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SMART STRUCTURES

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Tamper Indicating and Sensing Optical-Based Smart Structures

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INTRODUCTION

Smart materials and structures are part of a rapidly evolving, multidisciplinary approach to using a material's intrinsic properties or combining materials to achieve inherent intelligence (Rogers 1989; Ahmad, et al. 1990). Smart materials may be defined as materials that possess intrinsic properties capable of responding and adapting to external stimuli. The material's intelligence may be the result of its composition, processing, microstructure, presence of defects, or conditioning. Smart structures may be comprised of integrated smart materials and/or more discrete components such as actuators or sensors that, in combination, provide the required intelligence.

Optical fibers have been the basis of advanced polymer composites to prepare intelligent structures for the past ten years (Claus 1991). Optical fibers are small, immune to electromagnetic interference, and lightweight. They can be embedded in other materials, have an adjustable composition, and can operate in harsh environmental conditions. Optical fiber-based "smart structures" are able, via embedded or attached optical fiber (the "smart material") and the associated electronic circuitry, to monitor the polymer's physical integrity and structural behavior during use. The unique ability of optical fiber to act as a signal transmitter as well as to modulate a propagating optical signal as a response to external stimuli has led to numerous applications of optical fiber-based smart structures. Although capable of detecting electrical and chemical phenomena, optical fiber sensors have been developed primarily for determining strain, thermal expansion, and vibration of structural components.

Non-optical glass or polymer fibers are typically embedded in polymer structures to enhance strength and toughness, for example, panels for the automobile and aircraft industry. Replacing a portion of the structural fiber with optically-conducting fiber permits fabricating robust, optically-active structures such as tamper-indicating secure containers. Secure containers are optical fiber-based smart structures that offer the ability to continually or passively monitor the integrity of the container walls. Continually monitored secure containers monitor in real time, with a container breach activating the smart structure. Smart structure activation can produce numerous consequences within the container, depending on the specific application of the container, the size of the container and the complexity of the accompanying electronics. At a minimum, smart structures can be given the ability to recognize and record container breaching. Difficulty in defeating the tamper-indicating secure container depends on the smart materials' stealth and the smart structure's complexity. Complexity can be enhanced by incorporating the smart material into the container walls using additional, non-active decoy material.

In addition to tamper indication, the combination of optical fiber embedded in a polymer matrix lends itself to various sensing capabilities. Either the fiber can act as a buried sensor, for example, detecting radiation or temperature changes, or the polymer matrix can be made sensitive to pressure or specific chemical(s), causing the polymer to react and create a signal in the optical fiber. For example, chemical sensors can be prepared by embedding an optical fiber array into a polymer sheet that is then coated with another polymer sensitive to the specific chemical.

Similar to the manner in which discrete optical fibers function (light travelling down a high refractive index core

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reflecting off a lower refractive index cladding), a continuous, linear region of high(er) refractive index can be created in a clear polymer such as poly(methylmethacrylate), creating an optical path or channel. These clear polymer "windows" are capable of tamper indication as well as providing sensing capabilities. Waveguide circuitry written into the polymer window can be designed so that, when the window experiences a stimulus such as a temperature or pressure change, the stimulus is manifested in an attenuation or phase shift between sensing and reference waveguide paths.

The objective of this paper is to describe the design, construction, and potential applications of several optical-based smart structures. The properties of optical fiber/polymer matrix smart structures will be exemplified through the construction of a small, tamper-indicating secure container and tamper-indicating panels for a secure video system. Tamper-indicating and sensing capabilities of polymer windows containing channel waveguides, plus their integration into secure containers will be discussed. Problems associated with design, construction, and growth potential of optical-based smart structures to other technical areas will be addressed.

TWO FABRICATION TECHNIQUES FOR SMART STRUCTURES

Integral Container Fabrication

An integral structure is comprised of an optical fiber imbedded in a fiber-reinforced polymer matrix. The structure is fabricated by molding a combination of fibrous mat (fiberglass, aramid, or carbon) with a resin matrix (epoxy or polyester) into the desired shape using compression molding or resin transfer molding. The molded part is then wound with a continuous length of optical fiber to form the sensor. Reinforcing fibers provide additional structural integrity; an outside protective layer of fiber reinforced resin is molded to protect the optical fiber. The ends of the optical fiber are connected to the optical/electronic circuit.

Flat Plate Fabrication

Flat plate smart structures are fabricated by filament winding a continuous optical fiber over a polyurethane foam core. Threaded plastic rods are attached to opposite sides of the core plate to provide a uniform path for the winding of the fiber. The threads act as guides for the fiber so that the spacing is fixed. After winding is complete the optical fiber is covered with a protective layer of fiber-reinforced or unreinforced resin. The ends of the optical fiber are connected to the optical/electronic circuit. The completed flat plates can then be assembled to form shapes not conducive to integral fabrication for various reasons.

TAMPER-INDICATING SECURE CONTAINER

A tamper-indicating secure container was chosen to demonstrate the basic functionality of an integrally fabricated, optical fiber-polymer composite smart structure. The project was completed in three phases. The first phase was to design the container and electronics and determine a suitable optical fiber to be embedded in the polymer matrix. The second phase was to fabricate the container without using optical fiber to evaluate the fabrication process, assemble the electronics package, and evaluate optical fiber performance in the candidate resins. The final phase involved fabricating the container using optical fiber, connecting the electronic circuitry, and testing.

Optical Fiber

The optical fiber had a 100 μm diameter silica-based core and cladding and a protective polyimide buffer with a final outside diameter of 125 μm (Polymicro Technologies Incorporated FHZ100110125). It had a transmission range of 380-2500 nm and an operation temperature to 400°C. It was selected for its polyimide buffer, which is compatible with the container's epoxy resin formulation, and for its small outside diameter.

Container Design and Fabrication

The container consists of a five-sided drawer that slides into a five-sided outer shell (see Figure 1). Both the shell and drawer are composites consisting of glass reinforcing fiber in an epoxy resin matrix. The two container parts use a combination of reinforcing mat and filament wound, unidirectional fiber. Optical fibers are filament wound within the reinforcing layer, spaced sufficiently close that attempts to breach the container wall will damage them.

A combination of reinforcing mat, reinforcing fiber and optical fiber was wetted with polymer and wrapped on a machined mold mandrel to a thickness of approximately 0.25 cm to produce the shell. The ends of the optical fiber were inserted in Teflon® tubing to keep them clean for later attachment of connectors. The drawer was fabricated by winding a combination of reinforcing mat, reinforcing fiber and optical fiber around a mandrel, then putting the assembly into a mold so that it would cure to a fixed outside shape. The ends of the optical fiber were attached to optical connectors which were molded in place so that a continuous light path could be attained when the drawer was placed in the shell and the connectors were mated.

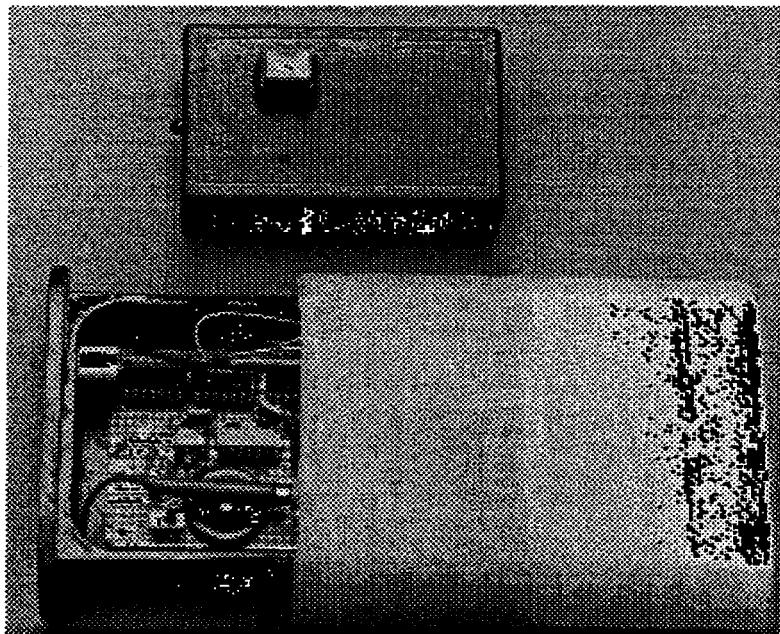


Figure 1. Drawer and Shell Container

OPTICAL FIBER-BASED TAMPER-INDICATING SECURE VIDEO CONTAINER

The objective of this study was to prepare a field-worthy stationary surveillance video system housed in a rectangular, six-sided metal box with a hinged lid. It was imperative that the metal box be secure even with camera lens viewing ports, vent holes, and power/connection cabling ports cut into it. It was also important that the video system be easily accessible when necessary. It was not necessary that the box security system be impenetrable, only that it be tamper-indicating.

A tamper-indicating secure container was prepared using flat panels with actively monitored optical fiber as the smart structure. Design constraints introduced by the steel box precluded preparing a single optical fiber-polymer matrix composite container. Instead, optical fiber was wound around six rigid polyurethane foam panels and assembled inside the steel box.

Optical Fiber

The optical fiber had a 100 μm diameter silica-based core and cladding and a protective acrylic buffer with a final outside diameter of 250 μm (Corning Incorporated 100/140 CPC3). It had attenuation of 3.6 db/km at 850 nm and an operating temperature of -60°C to 85°C. The low attenuation and rugged construction of this fiber were important factors in its selection. In mandrel wrap tests on a variety of fiber types and manufacturers, this fiber also showed the lowest bending loss, which is a very important feature considering that the complete 6-sided enclosure contains over 4 kilometers of optical fiber and requires over 7000 180-degree turns at a bend radius of 15 millimeters.

Secure Container Design

Constructing the secure container without design constraints would involve filament winding optical and strength-enhancing fibers into an integral container as described above. However, a separate container was not feasible due to design constraints. Consequently, the secure lining for the metal box was fabricated in six parts (i.e., panels) so that each panel could be positioned properly to ensure security. The secure container lid panel was designed to be optically coupled via two pin connectors to side wall panels so that jarring or opening the lid would trigger the alarm.

The secure holes required for the video system presented a special design and fabrication problem for the secure container. Simple filament winding in only one direction like that chosen for the panels does not allow any of the panel area adjacent to the hole to be covered by fiber unless winding is performed in multiple directions (envision infinite straight lines tangent to a circle). Optical fiber windings in different directions to secure the hole would result in an unacceptable buildup of fiber near the edge of the hole from overlap and require at least a 50% increase in fiber length. Consequently, alternative methods of winding the holes were pursued. The accepted design and method was to wind a separate fiber into a spiral to create a fiber "disk" several cm in diameter. The inner diameter of the fiber spiral equaled the hole's diameter. A conceptual drawing of the plate with longitudinal, angled and spiral windings is shown in Figure 2.

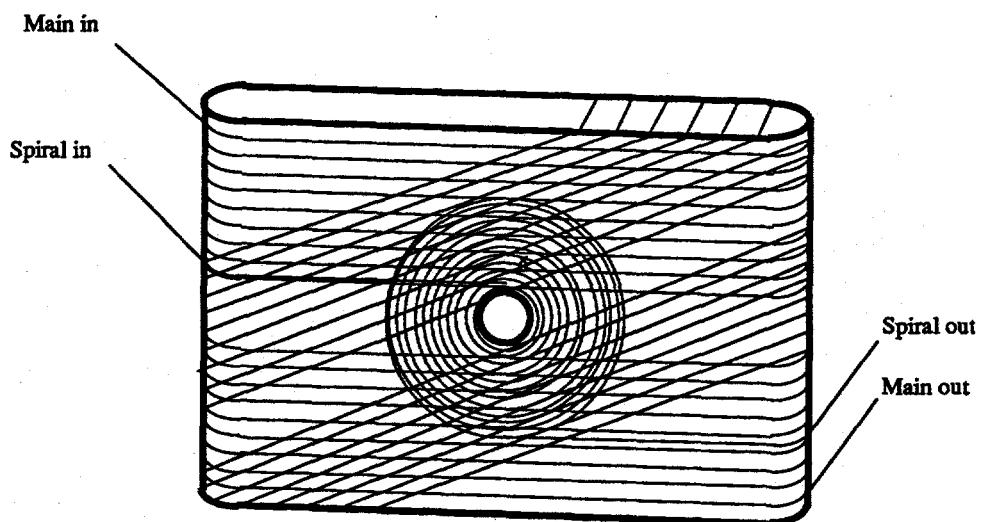


Figure 2. Filament Wound Flat Panel

Panel Winding

Panels wound using the process described above showed an acceptable level of signal attenuation over the entire fiber. Six separate panels were wound using this procedure. The spacing between adjacent threads was 488 μm . The fibers have an outer diameter of 250 μm so the space between fibers was 238 μm . The optical fiber was wound around each 2.86 cm thick panel in one continuous length. The front and back panels were wound vertically and the side panels were wound horizontally. This arrangement allowed a rounded edge to abut a flat face so that there was no gap between the panels. The top and front panels had "through holes" that required special treatment to ensure that the optic fibers covered the entire panel except for the holes. Since the fiber was wound in only one direction, each hole left an uncovered band the same width as the hole.

Spiral wound fiber was used to cover the space around the holes. These spiral disks were wound using a fixture with a hub the same diameter as the hole and two plates spaced 76 μm wider than the fiber diameter. Spokes were cut into the two plates to provide access to the fibers so that they could be bonded in place with silicone adhesive. When the adhesive was cured, the spirals were removed from the fixture intact without unwinding and were bonded over the holes in the foam panels. Extra fiber was left at either end of the spiral for direct splicing to the remaining wound fiber on the panel. The unfilled gaps on the panels not covered by a disk were filled with angled windings. The spiral windings were optically coupled in series with the flat windings in each panel.

After the panels were completed they were coated with a 0.1 mm coating of silicone adhesive to bond the fibers together and to provide flexible protection.

Final Assembly

The completed panels were arranged in the metal box so that there was less than a 250 μm gap between panels at the corners. During this step the fiber ends were routed to the bottom rear of the box where they were connected to the electronic couplers. After the panels were positioned in the box, they were lined on the inside with 0.6 cm thick polyurethane foam to provide additional fiber protection and a bonding surface for internal structures. A similar lining was bonded to both faces of the top panel (i.e., the lid) and strap handles attached so that it could be easily attached and removed. Optical continuity was attained between the top panel (lid) and the rest of the secure container by bonding two sets of optical mating connectors to the lid and the secure container walls. In this manner, the alarm would sound not only if a panel was breached, but also if an attempt was made to remove the lid.

All the viewing ports for the video system were made tamper-indicating by inserting a pane of tempered glass on the inside of the metal box and attaching a sensor to each piece of glass. If the tempered glass is tampered with, it will shatter into many small pieces, triggering the attached sensor.

ELECTRONICS PACKAGE DESIGN

Electronically active, tamper-indicating secure containers such as the two described above can be constructed to almost any size with careful selection of optical fiber, container design, and compatible electronics. Secure containers can also be prepared with passive systems (without active electronics), with container integrity being checked periodically with an optical time domain reflectometer (OTDR).

The integrity of the containers' optical fiber windings are actively monitored by circuitry housed within the container. The circuitry was designed to provide a basic example of the functionality that could be built into such containers. Depending on the container application, circuitry can be designed and miniaturized to reduce power consumption, provide telemetry, and initiate a range of responses. The circuitry implements an optical "pitch-catch" scheme. An infrared light-emitting diode (LED) or laser diode launches ("pitches") pulses of light into the embedded optical fiber. The pulses are 500 microseconds wide and are launched at a rate of approximately 20 Hz. The low-duty cycle extends the life of the circuit's batteries. When the optical fiber path is uninterrupted, the pulses arrive at

the receiving ("catch") end and are detected by a photodiode. The signal is amplified, shaped, and fed to a missing pulse detection circuit. The missing pulse circuit produces a logic 0 signal as long as the prescribed pulses are detected as expected. However, if one or more of the pulses do not arrive due to fiber breakage or an open container, a logic 1 is output by the missing pulse detector. The logic level can be used to initiate a response of practically any type. Since the pulses are expected at a 20 Hz rate, any breach lasting longer than 50 msec will be detected.

For both containers, the electronic circuitry was designed to demonstrate a basic example of the functionality that could be built into such containers. The possibilities are really only limited by the space and electrical power available. The secure container's electronic circuitry can be adapted and expanded to perform almost any function. For the secure containers constructed, tampering with the optical fiber or lid activates a buzzer. Discharging capacitors, telemetry, destructive devices, mechanical action, and writing of information to an electrically erasable programmable read-only memory (EEPROM) are just some of the responses that could also be activated by the triggering mechanism. Electronics can be expanded to include real-time recording of container intrusion, remote activation, periodic interrogation, and communication with other smart structures.

TAMPER-INDICATING SECURE/SENSING WINDOWS

Incorporating secure windows into secure containers was envisioned as a means of providing flexibility to a secure container system where visibility into or out of the container was desired. Container security is provided through optical fiber embedded into the container walls; window security is provided through optical channel waveguides written into the polymeric window. Optical fiber in the container wall can be coupled directly into the window waveguides creating a continuous optical path. An infrared light pulse generated at one end of the optical fiber traverses the continuous optical path and is interrogated at the terminus. A break in the light path at any point, either in the fiber or the window, interrupts the infrared signal which triggers an alarm or other device.

Channel optical waveguides are written in a polymer sheet using a ultraviolet laser fabrication technique. A focused laser beam is scanned across the polymer sheet to photoinduce regions of higher index of refraction. These continuous, high-refractive index regions effectively support a propagating radiation mode. An array of waveguide channels can be written at various spacing densities as small as a few microns, depending on the degree of security required. Because the channel waveguides can be written very precisely by the laser, the waveguides can be written into curved and uniquely-shaped windows. Interrupting the transmission of any one of the waveguides, such as when the window is broken, cut, or scored, is similar to breaking an optical fiber and would be sufficient to trigger an alarm or some other mechanical or electronic response mechanism.

Construction of waveguiding structures in clear polymer materials has been reported previously (Tomlinson et al. 1970; McFarland et al. 1991; Frank et al. 1992; Beeson et al., 1992), but using such structures for securing windows has not been demonstrated.

APPLICATIONS

The present work was performed to demonstrate the capabilities of optical fiber smart structure technology and to serve as a basis from which to expand smart structure capabilities. Electronically active secure containers such as the ones fabricated in this study can be expanded to almost any size by carefully selecting optical fiber, container design, and compatible electronics. Large containers for shipping, field use, or storing stationary objects can also be prepared with a passive system (without active electronics), with container integrity checked periodically using an OTDR. Polymer matrix adaptability permits the fabrication of complex-shaped containers and allows additional smart structures to be embedded. Embedding all of the container's components increases container ruggedness and security.

Smart structure electronics can be adapted and expanded to perform almost any function. For the containers prepared in the present study, tampering with the optical fiber triggers a buzzer. As previously discussed, the range of

possible responses is limited only by the practical concerns of the specific application. Electronics can be expanded to include real-time recording of container intrusion, remote activation, and communication with other smart structures.

The concept of smart materials fabricated from optical fibers has applications beyond secure containers. Wall panels can be prepared similarly to a secure container wall, only on a larger scale. Panels that join and interlock can be prepared so that the resultant wall becomes a single unit. Temporary secure buildings and limited access areas can be created in this manner.

The concept of polymer-embedded, optical fiber-based smart materials developed in the present study is also adaptable to sensors. Chemical sensors can be prepared by embedding an optical fiber array into a polymer sheet that is then coated with another polymer sensitive to the specific chemical. As the sensitive coating contacts the chemical, it swells, placing pressure on the optical array. Changes in the optical fiber refractive index can be detected through light attenuation. Special pressure sensors can also be designed using the same concept, with the pressure being exerted directly on the embedded optical fiber. The chemical or pressure sensors can be single, stand-alone units or part of a secure container wall.

Another option is the choice of optical fiber. A very interesting sensor/tamper indication combination can be achieved by using neutron-detecting scintillating fiber in the secure container. Scintillating fibers emit light upon interacting with neutrons. A polymer matrix secure container constructed with such fiber placed in a neutron environment would eliminate the laser diodes as a light source and use the light generated from the fiber. This light would travel down the fiber and be detected. Either breaching the container (i.e., cutting the fibers) or removing the container from the affected area would cause an alarm or other device to activate.

Channel waveguides are virtually invisible and, if non-visible light is used, they are unobtrusive and difficult to locate. The waveguide pattern and line density can be tailored to the application. For example, to secure 2 cm diameter spheres would require a grid line density slightly smaller than 2 cm. Secure windows also permit tagged (e.g., bar coded) inventory in a secure room to be interrogated with a laser tag reader without having to enter the room. In a "retrofit" manner, waveguides written on an adhesive-backed flexible film can be placed over existing windows to provide (additional) security.

The waveguides written into a window can also act as sensors to heat, chemicals, vibration, etc., depending on the window polymer, the waveguide pattern, and the associated electronics. For example, a waveguide channel can be branched at the edge of the window with each channel branch located on either side of the window pane. Light travelling through the channel will be split into the two channels and be detected on the opposite edge of the window. An external stimulus on one side of the window pane (for example, a hand on the window) will cause a difference in the waveguide conditions between the two sides of the window. Electronic circuitry detects differences in transmitted light intensity and/or phase between the two sides.

SUMMARY

This paper has presented an overview of the type of optical-based smart structures that can be designed and constructed. These smart structures are capable of responding to their environment. The examples given represent a modest sampling of the complexity that can be achieved in both design and practice. Tamper-indicating containers and smart, sensing windows demonstrate just a few of the applications. We have shown that optical-based smart structures can be made multifunctional with the sensing built in. The next generation smart structure will combine the sensing functionality of these optical-based smart structures with other sensors such as piezoelectrics and electro-rheological fluids to not only be able to respond to the environment, but to adapt to it as well. An example of functionality in this regime would be a piezosensor that senses pressure changes (e.g., shock waves), which then causes an electro-rheological fluid to change viscosity. A fiber sensor located in or near the electro-rheological fluid

senses the stiffness change and sends a signal through a feedback loop back to the piezosensor for additional adjustments to the electro-rheological fluid.

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