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Embedded “Structural Health Monitoring” system for fiber reinforced composite structures with wireless energy and data transmission

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Abstract

The European FP7 project “SmartFiber” is developing the world first full embedded optical “Structural Health Monitoring” (SHM) system for composite materials. This optical sensor system is designed to be embedded into carbon or glass fiber material for continuous monitoring of its mechanical properties. This paper presents the project goals and technologies and gives detailed information about the wireless data and energy transmission between the embedded module (interrogator) and the external read out unit. The aim of the SmartFiber project is to develop a system that can be embedded as one small unit containing sensor and data preprocessing, enabling the structural monitoring of the fiber material without disturbing its structure.

To reach this goal seven partners join their forces to combine the needed key-technologies like nanophotonics, advanced Fiber Bragg sensors (FBGs), automatic embedding and wireless data and power transmission, optimize and miniaturize them to build a “smart composite”.

1 Introduction

Objects and structures built from composite materials are nowadays well known from high end applications. Due to their superior characteristics and their less weight these materials are used in air and space industries, wind turbines, marine and automotive applications, benefiting from the superior strength-to-weight ratio, damage tolerance, durability and corrosion resistance to mention only some few examples.

Being still a “new” material, composite structures are designed mainly conservatively with huge tolerances, as extensive experiences are still missing and accurate simulation models for the mechanical loads get extraordinary complex. In addition, composite materials behave differently than what is known from conventional materials such as steel or aluminium where damages and stress effects can be often directly seen. Within the fiber laminate small cracks and delaminations can be present without any effects to the structural integrity but, when suddenly growing, they may cause full failure of the whole structure.

A continuous structural health monitoring system can deal with these issues, removing the need for a conservative design and allowing fully using the advantages of composite materials.

2 The SmartFiber project

The project framework is formed from 7 European partners bringing together their technology experiences to implement a smart composite. Further information about the project, the consortium members and their resources are given on the project webpage [1].

2.1 SmartFiber concept

Figure 1 gives an example of a possible application for the SmartFiber system. In this example, several FBG sensors and one SmartFiber interrogator unit are embedded into a wind blade. The external unit provides the embedded system with power and extracts the sensor data. This will make it possible to monitorize the structural parameters of the wind blade during operation without disturbing its structure.

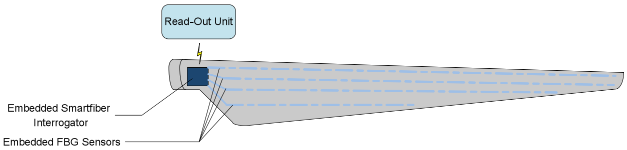

Figure 1 sample application for SmartFiber system

The SmartFiber concept combines four basic technologies to enable a “smart composite”, featuring an integrated structural health monitoring system. To reach this goal these key technologies will be combined and integrated into an optical interrogator as shown in Figure 2.

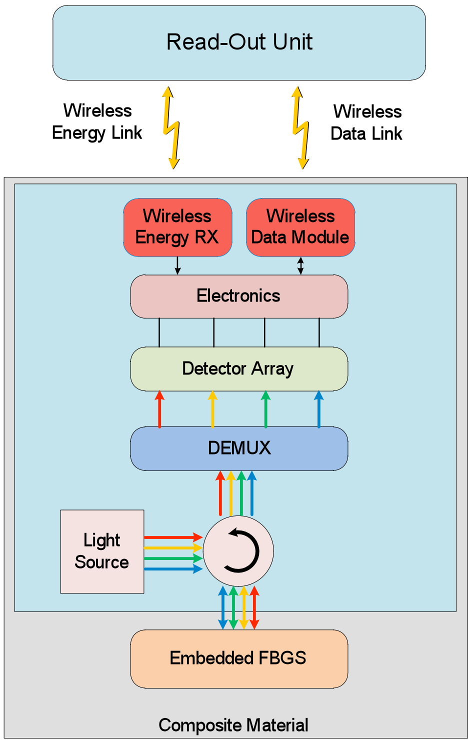

Figure 2 SmartFiber system architecture

Standard technologies for investigation of structures like ultrasonic sound inspection, radiography or visual surveillance are useful for spot tests or laboratory examinations but being in most cases work intensive, expensive and not feasible for continuous monitoring during the structure utilization.
Fiber Bragg Grating (FBGs) sensors are meant to fill this gap as they are in general good compatible with the composite structure fabrication process, compact, lightweight, immune to electromagnetic interferences with high resistance to corrosion and temperature.

Figure 2 gives a full overview of how the technologies shall interact within the interrogator. The core of the planned architecture is an optical de-multiplexer separating the spectral components of the reflected light coming from the FBGs. After being separated these spectral components are forwarded to a detector array for the conversion into electronic signals being processed and transmitted wireless to an external readout unit. As the interrogator shall be fully embedded the wireless link has to be the only connection to the outside, transferring data and energy through the composite material.

The SmartFiber concept combines the technologies of Nano-photonics, advanced FBGS, automatic embedding and wireless data and power transfer to achieve a “smart composite” (Figure 3) [1].

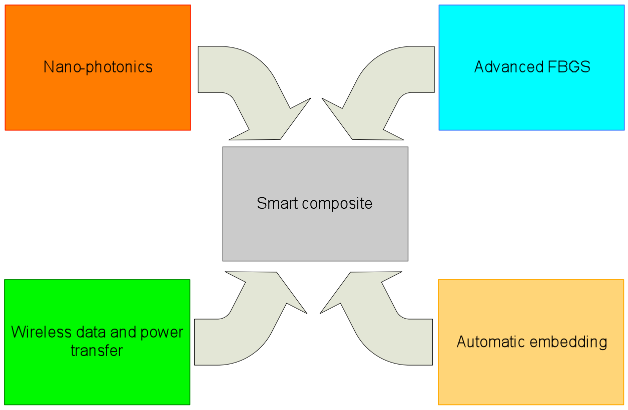

Figure 3 SmartFiber key technologies

2.2 SmartFiber technologies

The interrogator design can be separated into four key technologies that will be discussed in the following paragraphs [9].

2.2.1 Fibre Bragg Grating sensors (FBGs)

FBGs are built by writing a so-called Bragg grating in the core of an optical fiber, creating a periodic refractive index modulation for light travelling through it. When a broadband light is coupled into the fiber a narrow spectrum of frequencies will be reflected by the Bragg grating, the rest will propagate through the fiber to the other end (Figure 4). External influences may have an effect on the fiber and also on the Bragg grating, changing its reflection and transmission behaviour. This leads to changes in the reflected and transmitted spectrum, being used as sensor information. With this principle it is possible to create a fiber optical sensor for e.g. measuring mechanical strain of the fiber. When embedding this fiber into the composite material it is possible to build the required structural sensor within the composite itself [2].

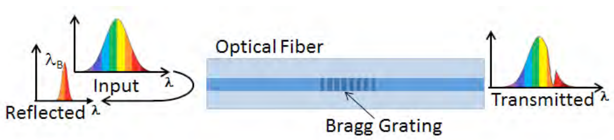

Figure 4 FBG sensor principle [9]

2.2.2 Nano-photonics

Nano-photonics technology allows the development of “Photonic Integrated Circuits” (PICs), equivalent to electrically circuits integrating optical functions in chip technology on one substrate. Possible functions can be for example light guides, light sources, detectors, optical modulators and switches, optical sensors, optical filters, optical wavelength multiplexers and de-multiplexers. Using same technologies as for electronic chips, different materials may be possible platforms for this technology, SmartFiber appeals to use silicon in combination with silicon oxide (Silicon on Insulator platform – SOI).

2.2.3 Automatic embedding

For a reliable SHM system the embedding process of FBGs and interrogator has to be repeatable and accurate with a minimum of tolerances and a negligible stress for the FBGs optical fiber. Another issue is the impact on the composite structure itself as every additional object within the laminates will weaken its structure similar to any undesired defect.

To fulfill these requirements two partners within the project are doing efforts in developing the right solutions. At Airborne Technology Center [4] a robot platform has been installed for the automatic placement of the optical fiber sensors and the interrogator. A feasible interrogator shape is also being developed at the University of Gent. The interrogator shape has to be developed to ideally vanish within the composite structure.

2.2.4 Wireless technology

Details about the design considerations, limitations and resulting decisions for the wireless link developed by Fraunhofer IIS will be given in the following sections. For the SmartFiber project the complete embedding of an optical sensor demands clearly the use of wireless data transmission and wireless energy transmission as even the embedding of medium or small size energy storages or cable connection is not feasible for the project applications.

Specification	Targeted value
Power requirements	**1.5 W**
Maximum data rate	**500 Kbps**
Maximum transmission distance	**10 cm**
Maximum size without antenna	**10 x 10 x 3 mm**
Materials	**Composite, Epoxy**

Table 1 Wireless link requirements

However, the targeted specifications (Table 1) for the wireless link are ambitious since the wireless system has to deal in addition with the involved materials (i.e. the composite structure and the interrogator device) [1], [3], [10]. The wireless link will be further described in the following sections.

3 Wireless energy and data transmission for embedded sensors

Embedded sensors always need a power source for operation as well as a data transmission link to transmit the sensor data to a read-out unit.

For a true embedding within the material it is mandatory to realize a wireless data transmission link to get rid of cable connections. This will make it possible to provide objects with integrated sensors to create the so called "smart and intelligent" objects. There are several standard and also non-standard technologies for the wireless transmission. Normally embedded sensors use protocols like Zigbee, WLAN or Bluetooth using available integrated transceiver circuits.

For the energy supply often batteries and other energy storage systems are used, which have to be replaced or recharged. Wireless power transmission can remove the need for batteries, thus reducing the system cost and size. However, there are not yet standards for wireless energy transmission. Although first solutions are coming [5], these technologies are quite new compared to the mentioned data transmission standards and are still far away from a daily use in actual applications [6].

To deal with the wireless transmission in the presence of different materials, regardless of thinking about energy transmission, data or both, it is essential to consider the materials influence on the wireless transmission properties. Surrounding materials can weaken the signal strength or detune the involved antennas, thus hindering any wireless communication. For the SmartFiber project Fraunhofer IIS has examined the possible technologies to match the project requirements and overcome the mentioned problems.

3.1 Technology selection

The technology selection mainly depends on the amount of energy and data to be transmitted as well as on the technology tolerance to the influence of composite materials.
Several state of the art wireless technologies were analysed with respect to the system requirements. Although there is a wide choice of transmission standards for wireless data transmission that could fulfill the scheduled data rate, only a few can be found for wireless energy transmission and even less that can provide both energy and data transmission links at the same time. Due to the planned interrogator size and eventually limited possibilities

for embedding different antennas the main goal is to find a similar transmission principle for both links.

After the analysis of the available wireless technologies for both data and energy transmission, passive RFID technology was chosen to be implemented for the interrogator link to an external read out unit. Unlike other technologies such as ZigBee or Bluetooth, which only provide a wireless data link, RFID offers transmission techniques for both data and energy. The aim is not to develop the wireless link in a way that the interrogator can act as an RFID transponder, but to use RFID transmission frequencies, modulation and coding schemes for the purposes of this project.

3.2 Passive RFID systems

Passive RFID systems consist of an active read out device (reader) and one or several passive transponders (tags). They are used for the wireless identification of objects with a tag attached to them. Within this tag there is a microcontroller with memory where identifiers and additional information can be stored. The main characteristic of passive RFID is that the involved transponders are full passive, gathering all their energy from a magnetic or electromagnetic field emitted by the reader. These functionalities are required in the SmartFiber implementation.

There are three common types for passive RFID systems available: Low frequency (LF) RFID at frequencies of 120 to 135 kHz, high frequency (HF) RFID at 13.56 MHz and ultra high frequency (UHF) RFID at 868 MHz [7].

3.3 Material influence

Apart from analyzing different transmission technologies to fulfill the project requirements, the general impact of composite materials on wireless transmission systems was investigated. Carbone fiber material has a strong influence on transmission systems due to its conductivity, although being much lower than what is known from normal conductors. Alternating magnetic or electromagnetic fields cause eddy currents within the carbon material leading to counter fields and weakening the original signal. Antennas covered with carbon material will be shielded from wave propagation similar to what is known from conductive metal shielding. The impact of this effect is strong frequency dependant, being worst for higher frequencies in the MHz and GHz range. In the case of LF bands, this impact is much smaller, leading only to small changes of antenna properties and attenuation [3], [10].

Glass fiber material is non conductive in general, acting for electrical circuits and wireless transmission similar as a dielectric isolator. However, it leads to detuning and losses for high frequency systems and antennas, again having more effect towards higher frequencies.

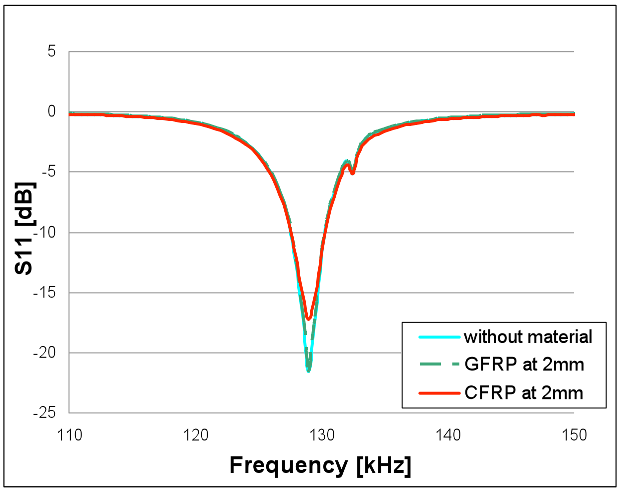

Figure 5 Material influence on LF Antenna

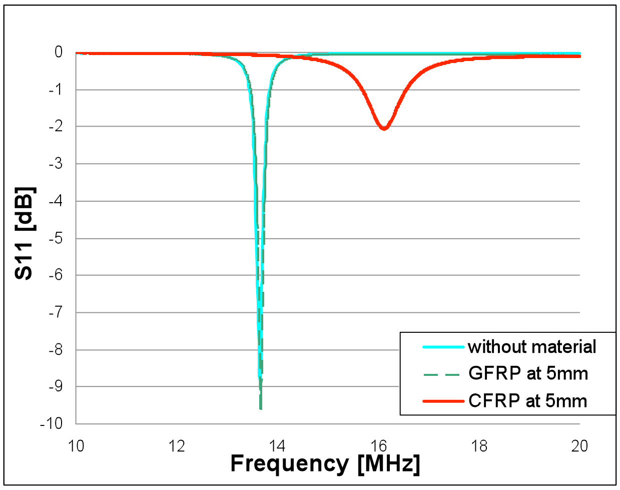

Figure 6 Material influence on HF Antenna

This can be seen in Figure 5 and Figure 6 showing measurements of the material influence on typical LF and HF coil antennas taken with a Agilent E6071C Network Analyser. Comparing the reflection coefficient of the antennas without and with composite material next to the antenna the described relation between material and frequency can be followed.

3.4 Frequency selection

In conclusion, when working with glass fiber materials one will have only a low impact on low frequency systems. In UHF systems material-matched antenna designs will be required. Carbon fiber material is more problematic due to its conductive characteristic making wireless communication through the material only possible for very low frequencies. It also forces to keep high frequency systems at least at a minimum distance away from the material to enable a proper operation. Finally, due to the wide range of different composite structures with different layer settings, different carbon and glass composite objects will have different impacts on the system performance.

	LF	HF	UHF and microwave
Range	Short	Short to medium	Long
Antenna size	Big	Medium	Small
Energy transmission	High	Medium	Low
Data rate	Low	Medium	High
Influence of composites	Low	Medium	High
Frequency selection	**Energy transmission**	**Data transmission**	-

Table 2 Transmission frequency comparison

Table 2 summarizes the interaction between transmission frequency, material influence and project requirements, which led to the decision to use LF technology for energy transmission and HF technology for data transmission. Both links will be developed in a similar way to the known RFID technology but being optimized for the SmartFiber requirements. By splitting these two wireless links it is possible to use the most adequate technology for each of them.

3.5 Inductive transmission basics

LF and HF RFID technology communicates with alternating magnetic fields, using coil antennas forming a weak coupled air gap transformer (Figure 7). The principle is very similar to common iron core transformer, known from power supplies.

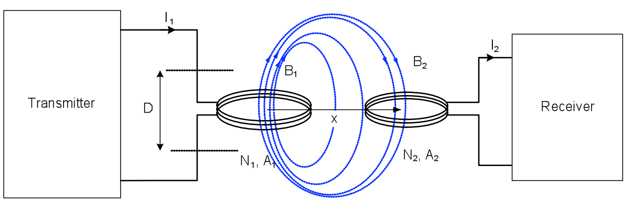

Figure 7 Inductive transmission system

The read out unit (transceiver) generates a strong magnetic field which is transmitted by its coil. The magnetic field will induce a current within a secondary coil situated in the proximity of the transmitting one and therefore energy will be transmitted over the air gap between these coils. By modulating the transmitted magnetic field it is also possible to transmit data.

The maximal transmission distance for such a system transmitting data and energy is limited by physical boundaries. As the link is working by means of magnetic coupling the field strength of the exposed magnetic field from the transmitter coil at the position of the receiving coil is the crucial factor. This magnetic field strength (*H*) is given by the transmitter coil size (*A*), its number of turns (*N*) and the current (*I*) through it. The chosen transmission frequency will give design specifications for the coil, as for example maximum values for inductivity, coil size and number of turns. Another aspect is that the magnetic field strength decreases over the distance. Within a distance of approx. the radius of the transmitting coil the decrease is moderate, continuing with 60dB/decate for higher distances. This is given by equation 1 with the coil radius r, the current I throw it, its number of turns N and the distance x.

$$B(x) = \mu \cdot H(x) = \frac{I \cdot N \cdot r^2}{2\sqrt{(r^2 + x^2)^3}} \qquad (1)$$

As a result the size and properties of the involved coil antennas will limit the operation area of the wireless inductive power transmission.

3.6 Wireless link concept

The entire concept of the wireless link is shown in Figure 8.

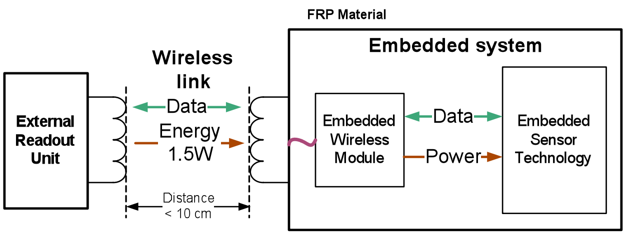

Figure 8 Wireless link concept

The connection between the external read out unit and the embedded wireless module is separated into three parts: a low data rate downlink with maximal 100 Kbps for the transmission of commands and settings to the embedded system, a high data rate uplink with 500 Kbps to transfer the sensor data fast enough towards the read out unit and the energy link, transferring the power into the embedded module. Within the whole SHM system, the wireless link shall be transparent to the other embedded modules by just forwarding data and energy towards the embedded electronics.

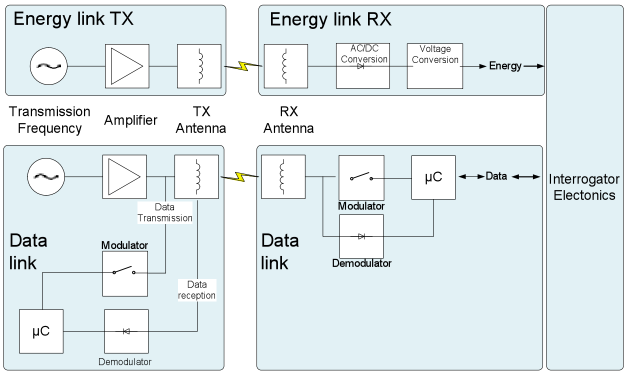

Figure 9 Wireless link details

3.6.1 Energy link

The two main challenges for the energy transmission design are the antennas and the receiving circuit with voltage rectification and conversion (Figure 9 top). The efficiency of both is essential for the whole energy transmission. For the antenna, it is mandatory to design coil antennas with low losses within the antenna structure, being well-tuned to the actual transmission frequency. Otherwise the antennas themselves will absorb part of the transmitted energy for the transmission circuit as well as for the receiver.

The voltage rectification and conversion circuits have the task to convert the incoming alternating energy from the antenna into a stabile dc power supply matched to the load circuit consumption in voltage and current. For a static consumption characteristic this is a single optimization task. However, as in the SmartFiber interrogator the power consumption can vary, a regulation loop for the power transmission system will be necessary. For doing so some intelligence must be located at the energy receiver circuit, perhaps with the use of some resources from the data link to transmit settings and regulation data to the power transmitter circuit.

3.6.2 Data link

The external data transmitter may use a similar architecture as the energy transmitter but with the difference that here the transmitted signal is not stable but it is modulated by a data stream. For the uplink data stream a reception circuit with detector and filtering is connected to the external transmitter antenna. The modulation and demodulation control is done by a microcontroller, being connected to the read-out unit electronics. On the embedded receiver part a similar architecture is used (Figure 9 bottom).

Unlike common data transmission systems the integrated receiver within the interrogator is not an active transmitter that generates a modulated transmission signal, but passive load modulation or backscattering technology is used. This will reduce power consumption for the embedded wireless data link and keeps it complementary to RFID technology.

The main challenge for the data transmission system is the high amount of sensor data resulting in the need of a high transmission data rate. The demanded 500 Kbps are more or less moderate compared to today state of the art transmissions for WLAN and Bluetooth at 2.4 GHz. But for the embedded link there is a strong limitation for the maximum transmission frequency due to the composite material influence. This limitation in frequency is also limiting the transmission data rate and has to be compensated by a modulation, coding and protocol optimization.

3.7 Actual work and goals

The chosen architecture for the wireless link module is being built in laboratory environment to test the technology and optimize the used components. The approach within this work is to develop adequate antennas for embedding and to test different transmission and receiving concepts. For the energy transmission link the actual results show a transmission of the demanded 1.5 Watt power over a distance of 10 cm. The actual goal for this part of work is to optimize and miniaturize the used antennas and circuits as well as to increase the efficiency.

For the data transmission a data rate of approximating 300 Kbps can be reached with actual PCB hardware, having an outlook on 800 Kbps with redesigned PCBs.

4 Future work

The next step within the SmartFiber project for the wireless link design is the integration of the wireless transmission modules into composite material. After that, the different parts of the interrogator will be connected and miniaturized in direction to the planed prototype dimension and shape.

Beside the project work some more investigation will be done on the interaction of wireless technologies and different composite materials as these structures are meant to have an increasing potential in future markets.

The concept of the SmartFiber wireless module can be transferred to a general concept for embedding electronics with wireless data transmission and wireless power supply.

5 Conclusions

This paper has tried to introduce the SmartFiber project with its concept for a full embedded structural health monitoring systems for composite materials with a focus on the wireless data and energy transmission system. The project requirements and involved materials lead to a concrete concept for the wireless part. The embedding of sensors into composite structures or other materials will be pushed on due to this work as it removes the problem of embedded power sources and read out connections. By withdrawing these limitations structural health monitoring of composited structures can be enabled during real application enlarging security and efficiency for the composite use.

6 Acknowledgements

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8 Authors

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