MULTIFUNCTIONAL COMPOSITES WITH INTEGRATED OPTICAL BUSSES FOR DATA AND SENSING APPLICATIONS

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ABSTRACT

Embedded communication busses are being widely investigated for complex composite structures such as military vehicles and advanced civil structures. The major difficulty with such busses is coupling external devices to embedded optical and electrical cables at ingress/egress points because physical connectors are awkward and prone to mechanical failure. In this work we present several techniques for *normal* incidence free-space optical data porting. These techniques are used to develop and demonstrate an integrated structural optical communication bus.

1. INTRODUCTION

Complex U.S. Army platforms, such as ground vehicles or rotorcraft, require the integration of a sophisticated array of sensors, actuators, controls, and communication devices. Conventionally, these devices are physically connectorized with electrical wires or optical fibers, which are then traced point-to-point within a vehicle. The number of cables, connectors, and pathways can become overwhelming, resulting in significant design and manufacturing costs. In addition, the vehicle structures must be designed to accommodate the volume of wiring, introducing cutouts and channels that can compromise structural design. For weight-critical applications like rotorcraft, the weight of the cabling itself can be a significant performance burden.

An alternative approach is to embed optical cabling into the structure (Sjogren, 2000). Optical waveguides inherently possesses much higher bandwidth and data rates than electrical conductors, so that the total volume of cabling can be greatly reduced. However, conventional optical cabling is relatively fragile and difficult to connectorize. By integrating the optical fibers into the vehicle structure, most likely a polymeric composite, the robustness and the survivability of the fibers can be greatly improved. However, connectorization to the optical fibers is still problematic. Conventional connectors are bulky and expensive; requiring polishing of fiber ends and physical attachment to exposed, unprotected fragile optical cables.

Here we introduce the concept of an integrated structural optical communication buss. Such a multifunctional material serves the role of traditional structural materials (supporting loads) in addition to serving as a local area network, shuttling data between the vehicle's many systems.

To be successful, such an integrated communication bus must posses several features. First, it must contain nodes that act as ingress and egress points for communication signals. Ideally these nodes should allow for reconfiguration of systems and be distributed throughout the structure so that systems may be "plugged in" at any point. Also, the system must posses sufficient bandwidth and be relatively inexpensive. Furthermore, it should be redundant with many communication paths between nodes, and it should be modular to allow for repair of certain parts of the vehicle in addition to allowing for reconfiguration. The system must also be minimally invasive so as not to introduce flaws that would undermine the structural function of the material. Most importantly, the communication system should be secure - impervious to interference, jamming, and interception.

The goal of the present work is to demonstrate the feasibility of integrated structural communication busses in army systems by introducing and demonstrating many of the key features of such a system. In the sections that follow, several concepts for porting signals into a structural material are discussed first. Then, a prototype is developed that demonstrates key aspects of passive porting techniques. Finally more sophisticated "active"

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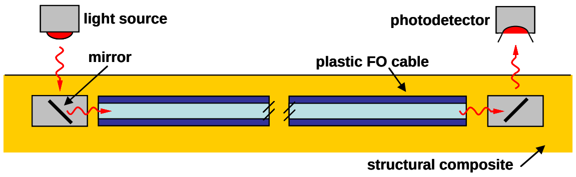
transceivers are developed for embedding in structural composite materials.

2. BACKGROUND – PORTING TECHNIQUES

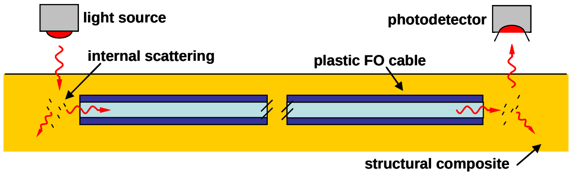
One of the principal challenges in constructing an integrated optical network is the development of the data nodes. Nodal design can be separated into passive and active techniques. A network based on passive principles directly distributes photons from the external data source throughout the network, where those same photons are ported out of the network to external optical data receivers. In contrast, in an active network these photons are at some point transformed into new photons.

Figure 1 shows some examples of passive networks. In Figure 1a, the photons from the external data source are reflected onto the cleaved face of the embedded optical fiber, which then transports the electrons to another reflective element that ports the photons out of the composite. In Figure 1b, photons are sent into the composite in the vicinity of a cleaved fiber end, and some photons are coupled into the fiber end through scattering effects in the composite. In Figure 1b, the cladding of the optical fiber is removed at the nodes, so that photons are coupled directly into the core. The methods of Figure 1b and 1c are likely to be much less efficient than conventional optical coupling techniques but could be sufficient for short-distance data transfer. For all cases, the unique challenge of the embedded structural network is to design passive optics that are efficient at coupling light between sources with detectors that are oriented normal to the plane of embedded optical fiber.

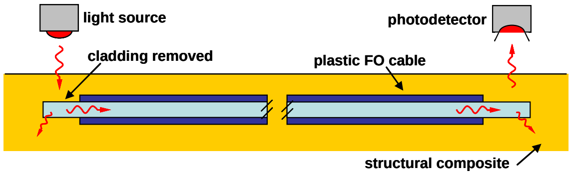
Figure 2 shows some examples of active networks. In order to eliminate problems, such as coupling efficiency and bandwidth-distance products of passives busses, we use the concept of the self-powered active transceivers using a fiber-optic bus. Normal incidence querying to these designs is more straightforward as compared to simple passive designs discussed previously and would allow for larger communication distances due to the active nature of the bus. Based on this concept, two self-powered active techniques have been employed. The first of which, shown in Figure 2a, utilizes semiconductor devices (photodiodes and lasers) as a method for optical to electrical to optical conversion.



(a) reflective element

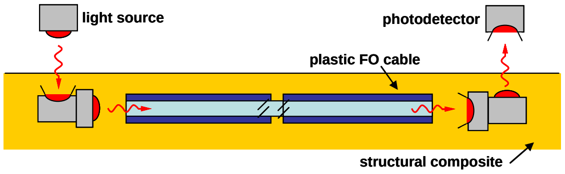


(b) simple scattering

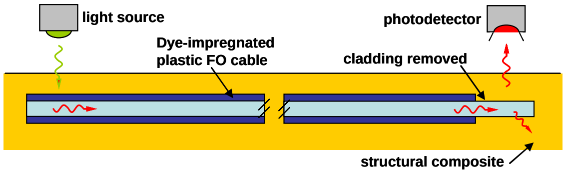


(c) direct core coupling

Figure 1: Passive node concepts.



(a) Self-powered transceiver



(b) Dye-impregnated optical fiber

Figure 2: Active node concepts.

The second method, shown in Figure 2b, employs dye impregnated fiber as an active component in the optical bus. In this case an optical to optical conversion takes place. The dye impregnated in the fiber uses light of a higher energy to stimulate electronic transitions in the dye molecules. These electronic transitions then give off light at a lower energy. This method is also preferable for normal incidence coupling since side illumination of the fiber is how the bus is accessed. Impregnated fiber offers the same advantages as traditional optical fiber busses such as large bandwidth and low weight but can overcome the greatest disadvantage of traditional optical fiber: the problem of coupling light into or out of a fiber at ingress/egress points.

3. EXPERIMENTAL

3.1 Integrated Passive Optical Bus Prototypes

3.1.1 Prototype Design

To demonstrate the concept of an integrated passive optical data bus, two composites were constructed according to the design of Figure 3. Nodes 4 and 5 are simple nodes each coupled to the end of a single optical fiber. Nodes 1 and 2 are each coupled to two optical fibers, with Node 2 oriented as a pass-through node. Node 3 is coupled to four optical fibers, in a configuration sometimes referred to as a "star coupler."

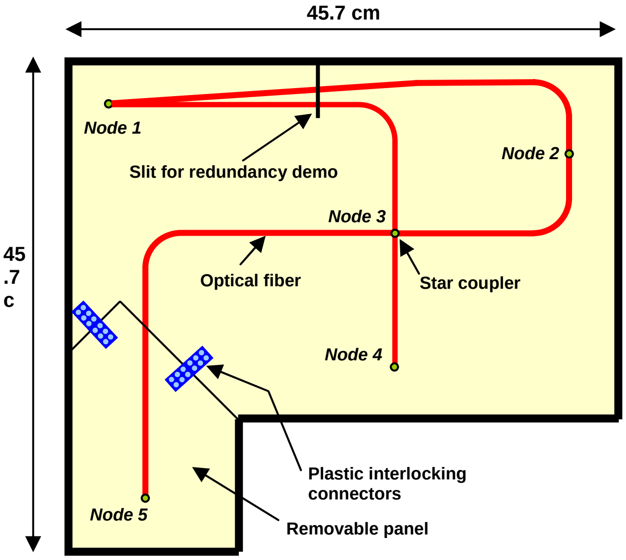


Figure 3: Integrated optical data network prototype.

To demonstrate modularity, a V-shaped cut travels through the composite panel between Nodes 3 and 5, allowing the composite to be separated into two pieces. The pieces can be physically joined through a pair of interlocking plastic connectors (Legos®) that are adhesively bonded to each component. The V-shaped cut is self-aligning, ensuring that the cut ends of the embedded optical fiber in each panel are highly aligned during assembly.

To demonstrate network redundancy, a straight, thin slit is cut through the two optical fibers coupled to Node 1. The cut is thin enough to allow for light to couple efficiently across the slit through the cut optical fiber. The transmission through either fiber, however, can be interrupted by inserting a thin piece of metal foil into the slit to separate the fiber ends.

3.1.2 Prototype Fabrication

To fabricate the composite prototypes, three plies of 24 oz/yd2, 45.7 cm × 45.7 cm glass fabric were cut and stacked. 0.5-mm outer diameter plastic optical fiber (Industrial Fiber Optics, Tempe, AZ) was woven through the central fabric ply according to the schematic shown in Figure 3. A single continuous fiber was traced from Node 1 to Node 4, and a second continuous fiber was traced from Node 1 to Node 5. Plastic fiber is used primarily due to its large waveguiding cross-sectional area, which simplifies passive porting. Its low cost and mechanical toughness (relative to glass optical fiber) are also attractive. The relatively high transmission loss in plastic optical fibers makes them incompatible with long distance (many km) telecommunication applications but is completely acceptable for the short distances expected for integrated structural networks in vehicle applications. In fact, most existing applications of optical fiber in automotive applications utilize plastic optical fiber (Lupini, 2004).

The three fabric plies were placed on an aluminum plate covered with release film. 350 g of SC-15 epoxy resin was combined with 140 g of SC-15 curing agent and manually wet into the stacked fabric layers, which were then covered with a second release ply and aluminum plate. The entire assembly was then placed under 8.9-kPa pressure for 24 hours at room temperature.

The V-cut between Nodes 3 and 5 was cut using a diamond saw. The separated panels were then butted against each other, clamped in place, and then bonded to the plastic connectors. The slit through the fibers from Node 1 were cut using a 0.30 mm diamond saw blade.

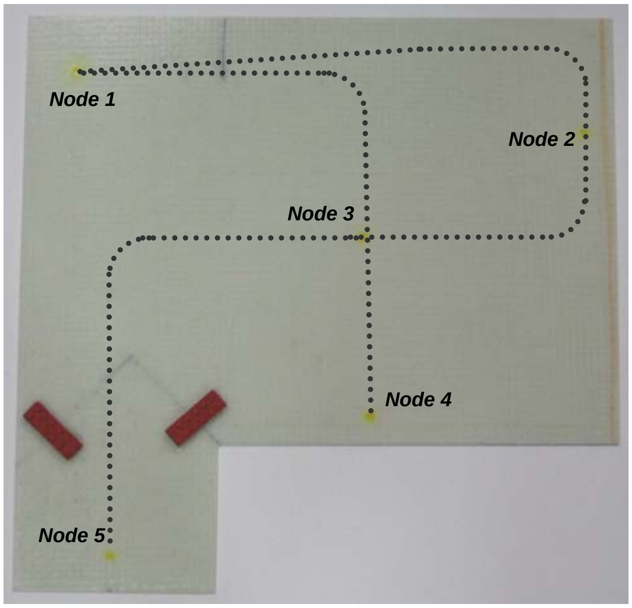


Figure 4: Integrated optical data network prototype.

For the first prototype, nodes were constructed by drilling a 6.35-mm diameter hole through each nodal position, and then backfilling with EPON 828 epoxy resin. This design is analogous to the simple scattering concept of Figure 1b. For the second prototype, the cladding on the optical fibers at each nodal position was removed manually, prior to resin wet-out, by carefully sanding with 400-grit sandpaper over approximately 1.0 cm of fiber length. The preform was then processed as described above, with no additional drilling or resin infiltration at each node. This nodal design is shown schematically in Figure 1c.

Figure 4 shows a photograph of the nodal composite prototype constructed as in Figure 3 using drilled and backfilled nodes. The dashed lines indicate the paths of the optical fibers.

3.1.3 Qualitative Interrogation of Nodal Composite

To qualitatively demonstrate the principle of data transmission through the nodal composite, a circuit was designed and constructed to convert music from a personal music player into an analog optical signal. The optical source was interchangeable between various wavelength LEDs (Super Bright LEDs Inc.), and an 850-nm vertical cavity surface emitting laser (VCSEL) (ULM Photonics). A second device was constructed using a BPW34 photovoltaic detector (Vishay Semiconductor) source onto the detector resulted in clear, loud music in the speakers. To test the effectiveness of various nodal configurations, the optical music source was placed on one node and the speaker-detector was place on another node. The quality of sound, a combination of volume and clarity, was reported as a measure of network efficiency. Note that the frequency of audible sound, as high as approximately 20 kHz, implies that our music-based experiment is interrogating the network at a data rate of approximately 20 kbps.

3.2 Active Optical Bus Prototypes

3.2.1 Transponder with PD Array

Off-the-shelf parts were used to fabricate the photodiode (PD) array/VCSEL active transceiver device. Vishay Semiconductor BPW34 silicon PIN photodiodes were connected in series, which were then used to drive an ULM Photonics ULM850-04-TN-ULCBPP 850 nm VCSEL that was directly connectorized to a Promax Prolite-20 fiber optic test meter through a fiber optic cable. In order to power the device through the input signal and thus achieve self–powering, multiple photodiodes were used. This supplies sufficient power generation to drive the VCSEL. A laser-based light source is used, as compared to an LED, due to its increased efficiency once the laser reaches its threshold current. A VCSEL, in particular, has a very low threshold current compared to conventional edge emitting lasers.

A picture of the self-powered transceiver device is shown in Figure 5. A photodiode array has been assembled and is used to drive a VCSEL which is used due to its low threshold current. Normal incidence coupling of the optical signal is achieved through the photodiode array. This is more efficient for normal incidence than shining light on cleaved ends of an embedded fiber.

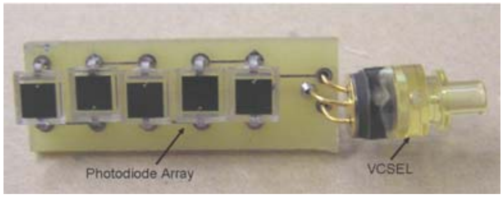


Figure 5: Self-Powered transceiver device using photodiode array and VCSEL.

3.2.2 Impregnated Dye-Fiber

Polystyrene impregnated fiber of 0.5mm diameter was used. The fiber had an emission wavelength of 635nm. Side illumination of the fiber was used to pump the optical bus. Since side illumination of impregnated dyes is possible, the need to couple to a fiber using conventional methods (i.e. physical connectorization) does not exist. Another advantage of this technique is that electronic transitions for some dye molecules can occur on the order of picoseconds which would indicate that this method has the potential for very high speed data transmission (Murov et al., 1993).

A picture of the dye impregnated optical fiber bus is shown in Figure 6. In this configuration, a green laser is used to pump the dye impregnated fiber.

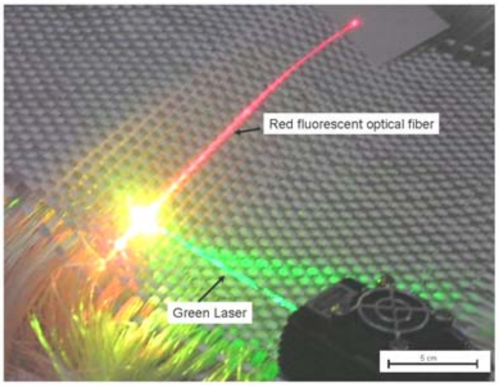


Figure 6: Red Fluorescent Fiber weaved into a composite yarn being side illuminated by a green laser.

3.2.2 Quantitative Measurements

To quantify the efficiency of the self-powered active transponder, DC measurements were performed using a Mile Luce M100 light source connected to a fiberscope. For data transmission measurements the device was driven by an 808nm solid state laser source.

For the dye fibers, a 532nm 100mW green laser was used to pump a dye impregnated fiber that emitted wavelengths in the red part of the spectrum. An acousto-optic modulator was used to modulate the pump laser so that data transmission measurements could be taken.

4. RESULTS

4.1 Qualitative Performance of Integrated Passive Optical Bus Prototype

As a first comparison, LED optical sources were compared to the VCSEL optical source. In general, the VCSEL optical source was found to be significantly more efficient than the LED sources. It is not clear if this result indicates that collimated light is inherently more efficient at passive coupling than diffuse light, or if the difference is simply due to the higher intensity of the VCSEL as compared to the LED. The VCSEL light source was used for all subsequent experiments.

Comparing the drilled-out versus sanded nodes, in general the sanded node approach was found to be somewhat more effective. Note that the drilled nodes have only cured resin between the fiber end and the outer face of the composite, while the sanded nodes are separated from the composite surface by an intact fabric layer. This result shows that the external light source is able to efficiently travel through at least one layer of glass-epoxy composite to couple to an embedded optical fiber. The sanded node demonstration panel is used for all subsequent experiments.

To demonstrate simple porting, the light source was placed on Node 1, and the detector on Node 2. Sound quality was good, clear but somewhat attenuated compared to direct coupling (shining the light source directly on the detector). Moving the detector or light source closer to and farther from the nodes resulted in gradual attenuation, with detectable but very quiet sound at distances as far as 5 cm from the composite surface. As separation distance increased, the sensitivity of the arrangement to alignment and orientation increased significantly.

Moving the detector from Node 2 to Node 3 resulted in similar sound quality. Moving the detector to Node 4 resulted in some attenuation of volume. Moving the detector to Node 5 resulted in significant sound attenuation, although clear music was still audible. Moving the source from Node 1 to Node 3 resulted in a sound quality at Node 5 somewhat softer than earlier simple node-to-node configurations. This result shows that porting across cut, aligned, fiber ends is relatively efficient, and that transmission between physically connected discrete structural components is practical.

With the optical source still at Node 3 the detector was moved to Nodes 1, 2, and 4. In all cases sound was detectable, although somewhat soft. This result shows that the "star coupler" is reasonably efficient at passively distributing a single source to multiple output nodes.

The source was then moved back to Node 1, and the detector placed on Node 3. Sound quality was good. A piece of metal foil was than placed in the slit to cover the fiber between Nodes 1 and 2. The music was still audible, but softer. The foil was then moved to cover the fiber between Nodes 1 and 3. The music was noticeably softer, but still audible. Covering both fibers resulted in no audible sound transmission.

4.2 Performance of the Active Optical Bus Prototypes

Efficiency measurements of the self-powered active transponder indicated a 2.5% differential efficiency after the VCSEL reaches its threshold current. The results of these measurements are shown in Figure 7. Notice that before the VCSEL reaches its threshold current, the efficiency is only 0.025% and then increases dramatically by a factor of 100 after threshold. Transmission speed measurements for the device, shown in Figure 8, indicate that the signal rise time is less than 1 μs which corresponds to data transmission rates of greater that 1 MHz. Uniform illumination of the diodes is critical in achieving maximum possible data transmission rates.

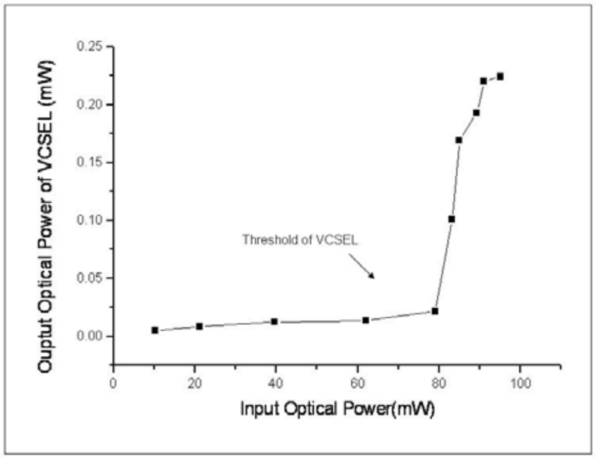


Figure 7: Input power vs. output power for the self powered transceiver device. The VCSEL reaches it's threshold at the knee of the curve and the differential efficiency is greatly increased.

Figure 9 shows the dye impregnated fiber response under data transmission. Data rates of greater than 15MHz were measured but are believed to be limited to this speed by the limitations of the experimental setup.

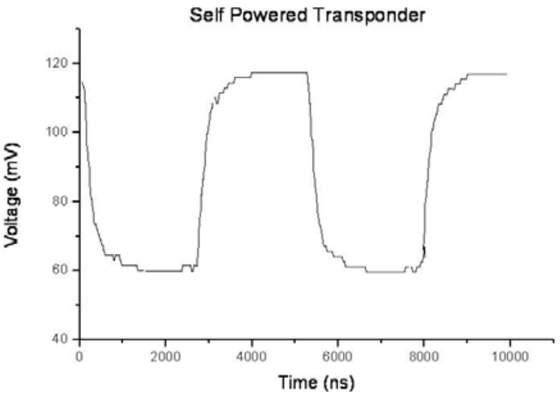


Figure 8: Data transmission with self powered active transponder

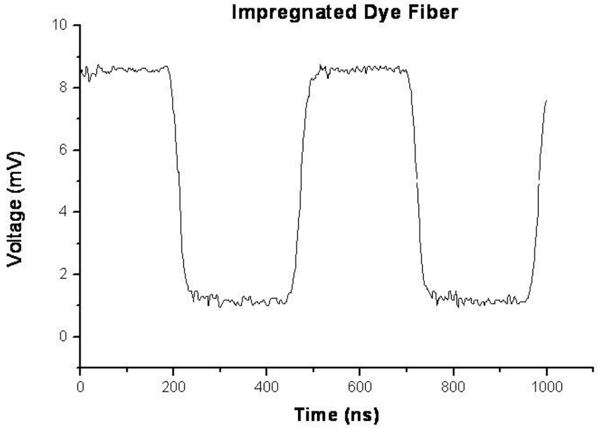


Figure 9: Data transmission using impregnated dye fiber.

The active transponder PD array proves to be the most efficient design in terms of optical efficiency. This advantage is due to the fact that after the laser has reached threshold it can provide considerably more output power than other methods. This design is also likely to be mechanically and environmentally robust (Teitelbaum et al., 2005). The dye fiber proves to be the fastest method, although the speeds measured here were limited by the experimental setup. Ultimately, the dye fiber's speed is limited by the electronic transition time in the dye. Since some of the dyes have electronic transitions that occur on the picosecond level it is possible to achieve speeds much greater than shown here. The dye fiber is the most integratable of the self-powered active methods presented here because all that is necessary is to weave a dye fiber into the weave with normal structural fiberglass weaves (Gubbola et al., 2004). For the transponder with PD array, electronic components would have to be embedded in the structure, complicating the integration process. Both techniques allow for normal incidence communication and overcome the problem of physical connectorization for communicating with the bus at ingress/egress points.

5. CONCLUSIONS

In this work, we have developed a prototype demonstrating several passive concepts and shown that optical busses can be incorporated into composites. These optical communication busses are modular, redundant, non-invasive, inexpensive, and information can easily be ported into and out of the material. We have also demonstrated active porting techniques that can be integrated into structural materials. These techniques include a self-powered transceiver with integrated photodiode array as well as a novel dye-impregnated optical fiber. Ongoing work is focused on quantitative measurements of the efficiency of passive techniques.

The transponder concepts discussed here represent a range of potential device solutions, each with particular advantages and shortcomings. Work is continuing to improve device performance, compactness, and robustness. While these efforts focus on simple porting of data, additional studies are underway to investigate the use of optical encoders for sensor applications. In principle, it may be possible to completely embed sensor networks and transponders into structures, enabling non-invasive environmental and structural health monitoring. If successful, these devices could greatly reduce vehicle manufacturing and design costs, while improving survivability and modularity.

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