OPTICAL SENSORS BASED ON STRUCTURAL FIBERS

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Abstract

Optical fiber based sensors are well established as superior to other (especially the electrically conductive) types of sensors within the same applications due to their: light weight, flexibility, sensitivity, large surface area, potential for multi-functionality and multiplexing, immunity to interference with electromagnetic fields, resilience to harsh environmental conditions as well as their safe and hazard-free use during biological interaction. Also, as the lightwaves can cross over cavities and gaps, there is no essential need for continuity in the structure; as it is required in electrically conductive materials. Nevertheless, silica glass - and many polymeric - optical fiber sensors have limited stretchability and fail at low strains; which is not suitable for applications that require higher mechanical compliance such as wearable and stretchable electronics. Therefore, this work investigates the possibilities for utilizing structural fibers (the building blocks of fibrous materials) and using them for light wave-guidance, with a study for the intensity modulation under external mechanical-strains. In particular, elastomeric fibers will be used; as they have a relatively high refractive index (thus, allows the total internal reflection of lightwaves), and high mechanical compliance with elastic stretchability up to 100%. The outcomes of this work should lead to novel sensory materials with high stretchability which are essential for many applications such as robotics and wearable devices.

Keywords: Elastic fiber; light wave-guidance; optical fiber sensors; stretchable sensors; structural health monitoring

1. INTRODUCTION

The elder population is expected to be doubled from 11% to 22% between the years 2000 and 2050 [1], which urges for developing more convenient and cost efficient long term health monitoring systems. Similarly, athletes need continuous monitoring for their vital parameters for more effective training programs. Therefore, the “portable monitoring devices” are proposed to be the current trending solution for these problems, especially if these monitoring devices are *flexible* with *comfortable* and *unobtrusive* characteristics that allow autonomous life of the patient and can be integrated in cloth. This created the new platforms for *wearable computing* and the desirable *functional biomedical textiles*.

Optical fiber sensors (OFS) have a great potential to act as a very convenient method for monitoring the health and the vital activities of the body. The importance of OFS can be attributed to their: light weight, flexibility, sensitivity, multi-functional and multiplexing potentials, large surface area, resilience to harsh environmental conditions as well as their safe and hazard-free use. In their simplest forms, optical fibers consist of two concentric layers from materials that are named the *core* and the *cladding* (sometimes there is a third protective jacket that houses the internal materials), which have different *refractive index:*

$$n_r = \frac{c}{v} \tag{1}$$

Where c is the speed of light in vacuum, and v is the speed of light in the material.

Optical fibers transmit the lightwave from the *source* to the *detector* based on the *total internal reflection* principle (shown in **Figure 1**); where the lightwave is confined within the higher refractive index core (n_{co}) of the fiber that is higher than the refractive index of the cladding (n_{co}), as long as the incident beam hits their interface with an angle greater than the critical incident angle:

$$\theta_c = \sin^{-1}(\frac{n_{cl}}{n_{co}}) \tag{2}$$

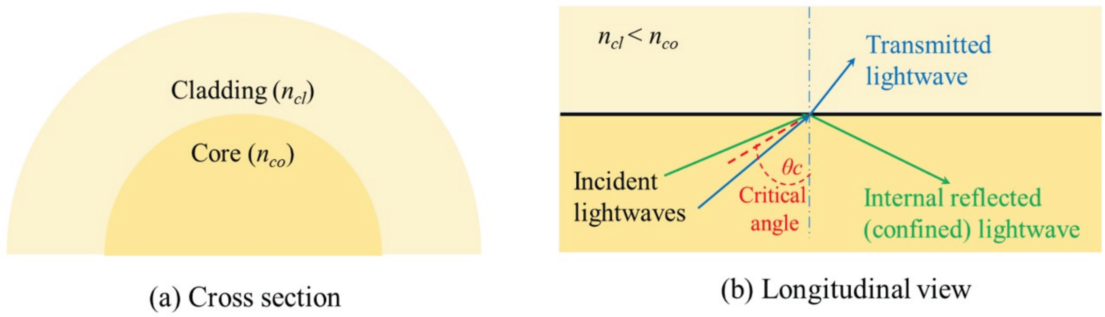


Figure 1 The physical principle for lightwave confinement within the core of an optical fiber

Optical fibers can be categorized according to their material which can be silica-glass based (GOF), or based on polymeric materials (POF). According to the refractive index profile across the radius of the fiber, optical fibers can also be classified as: *step indexed fibers*, where the interface between the core and the cladding is sharp and the refractive index that is constant within the core changes suddenly from this higher value to a lower value in the cladding. *Gradient indexed fibers*, on the other hand, having a fuzzy interface and the refractive index changes gradually between the core and the cladding that result in graded-index (GI) fibers with a continuous radial decrease in the refractive index, or the multistep-index (MI) fibers with a stepwise change in the values across the radius. The values of the refractive indecies of the core and cladding also define the *numerical aperture* (NA) of the fiber:

$$NA = \sqrt{n_{co}^2 - n_{cl}^2} \tag{3}$$

This defines with the core's radius *a* [nm] the number of waveguides traveling through the fiber. For a lightwave with a wavelength λ [nm], the normalized frequency (V) can be defined as

$$V = \frac{NA.2\pi a}{\lambda} \tag{4}$$

The number of propagating modes (N) within a fiber are given as:

$$N = \frac{V^2}{2} \tag{5}$$

Optical fibers are called *single mode fibers* when they are able to guide a single wave across their lengths, which occurs at V values below 2.405 [2], while the fiber can guide multiple waves (called *multi-mode fibers*) for normalized frequencies above this value and they are identified with a *modal dispersion* (where the time of traveling of each mode along the fiber is different). It can be observed that for a given setup of materials (i.e. known refractive index) and input source (i.e. known λ), the fiber can be single-mode or multi-mode according to the diameter (a) and the single-mode fibers dominate at smaller core diameters.

The intensity of the guided lightwave usually *attenuates* along the fiber and this attenuation coefficient α [dB km^{-1}] is an important fiber property that can be affected with the absorption and dispersion from pollutants. The attenuation is greatly affected with the bending of the fiber which can be a deformation during manufacturing or localized pressure on the scale of the fiber's diameter (referred to as *microbend*) or on a bigger scale such as that in loops with bigger radii of curvature (referred to as *macrobend*). Therefore, any local variation in the condition around the fiber embedded in a structure might lead to an observable change in the intensity of the lightwave guided based on the above mentioned *total reflection*.

Optical fibers were successfully used in logging different parameters based on the strain monitoring such as: breathing pattern, lung volume and the assessment for the oxygen supply to tissues, cardiac and heartbeat rate, blood pressure, pressure on tissue, and loading of cutaneous tissue layers, shear stress in tissues. Similarly, the Bragg-Grating was implemented to sensitively measure the temperature. Based on the reflection principles, OFS were used also to monitor blood flow, perfusion of tissues, hemoglobin volume, and saturation of oxygen in tissue and arteries as well as the electrolyte (sweat, humidity, pH) balance [2-6]. An overview of a possible application for utilizing the optical fibers (and other sensors) to record the human physiological parameters is shown in **Figure 2**.

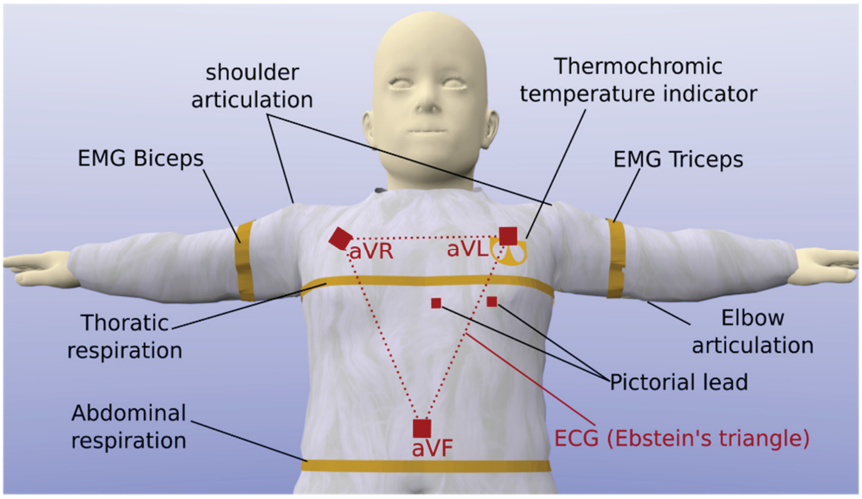


Figure 2 Multiple sensing elements for continuous monitoring of physiological and movement data [7]

It is interesting to observe that most fibers used in textile and clothing manufacturing are having a relatively high refractive index, as shown in **Table 1**, which provides the “theoretical” conditions for total internal reflection. Most of these fibers, however, have a difference between the refractive index in their axial and radial directions which affects the light path and results in a short distance for carrying out the light signal, and impedes their use for light transfer.

The aim of this study is to investigate the textile structural fibers as means for guiding the lightwaves, and analyze their response to external stimulants, particularly the mechanical strains, which should appear as a change of the intensity of the signal collected from these fibers.

2. EXPERIMENTAL METHODS

A home-built setup for carrying out the experiments was constructed based on an electronic circuit with a light emitting diode (a source) with adjustable light intensity and a photo-resistant (a receiver). Polymeric optical fiber was used to transmit the light between the source and the receiver as shown in **Figure 3**. The optical fiber was cut and a short length of the structural fibers was inserted for measurement as schematically demonstrated in the inset of **Figure 3**. The circuit was connected to a personal computer (PC) and a logging of the light intensity signal was collected for the sample at different conditions. That is: samples without external loading, and samples under the application of periodic tension-compression loading.

Table 1 The refractive index for some natural and synthetic fibers in two directions that are parallel and perpendicular to the fiber's axis [8]

Fiber	$n_{\parallel}$	$n_{\perp}$
Cotton	1.578	1.532
Ramie and flax	1.596	1.528
Viscose rayon	1.539	1.519
Secondary acetate	1.476	1.470
Triacetate	1.474	1.479
Wool	1.553	1.542
Silk	1.591	1.538
Casein	1.542	1.542
Vicara (zein)	1.536	1.536
Nylon	1.582	1.519
Terylene polyester fibre	1.725	1.537
Orlon acrylic fibre	1.500	1.500
Acrilan acrylic fibre	1.520	1.524
Polyethylene	1.556	1.512
Glass	1.547	1.547

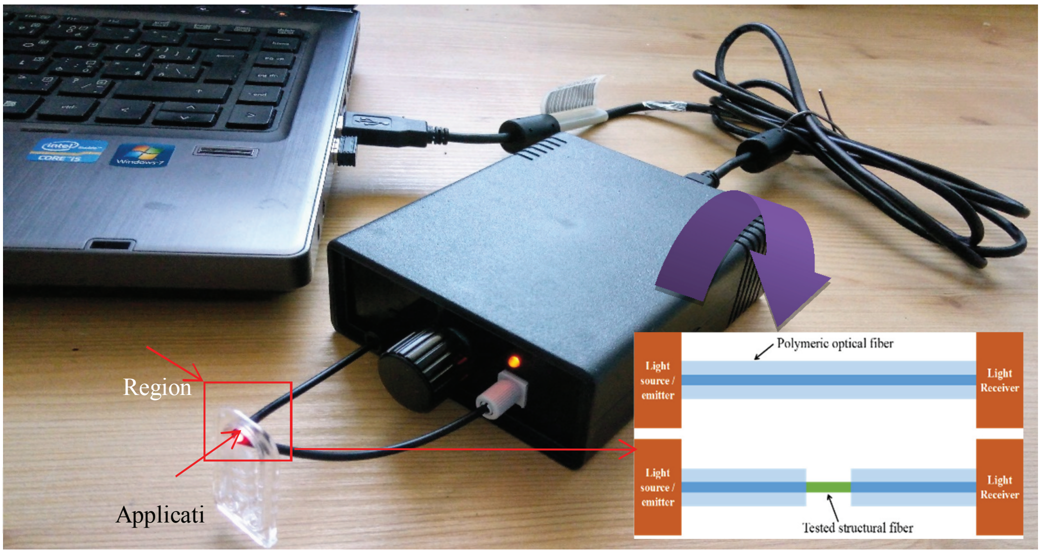


Figure 3 Experimental setup. The inset schematically represents the arrangement for fiber testing

3. RESULTS AND DISCUSSION

The collected signal for the sample without loading is plotted with the blue color in **Figure 4** which shows a slight noise during the operation. The application of external load to the fiber resulted in a variable signal that is shown with the red color in **Figure 4**, and the descriptive statistics for both signals are listed in **Table 2**.

These results demonstrate a reasonable response of the optical fiber to stimulating loads, which implies a possible application in using these fibers in detecting the mechanical behavior of a loaded structure.

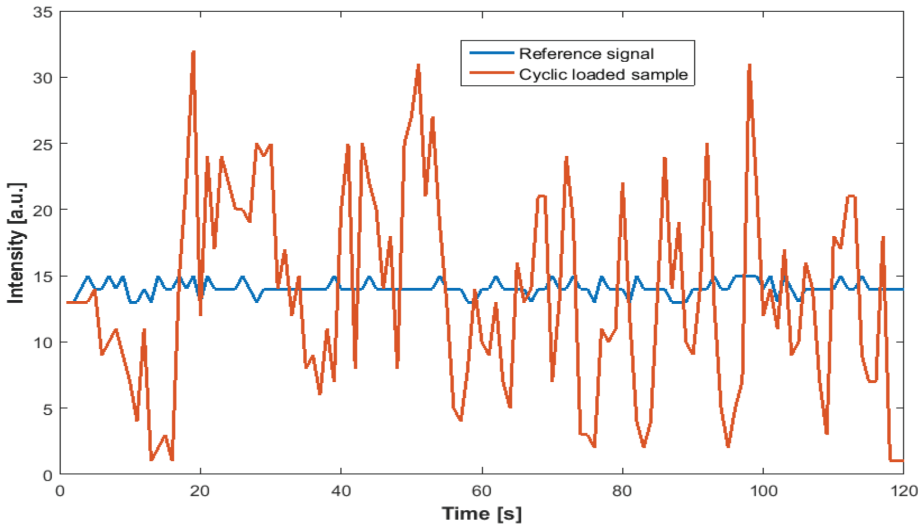


Figure 4 Intensity of transmitted light signal in the reference (static) sample compared to the sample under dynamic loading

Table 2 Descriptive statistics for the collected signals

	Reference signal	Loaded signal
Average [a.u.]	14.07	13.23
STD [a.u.]	0.59	7.71
Min [a.u.]	13.00	1.00
Max [a.u.]	15.00	32.00

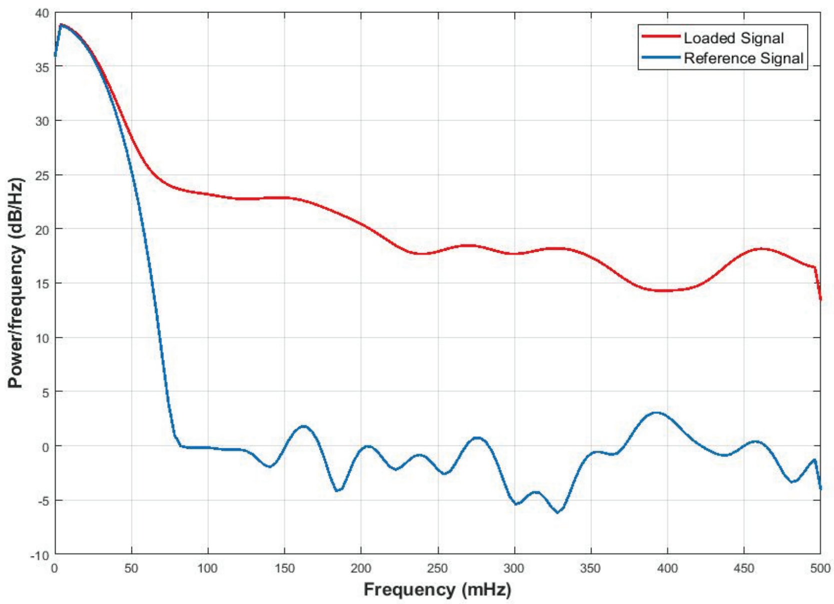
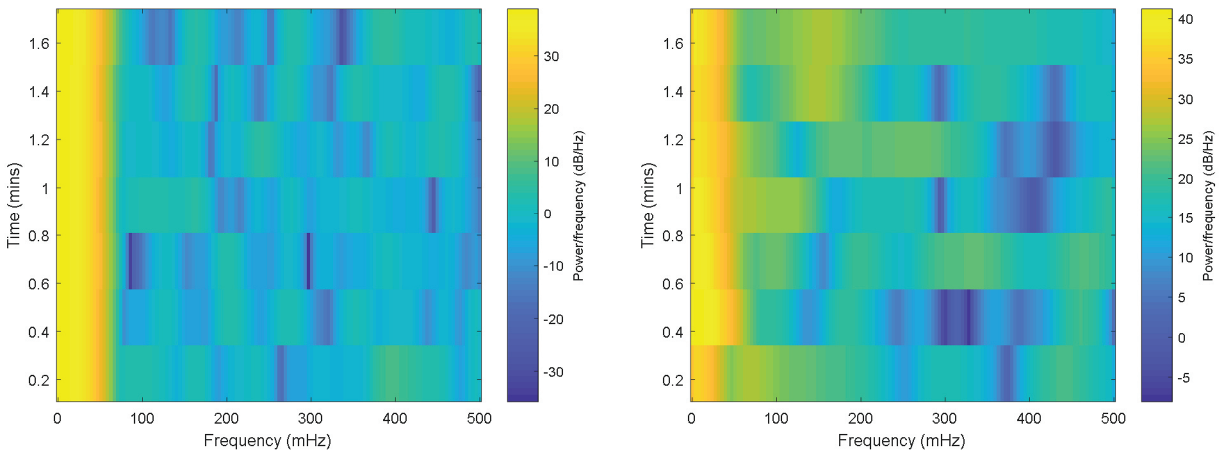


Figure 5 Welch Power Spectral Density Estimate for both collected signals

The Fast Fourier Transform (FFT) of loaded and unloaded samples is given in **Figure 5**, which shows the dominant frequency for both cases to be located at about 4 mHz. This means the possibility of the tested fiber to maintain its natural frequency even under loading and the negligible effect of loading on the structure of the fiber. In addition, it can be shown that the power for the loaded case is about 20% higher than the unloaded case. This demonstrates the sensitivity of the fiber and its ability to detect the behavior of a structure with changes in this range.



Reference signal

Loaded signal

Figure 6 Spectrographic analysis of the collected signals in the Time-Frequency domain

Moreover, the time-frequency for the two signals is presented in **Figure 6**, where the power for the dominant frequency in the case of loaded sample is clearer than the reference sample. This means that the response of the optical fiber sensor is high enough to detect the behavior of structures under harsh loaded conditions. Moreover, noises for the reference signal are small while the low power is shown with loaded case after 50 Hz compared to the reference case. It means that the sensor can be used to detect the accurate structures behavior. These results suggest that the performance of these optical fiber sensors is high in time and frequency domains and can be used to evaluate and assess the behavior of materials and structures.

4. CONCLUSION

The preliminary results presented in this work show the potential use of structural fibers for carrying lightwaves and working as sensory elements in fibrous materials. However, these fibers suffer from rapid loss of light intensity, and optimizing their working lengths and positioning in the sample are necessary. The presented setup is a step in that direction and further study will continue to optimize their working parameters.

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