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Integration of carboxymethyl cellulose waveguides for smart textile optical sensors

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***Abstract*—The development of novel textile materials capable of controlled interaction with the environment has contributed to the growth of smart textiles. Nevertheless, the ubiquitous integration of plastic and electronic components into textile structures will bring new challenges regarding the use of material resources and waste management. Focusing on this problem, the present work explores the use of carboxymethyl cellulose (CMC)-based optical waveguides to create textile-based optical sensors. Following an interdisciplinary approach, the research was conducted by combining methods from textile design, material science, and photonics. CMC optical fiber and planar waveguide were compared in corresponding textile structures. We present the laboratory testing results of initial proof of concept samples of bio-based woven smart textiles demonstrating their touch, bending, and water optical sensing capabilities.**

***Index Terms*—cellulose, optical waveguides, smart textile, weaving.**

I. Introduction

The development of novel textile materials capable of controlled interaction with the environment has contributed to the growth of smart textiles. Humidity-responsive fabrics for sportswear [1], or pressure sensing knits for posture correction [2], are some examples of applications for these novel data exchange materials. Although fascinating, the field of smart textiles is not free of pressing concerns. The ubiquitous integration of functional components, such as conductive yarns, or microcontrollers into textile structures creates complex multi-material substrates. Accounting for the textile waste [3] and electronic waste crisis [4] we are currently facing, the creation of smart textiles composites will bring challenges regarding material resources and waste management. Hence, there is an urgent need to integrate bio-design guidelines and aim for more sustainable options. In this context, the present work explores the use of a bio-based material for the creation of textile-based optical sensors. In recent years, cellulose has been studied as a candidate material for preparing optical waveguides [5], [6]. In this work, we utilized carboxymethyl cellulose (CMC)-based optical waveguides developed by Jaiswal et al. [7], and additionally, prepared planar waveguides from CMC. Although still under development, these flexible, biocompatible, biodegradable, renewable, and non-toxic optical waveguides have been proven to be good alternatives to traditional polymer optical fibers (POFs), a commonly utilized material in the field of smart textiles [8]. In addition, as an active material, CMC fibers waveguides are sensitive to water, humidity [9], touch, and respiratory rate [7]. Therefore, this work explores cellulose optical waveguides' use in textile constructions, studying their potential to create light-emitting fabrics and soft sensors. Following an interdisciplinary approach, the research was conducted by combining methods from textile design, material science, and photonics. The optical characterization of the utilized CMC fiber waveguides has been shown in previous work [7] and attenuation coefficients of CMC planar waveguides were measured in this work. Weaving was the chosen method for the waveguides integration into textiles, and different structures were chosen to understand its relation with attenuation values. Finally, we present the laboratory testing results of initial proof of concept samples of bio-based smart textiles demonstrating their capabilities for touch, bending, and water optical sensing.

II. Smart Textiles and Optical Fibers

Smart textiles are fiber-based structures capable of interacting with environmental conditions or stimuli through sensing and reacting mechanisms [10]. These novel materials combined with digital technologies for data processing have been applied to different contexts ranging from healthcare to performance [11]. Particularly in the case of plastic optical fibers waveguides (POFs), with attenuation value of 12 dB/km [12], research has been conducted on their potential use in smart textiles design [8]. In comparison with brittle glass optical fibers (GOFs), and thanks to their small diameter, flexibility, strength, and low weight, POFs are a suitable material to be embedded into textile composites to create light-transmitting smart textiles. Weaving has been proven to be the most efficient method for this integration [13] but successful prototypes have also been achieved with knitting and embroidery [14], [15]. In these cases, light can work as an actuator, allowing the design of different dynamic visual patterns that can be programmed according to a code [13]. In addition, POFs can be used as sensors by measuring the changes in light intensity caused by movement, pressure, pH, humidity, or contact [8], [16]. Nevertheless, traditional POFs are made with fossil fuel-based materials like polymethylmethacrylate (PMMA), polystyrene (PS), or polycarbonate (PC) [6]. Through use and degradation, these materials can form microplastics, leading to impairment of health and accumulation in the environment [12]. In addition, once added to a combination of textile fibers, separation and recycling become challenging. Due to these reasons, it is crucial to seek more sustainable alternatives to POFs.

III. Cellulose optical waveguides

The present paper will focus on the use of CMC waveguides that are renewably sourced, biodegradable, biocompatible, and non-toxic alternatives to POFs. In addition, as an active material, CMC fibers have been shown to be sensitive to water and humidity [9]. Preliminary results showed that they could be used as touch and respiratory rate sensors [7]. Specifically, we use both fiber (one-dimensional) and planar (two-dimensional) waveguides, which enable the comparison of different laboratory manufacturing processes, optical properties, sensing, and actuating capabilities.

A. CMC optical fiber waveguides

The CMC optical fiber waveguides were prepared via a wet-spinning process described in our previous work [7]. Briefly, a 5% w/w aqueous CMC solution was extruded via a spinning needle of controlled diameter (15G) into a coagulation bath containing aluminum sulfate solution. Upon entering the bath, the CMC solution was crosslinked via Al^{3+} ions and precipitated into a fiber. The fibers were then dried under tension to yield the final OF waveguide of ca. 320 µm diameter. Their resulting attenuation value is 1.6 dB/cm [7].

B. CMC optical planar waveguides

For preparing planar waveguides, films were prepared from aqueous CMC solutions (1% w/w) via water solvent casting. Thick CMC films (greater than 100 µm thickness) were brittle and hence, 30 wt.% vegetable-derived glycerol (EMPROVE®, Merck) was added to the CMC solutions as a plasticizer. A measured mass of CMC solution was poured while avoiding air bubbles into flat plastic molds upon which the samples were dried in ambient conditions. After approximately 48 hours, dried CMC films were detached from the molds. The resultant CMC films were flat, flexible, and transparent with an average thickness of ca. 130 µm. Due to their film format, they can be cut into different lengths and widths, following either curve or straight lines. The attenuation values were later measured and the results are presented in section VI. Results.

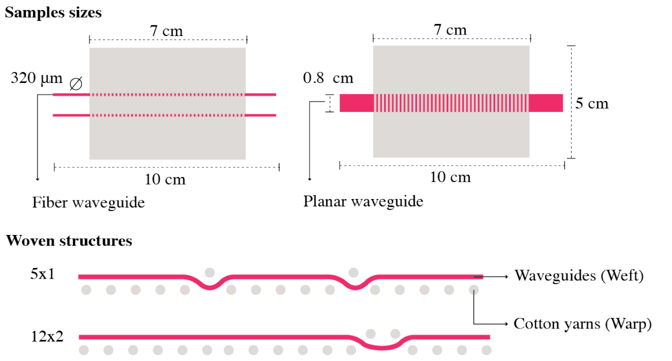

Fig. 1. Size and shape of fiber and planar CMC-waveguides integrated into cotton textile samples. The selected weaving structures are 5x1 satin and 12x2 floats, resulting in 4 samples for later testing.

IV. Optical textile sensors construction

As proof of concept, optical textile samples were created to test them as touch, bending, and humidity sensors (Fig. 1). Both CMC fiber and CMC planar waveguides were used, in combination with mercerized cotton yarns, aiming for all-cellulose samples. A pair was made using water-repellent polyester yarns, to compare the effect they could have on the humidity measurements. Weaving was the chosen method for the integration of the different materials into one textile structure. This textile technique is based on the use of warp yarns running lengthwise and weft yarns running widthwise [17], which allows incorporating different individual materials without creating extra friction, tension, or bending in the crossing points (as in comparison with knitting loops). In this case, two different simple woven structures were chosen: 5x1 satin and 12x2 floats to compare how they could affect the behavior of the cellulose waveguides (Fig. 1). The size of the samples was defined by the maximum length of 10 cm, which was adequate for lab testing with a photodetector. Due to the attenuation levels, longer samples would have resulted in too much scattering and insufficient light at the end to measure. All the samples were done by hand in a TC2 XS Jacquard loom (Tronrud Engineering Moss).

V. Laboratory testing

Firstly, the attenuation of planar CMC waveguides was measured to complement the existing attenuation values of the CMC fiber waveguides. Planar CMC waveguides were prepared with and without glycerol plasticizer. Pure CMC samples were 100, 150, 200, and 250 µm thick. Correspondingly, CMC with glycerol samples were prepared at 70 and 150 µm thickness. As light inputs, a visible range laser at 637 nm with 10 mW intensity and near-infrared superluminescent light-emitting diode (SLED) at 1050 nm with 12.9 mW. Input light was coupled with single-mode (SM) fiber (9/125 µm core/cladding diameter) and micromanipulators to planar waveguide (Fig. 2). Output light was coupled directly from planar waveguides to silicon detector (S120C, 400-1100 nm, Thorlabs). Planar waveguide width was less than detector aperture diameter 9.5 mm. The length of planar waveguides

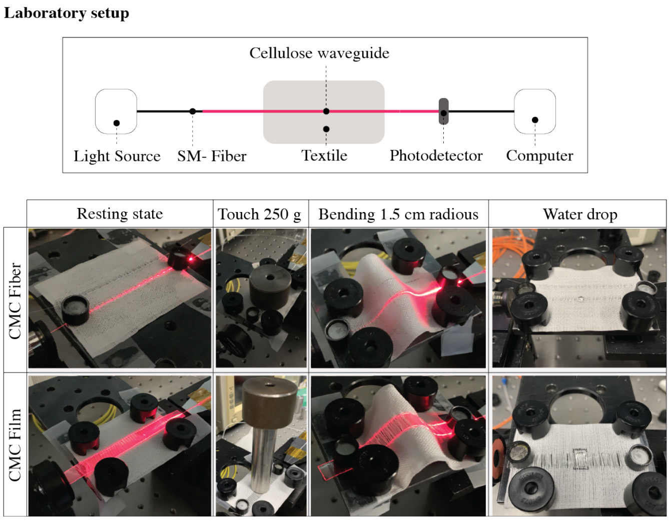

Fig. 2. Laboratory setup for light intensity measurements utilizing a SM Fiber and Photodetector. A 250 g weight, bending and a water droplet were utilized for sensing measurements.

TABLE I
ATTENUATION VALUES OF CMC PLANAR WAVEGUIDES

Sample	637 nm dB/cm	1050 nm dB/cm
CMC 100 µm	2.43	1.78
CMC 150 µm	1.82	1.01
CMC 200 µm	1.82	1.27
CMC 250 µm	1.76	1.00
CMC 70 µm with glycerol	2.20	
CMC 150 µm with glycerol	1.77	

was selected so that the laser beam spreads less than what was the width of the waveguide. That means less than 7 cm long waveguides. Secondly, the resulting 4 textile samples (Fig. 1) were tested on the same laboratory setup. For each sample, a "resting state" measurement was done as baseline. For touch, a 250 g round weight was positioned onto the middle of the samples. In the case of bending, the samples were placed with a 1.5 cm radius. Finally, for water sensing purposes, a water droplet was added onto the middle of the textile sensors (Fig. 2). Every measurement was repeated 4 times.

VI. RESULTS

In the case of planar CMC waveguides, the lowest measured attenuations were about 1.8 dB/cm at 637 nm and 1.0 dB/cm at 1050 nm (Table I). Glycerol plasticizer addition did not affect attenuation values. Such attenuation values indicate that the CMC waveguide sensors could be as long as 10-20 cm. In the case of the sensors, changes in light intensity values were observed in all samples when applying weight (for touch), curving them (for bending), and adding the water droplet (for humidity) (Fig. 3). In general terms, CMC fiber waveguides give bigger ranges of values than the planar ones, thus making them more sensitive. On the other hand, planar waveguides give higher light intensity values, mainly due to their bigger transmission area. Both fiber and planar waveguides have

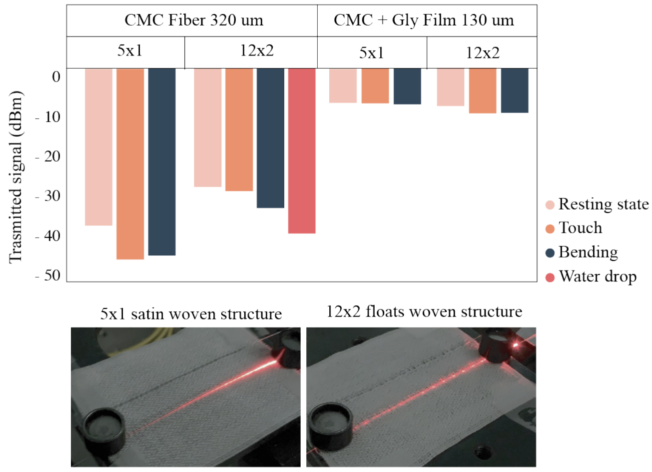

Fig. 3. Resulting light intensity changes on textile samples when touching, bending or adding water drop. Higher attenuation can be observed in 5x1 satin structures in comparison to 12x2 floats.

still high insertion losses, because fiber and planar waveguide ends are not yet polished. Regarding the woven structures, they do affect the light intensity, especially in CMC fibers which had a higher attenuation in 5x1 structures (Fig. 3). This could be explained by the bigger amount of warp yarns interlacing, creating more small bendings, thus, increasing the light scattering . In the case of the humidity/water sensing, the cotton and polyester yarns make the recovery of the CMC from wet to dry slower, in comparison with CMC fibers alone. Since polyester does not absorb the water, the water droplet stays on the surface for a longer time before it evaporates. This makes the fiber/film to be in contact with water for longer, increasing the attenuation in comparison with the cotton samples. Both CMC fibers and planar waveguides swell and change their initial shape.

VII. CONCLUSIONS

The present work addressed the potential of bio-based carboxymethyl cellulose (CMC) waveguides as a suitable material for the creation of textile optical sensors. The results showcased that both planar and fiber waveguides can be used for light-emitting textiles. In addition, by measuring the changes in light intensity using a photodetector, it is possible to detect a change of state when the samples experience touching, bending, or wetting. Therefore, we can infer their capacity as optical sensors. Due to the current attenuation values, small samples were produced and future work needs to be done on more extensive lab analysis, light transmission efficiency, scaling of production, and cladding. Nevertheless, the results are promising and could be later applied to context-based research, such as light-therapy devices or disposable sensors.

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