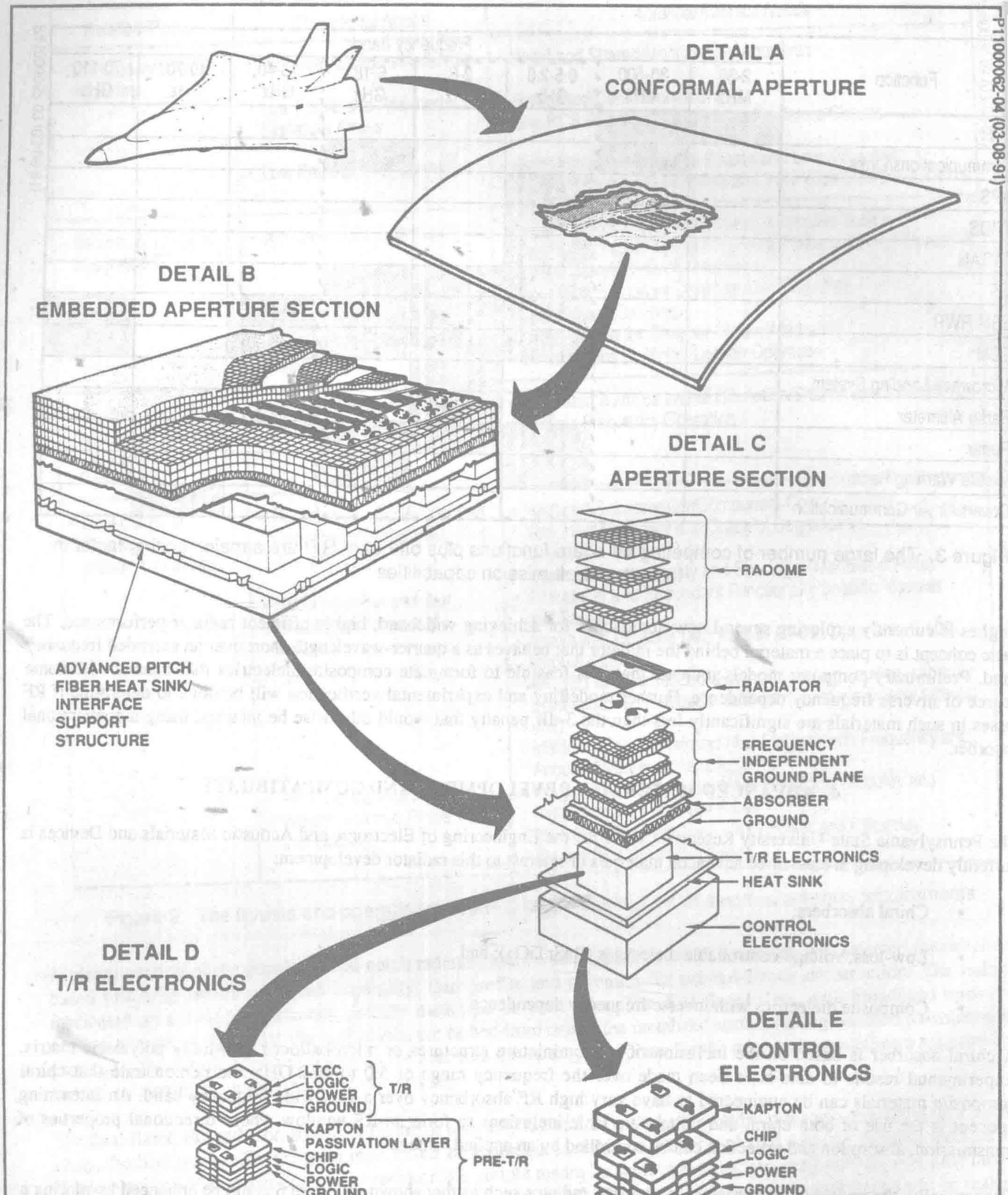

Figure 4. Structurally integratable, embedded/conformal aperture

Vehicle Type	Skin Environment: Temperature (°F) Min	Max	Strain Microin/In	Vibration Freq (Hz)	PSD (G^2 /Hz)	Predominant Skin Material
Strategic Aircraft	- 65	200				Aluminun Graphite/Expoxy
Tactical Aircraft	- 65	350				GR/BMI, GR/TP Aluminum (Adv. Alloys)
Surveillance Aircraft	- 65	600		100 - 500	200	Titanium
Hypersonic Aircraft	100	3000	Static Load 3000-4000			Metal Matrix Composition TI (Hi Temperature)
V/STOL Aircraft	- 65	250	Dynamic Load			GR/EP, GR/TP, GR/BMI Aluminun (Adv. Alloys)
Transport Aircraft	- 65	200	Approx 1000			Aluminum
ASW Aircraft	- 65	200				Aluminum
Long Endurance Aircraft	- 65	165		50 - 200	50	GR/EP, GR/TP Fiberglass, Kevlar
Rotary Wing Aircraft	- 65	200				GR/EP, Fiberglass Aluminum (Adv. Alloys)

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Figure 5. Structural design requirements versus vehicle type

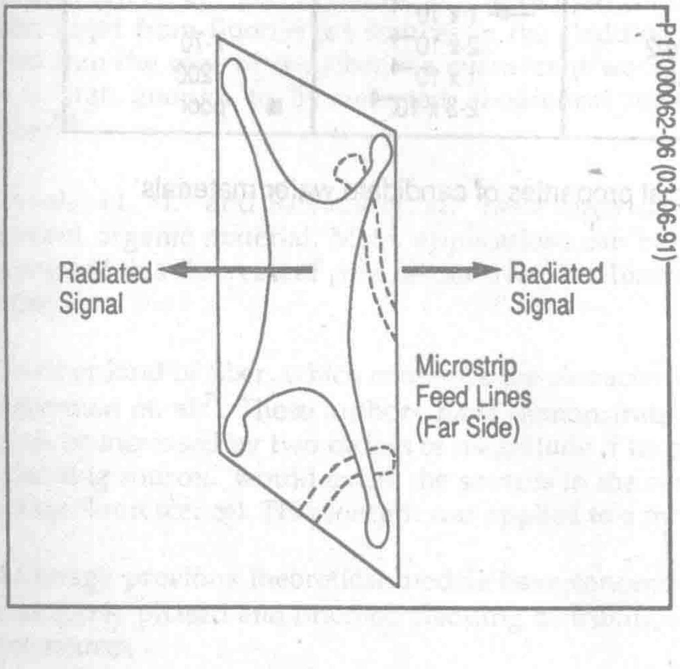

Figure 6. Dual-flared slot radiator normally radiates in both the forward and reverse directions

and materials research show that formulation of dielectrics with a $(1/f)^{1/2}$ dependency is already feasible. It is expected that continuing materials development will yield multilayer composite dielectrics with higher orders of frequency dependency in the near future.

Candidate wafer materials for the T/R electronics and control electronics are listed in Figure 7, along with critical electrical, mechanical and thermal properties. The materials development program will require a thorough evaluation and compatibility analysis of the properties of these advanced materials. The result of this investigation will be innovative, high-density packaging for structurally integrated, embedded/conformal apertures.

5. SUMMARY AND CONCLUSIONS

Hughes is developing a technology roadmap to identify the critical technologies required to implement the "smart skins" concept in a timely manner. These technologies are being developed for an antenna system architecture which is wideband, embedded/conformal and structurally integratable. A key element in this development is a wideband, low-profile, conformal/arrayable radiator known as the dual-flared slot. Advanced absorber and dielectric materials are being developed at The Pennsylvania State University to achieve significant improvements in aperture performance, including low profile, structural integrity, low RCS and wider operating bandwidths.

6. REFERENCE

1. M. J. Povinelli, "A Planar Broad-Band Flared Microstrip Slot Antenna," IEEE Trans. Antennas Propagat., vol. AP-35, pp. 968-972, August 1987.

Material	*CTE Parts per Million per °K at Room Temperature*	*Thermal Conductivity W/m°K*	*Dissipation Factor at X-Band*	*Flexure Strength MPa*
Aluminum Nitride	3	200	4×10^{-4}	280-450
Beryllia	7.8	260	1×10^{-4}	245
Single Crystal Silicon	2.7	130-1240	■ $\sim 10^{-3}$	■ 14
Silicon Carbide	3.8	270	■ $\sim 5 \times 10^{-2}$	440-660
Alumina	6.8	■ 20-40	6×10^{-4}	294
			→ 1×10^{-4}	
Fused Silica	■ 0.56	■ 0.5 to 2	2×10^{-4}	7-70
Sapphire	~6	■ 20-40	1×10^{-4}	~200
LTCC	~7	■ ~16	$2\text{-}3 \times 10^{-4}$	■ poor

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Figure 7. Critical electrical, mechanical and thermal properties of candidate wafer materials

Excitation efficiency of an optical fiber core source

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ABSTRACT

The exact field solution of a step index profile fiber was used to determine the excitation efficiency of a distribution of sources in the core of an optical fiber. We have compared previous results of a thin-film cladding source distribution to its core source counterpart. The behaviour of P_{eff} with the fiber parameters was examined and found to be similar to the behaviour exhibited by cladding sources. It was also found that a core source fiber is two orders of magnitude more efficient than a fiber with a bulk distribution of cladding sources. This result agrees, qualitatively, with previous one obtained experimentally.

1. INTRODUCTION

Active optical fiber sensors have been developed for chemical purposes. They have either a fluorescent cladding, a fluorescent core or both fluorescent cladding and core which interact with the external medium and modulate the signal in the fiber.

Lieberman et. al.[1] and Blyler et. al.[2], have used fluorescent cladding optical fiber for detecting chemical species. Light from fluorescent sources in the cladding is modulated by the external medium and can be injected into the core of the fiber via evanescent wave interaction. Although the signal generated by this fiber is high enough to be detected, theoretical models have indicated that this sensor is not very efficient[3,4].

Tanaka et. al.[5] and Sawada et. al.[6] have reported on a plastic optical fiber with a core doped with fluorescent organic material. Many applications can be derived from this fiber including gas sensing. The advantage of this fluorescent core sensor over the fluorescent cladding sensor lies in the fact that it is more efficient.

Another kind of fiber, which combines the characteristics of the sensors discussed above, was envisioned by Lieberman et. al.[7]. These authors have demonstrated that the coupling efficiency of a cladded source fiber can be increased by two orders of magnitude if its core is made fluorescent. In this case, radiation from the cladding sources would excite the sources in the core of the fiber yielding the increase in the efficiency (two stage fluorescence). This concept was applied to a molecular oxygen sensor.

Although previous theoretical models have concentrated on the excitation efficiency of an optical fiber by a randomly phased and oriented cladding distribution of sources[3,4,8], a similar model was not available for core sources.

In this paper, we extend previous work on the excitation efficiency of cladding sources in order to account for a core source distribution. We have determined the excitation efficiency of such fiber, namely, the ratio of the power that is excited in the core of the fiber as bound modes, P_{core}, to the total power radiated by the sources, $P_{tot} = P_{rad} + 2P_{core}$. In the previous relation P_{rad} is the power due to the radiation modes and the multiplicative factor of 2 was introduced to take into account both forward and backward propagating bound modes. Fiber with sources uniformly distributed in the core is treated. The sources are assumed to have random phase and orientation. The fields of the exact solution of an infinity cladding fiber was used.

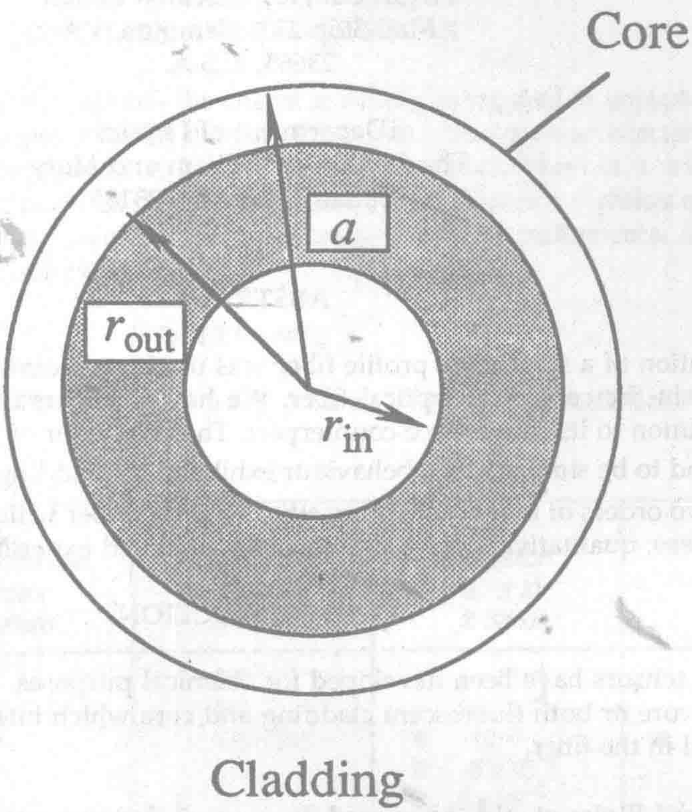

Figure 1. Sources uniformly distributed in the core between the radius r_{in} and r_{out}.

2. THEORY

The core sources can be treated as many infinitesimal electric currents with random phase and orientation which excite radiation fields and bound modes[3,4,8]. The radiation fields radiate away from the fiber however, the bound modes are trapped inside the core and propagate in both forward and backward directions[9]. The expressions for P_{rad} and P_{core} follow:

$$P_{rad} = \sqrt{\frac{\mu_o}{\varepsilon_o}}\,\frac{n_{clad} k^2 S L}{4}\left(r_{out}^2 - r_{in}^2\right) \tag{1}$$

$$P_{core} = \sum_{\nu,\,\mu} \frac{1}{16 P_{\nu,\mu}} \int_{V_{source}} S \;|e_{\nu,\mu}(r)|^2 \, dV \tag{2}$$