LIGHT TISSUE

Use of light-transmission properties of functional cellulose materials for the creation of bio-based smart textiles

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Throughout the writing of this thesis I have received a great deal of support and assistance.

I would first like to thank my supervisor, ***Pirjo Kääriäinen***, whose expertise in interdisciplinary research between Design and Science was invaluable to help me navigate the process and trust in my knowledge.

I would like to acknowledge my advisor, ***Emmi Pouta***, for her endless support, enthusiasm and encouragement to keep contributing to the exciting smart textiles research. Her generosity when sharing knowledge contributed greatly to my growth as a smart textile designer and practitioner.

I would also like to thank the **BIOPTICS team**, especially to ***Aayush Jaiswal, Ari Hokkanen and Marie Gestranius*** with whom I worked closely during the whole process. They shared their time and knowledge, and our mutual trust enabled us to come with innovative ideas.

Special thanks to ***Vertti Virasjoki*** for the amazing photography work which help me to communicate the potential of the project.

Finally, I would like to thank ***my family and friends***, who supported me with understanding, laughter, food, critical eyes, and talented helping hands.

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Abstract

The creation of new textile structures capable of interacting with environmental conditions has contributed to the growing field of smart-textiles and wearable technologies. Nevertheless, their ubiquitous integration of functional components such as conductive yarns or microcontrollers will bring new challenges regarding the use of material resources and waste management. To address this issue, the following project explores the potential of synthesized cellulose as a light-transmitting material for the creation of bio-based smart textiles. Following a practice-based approach and design-driven research methods, exploratory textile samples were created in the context of interdisciplinary work between material science and design disciplines. The resulting textile sensors and light actuators were analyzed to get quantitative data regarding their behavior, and subjective assessment methods for evaluation were used to obtain qualitative data. As a contribution, this thesis presents novel experimental samples of bio-based smart textiles, and an example of how textile design knowledge can have a role in fundamental material research. The results are part of the FinnCERES funded research project BIOPTICS, in collaboration between Aalto University, Tampere University, and VTT.

Glossary

Smart Textiles
Smart textiles are fiber-based structures capable of interacting with environmental conditions or stimuli by reacting to them through sensing and reacting mechanisms (Ilén, 2015).

Sensor
A device which detects or measures a physical property and records, indicates, or otherwise responds to it (Oxford languages, 2021).

Actuator
A device that causes a machine or other device to operate (Oxford languages, 2021). For the case of this thesis, actuator will have a broader meaning, refering to any type of output for smart textiles, such as light, sound and movement.

Bio-Design
Bio-Design has emerged as an extension of Bio-Inspired Design, incorporating "the lifelike properties of living or once living organisms and their processes and their reappropriation to human-facing contexts and industries." (Esat et al., 2018, p. 1031).

Bio-based material
Materials that are wholly or partly derived from biomass, such as plants, trees or animals (Lee et al., 2020).

Cellulose
Important structural component of the primary cell walls of green plants, cellulose is the most abundant organic polymer of Earth (Klemm et al., 2005).

CMC
Type of functional cellulose used in powder format. Is the most common water-soluble derivative of cellulose. Its main qualities are high viscosity, nontoxicity, and is hypoallergenic. (Kataja et al., 2018)

MC
Type of functional cellulose similar to CMC. This powder is also soluble in water at low temperature. When heated, MC solutions solidify and shapes can be controlled. (Kataja et al., 2018)

Optical waveguide
Physical structure that guides electromagnetic waves in the optical spectrum. Optical waveguides can be classified according to their geometry: planar, strip, or fiber waveguides (Tong, 2014).

Optical Fibers
Optical fibers or fiber waveguides are flexible and thin fibers (around 0.1 to 0,5 mm) made out of plastic or glass, based on a coaxial structure capable of transporting light (Orelma et al., 2020)

POF
Plastic optical fibers (Sanghera et al. 2002).

GOF
Glass optical fibers (Sanghera et al. 2002).

BOF
Bio-based optical fibers (Orelma et., al 2020).

Core
Center of the fiber, optically transparent material with a high refractive index (Reimer et al., 2021).

Cladding
Cover of the fiber, material with a lower refractive index (Reimer et al., 2021).

Refractive index
Measure of the bending of a ray of light when passing from one medium into another (Encyclopaedia Britannica, 2021)

Light intensity
Photometric quantity. In this thesis it will be measure in dBm.

dBm
Decibel-milliwatts is a unit of level used to indicate that a power level is expressed in decibels (dB) with reference to one milliwatt (mW).

Scattering of light
Is the phenomenon by which a beam of light is redirected in many different directions when it interacts with a particle of matter (Senior et al., 2009).

Light attenuation
Refers to the reduction of light intensity as it travels through a medium due to absorption or scattering of photons (Mini Physics, 2021).

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01

Introduction

1.1 Context

As a designer, I have always been interested in the intersection between design, materials, people, and crafts. During my professional life, I have started to explore the world of textiles as they represent heritage, identities, narratives, and techniques in which new machines and digital technologies open a new world of possibilities.

On my path at Aalto University, I have had the chance to delve deeper into textile knowledge and new media tools, such as coding or electronics, and to work with an interdisciplinary team at the school of Electrical Engineering creating wearable prototypes for medical rehabilitation.

Having a desk full of batteries, electronics, cables, metals, and plastics, intermingled with cotton and polyester yarns has led me to question the use of materials and resources in the field of smart textiles. This is when the opportunity to work with a group of material scientists appeared, and I joined the research project BIOPTICS, a collaborative research between Aalto University, Tampere University, and VTT. As a FinnCERES founded research, during 2021, they have developed novel bio-based cellulose optical fibers capable of transmitting light with the aim of competing with traditional plastic or glass optical fibers. My contribution to the BIOPTICS research team has been to apply my textile and design knowledge to create smart textiles using novel biomaterial to transmit light that can be seen and measured.

BIOPTICS, led by Olli Ikkala (Aalto), Pirjo Kääriäinen (Aalto), and Hannes Orelma (VTT), aims to develop biocomposite optical fibers for smart textiles and biomedical applications, especially for sensing and therapy purposes. The multidisciplinary research is expected to open new avenues for lignocellulose-based optical biomaterials (FinnCERES 2021).

Figure 1 Bio-based optical fiber

1.2 Relevance of the topic

The creation of new textile materials capable of interacting with environmental conditions has contributed to the growing field of smart-textiles and wearable technologies. Humidity-reacting fabrics for sportswear (Yao et al., 2015), non-wovens with probiotics for intimate health (Tomasello et al., 2020), touch-sensing denim jackets (Poupyrev et al., 2016) or pressure-sensing knits for posture correction (Ou et al., 2019), are just some examples of ways for data exchange technologies to be in closer contact to our skin and bodies. At the moment, the global market of smart textiles is expected to reach $11.4 Billion by 2027 (Smart Textiles Market, 2021), meaning that expertise from science, engineering, textiles and design will be much in need in the near future. This represents an interesting professional field of work, and designers will have a fundamental role in the development of new technologies in which materials are able not just to react to stimuli but to interact, change, and adapt (Barati et al., 2019).
However, as with any new technology development, the field of smart textiles and wearables comes with concerns. In addition to the ethical issues of data collection, problems can be caused by the ubiquitous integration of functional components, such as conductive yarns or microcontrollers into textile structures. Accounting for the textile waste (European Parliament, 2021) and electronic waste crisis (UN's Global E-waste Monitor, 2020) which 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 methods and sustainability goals for the development of new smart textiles, incorporating eco-design guidelines for material innovation.

Therefore, this project is situated in the intersection between smart textiles, fiber optics, and bio-design, to present new possibilities for the creation of bio-based smart textiles using light transmission.

1.3 Research questions

As part of an interdisciplinary research project working on an underdeveloped material in a very initial phase, my role in the team had to be clearly defined to avoid confusion. The main initial task assigned to me was to create new smart textile samples using bio-based optical fibers (BOF). With this in mind and following my own motivations, I discarded the path of conceptual design in which I could have used commercial plastic optical fibers to create context-based prototypes. Instead, I focused on material development working closely with the team of material and photonics scientists as well as using the BOF and also other formats of the functionalized cellulose material, such as gels and films, to integrate them into textile structures.

Due to the material focus and its intrinsic complexity, the scope of this thesis has been limited by excluding the issues of light coupling, light source, or power; optimization of cellulose materials concerning washability or durability are also not within the scope of this thesis as they will be solved at a later stage by the BIOPTICS team. Finally, the competitive advantage of cellulose as a renewable material is sufficient for this project to be presented as a better solution than plastic or metals, but deeper studies must later determine its degree of sustainability.

As a result, the research questions that have guided the process are the following:

Can we integrate functionalized cellulose into textile structures for the creation of a bio smart-textile based on light transmission?

By doing so, does the integration enable sensing and actuation capabilities?

Can these new insights inform practice-based creative exploration for the creation of new smart textiles?

1.4 Contributions

This project aims to contribute new design-specific knowledge to the field of smart textiles with a focus on biomaterials. It introduces novel uses of functionalized cellulose for light transmission, integrated into textile constructions. Based on practice-based material exploration and laboratory testing, bio-based textile sensors and light actuators are presented as feasible examples. The displayed information can be used by textile practitioners, material scientists, and engineers to continue to develop similar materials and new multifunctional bio smart textile components, utilizing cellulose-based fiber optics, and points directions for interdisciplinary eTextile research. Finally, the project expects to increase the understanding of the role of textile and design knowledge in fundamental material research.

02

Background Research

BIOPTICS aims to develop biocomposite optical fibers for smart textiles and biomedical applications, especially for sensing and therapy purposes. The multidisciplinary research is expected to open new avenues for lignocellulose-based optical biomaterials (FinnCERES 2021).

TEAM

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Department of Design

02 Background Research

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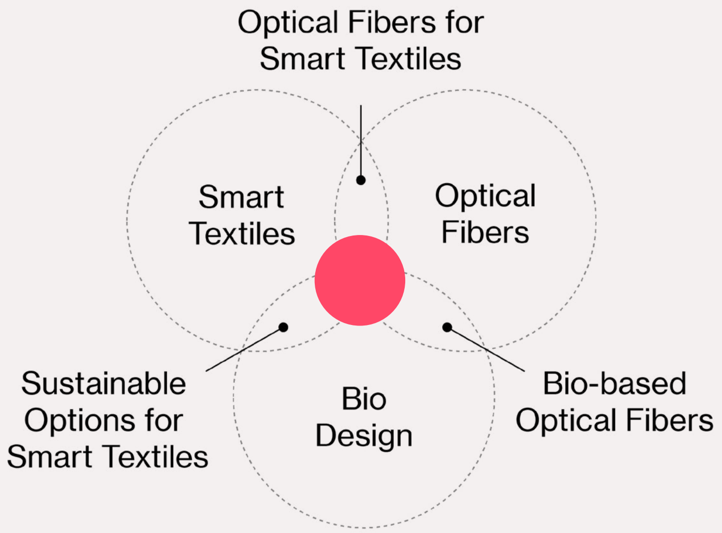

Figure 2 Background research

Due to the interdisciplinary nature of the project, three different bodies of knowledge were distinguished: Smart Textiles, Fiber Optics, and Bio Design (Figure 2). Each of these fields and their intersections were surveyed to understand the current state of the art and the relevance of the topic. The project proposal of a bio-based smart textile is situated in the center, where all of the related fields are crossing.

Figure 3 Laura Devendorf, 2021

2.1 Smart Textiles

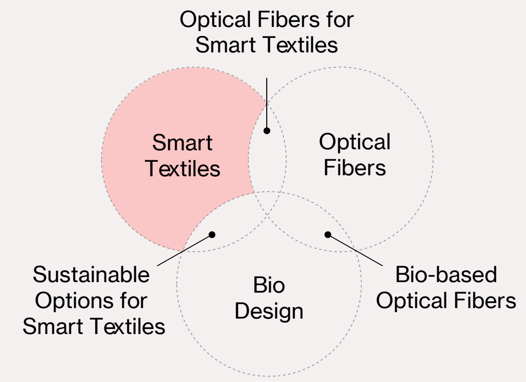

Figure 4 Background research

Smart textiles are fiber-based structures capable of interacting with environmental conditions or stimuli by reacting to them through sensing and reacting mechanisms (Ilén, 2015). According to Tao (2001), they can be categorized based on their manner of reaction into passive smart which are only capable of sensing, active smart that can sense and react, and very smart materials, which “react and adapt themselves accordingly” (p. 3).

The sensing and reacting mechanisms of smart textiles can be based on smart materials such as thermochromic pigments (Figure 3) or active bacteria (Devendorf et al., 2016 & Yao et al., 2015), or in the integration of electronic components and/or conductive materials. Smart textiles with integrated electrical properties are called Electronic Textiles or eTextiles. eTextiles are complex compositions of fabric-based substrates and small components with information processing capabilities and physical outputs such as measuring, monitoring, energy harvesting, cooling, heating, lighting, or sound (Ilén, 2016). During the last twenty years, the advance of electronics miniaturization, conductive fibers, flexible electronics, and sensing technologies have had an impact in significant development of the eTextiles field (Stoppa et al., 2014), targeting textiles requirements like washability, flexibility, body compatibility, durability, and lately, sustainability. These new materials and digital technologies have been applied to different contexts, but mostly related to human body data collection and clothing in the field of Wearable Technology for health care, sports, performance, and games among others (Baurley, 2004). The impact of this field can be estimated based on the growth of the global market for smart textiles which is expected to reach $11.4 Billion by 2027 (Smart Textiles Market, 2021), meaning more sustainable material alternatives will be needed in the future.

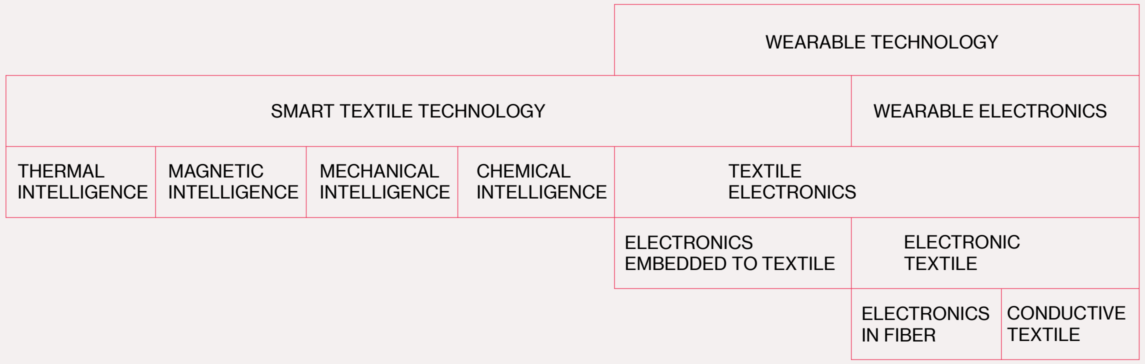

Figure 5 Smart Textiles and Wearable Technology (Ilén, 2016)

Construction methods for integration

Smart and Electronic Textiles construction methods combine unified traditional techniques, such as weaving or knitting, with new processes for the integration of electrical components like LEDs (Hardy et al. 2019) or circuit filaments (Komolafe et al. 2019) to mention a few. This integration can be made simultaneously during the production of the textile material, or later when the textile substrate is ready. As Veja (2015) explains, “this difference can also be viewed as the integration of electronics into the textile construction, or applied onto a textile substrate”. (p. 2)

In the first case, the electronic properties are built *into* the fabric itself utilizing textile fabrication methods to create woven, knitted or tufted fabrics, nets and braids (Castano et al., 2014).
An example would be to create a touch sensor by weaving conductive yarns together with traditional yarns on a jacquard loom as seen in Figure 7 (Pouta, 2019).

When working *onto* a textile fabric, the electronic components are attached on the textile surface by using techniques like embroidery (Mecnika et al., 2014), lamination (Smith (Ed.)., 2010), 3D printing (Grimmelsmann et al., 2016), printing (Berzowska, 2005), or stitching (Perner-Wilson et al., 2010). An example of this is the project Connextyle by Jessica Smarsh, using lamination onto knitting for the creation of flexible electrodes (Smarsh, 2021).

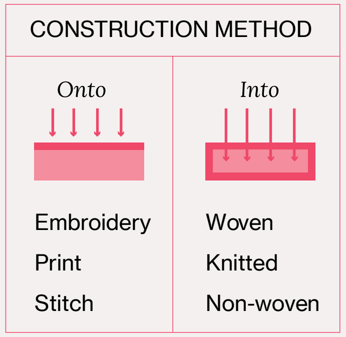

Figure 6 Smart textiles integration methods (Veja, 2015)

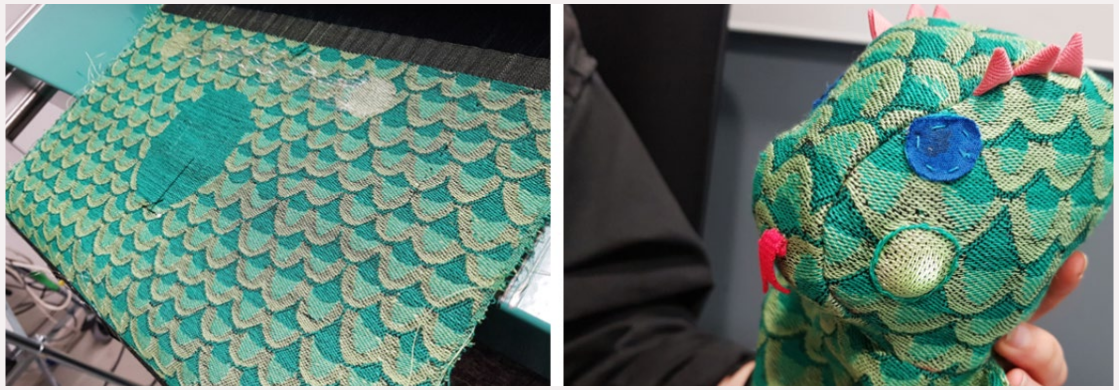

Figure 7 Woven textile sensor (Pouta 2019)

Smart Textiles units

Considering the capabilities of smart textiles to gather data and generate outputs, the main three components that may be present are sensors or inputs, actuators or outputs, and control units (Tao, 2001). As an analogy with the body, these units can be understood as the senses, the muscles and the brain (Figure 8). The way these units are made and integrated into or onto the fabric may vary from complexity, cost, and availability, ranging from DIY options to industrial solutions. For example, the Arduino LilyPad board (Buechley et al., 2010) has enabled a wide amateur audience to start integrating electronics using ready-made components and fast prototyping techniques.

For the case of sensors and actuators, their capacities are based on the following materials (Tao, 2001) :

- Photo-sensitive materials
- Optical fibers
- Conductive polymers
- Thermal sensitive materials
- Shape-memory materials
- Intelligent coating/membrane
- Chemical responsive polymers
- Mechanical responsive materials
- Microcapsules
- Micro and nanomaterials.

In this list, fiber optics appear as a key material, which can be used both to create sensors and to be used as light output. Thus, it is one of the enabling materials in smart textile development, and the next section will introduce its properties more in detail.

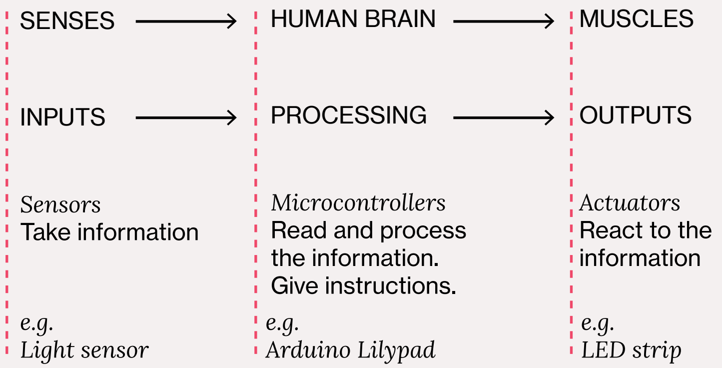

Figure 8 Smart Textiles units

2.2 Optical Fibers

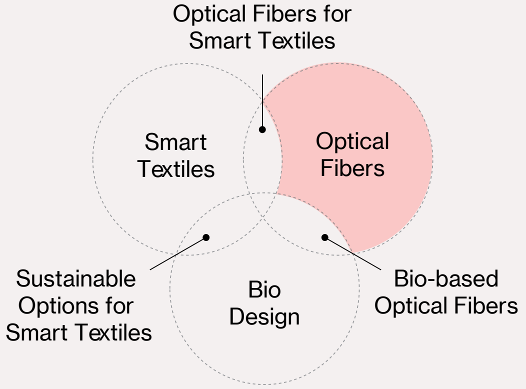

Figure 9 Background research

Optical fibers or fiber waveguides are flexible and thin fibers (around 0.1 to 0,5 mm) made out of plastic or glass, based on a coaxial structure capable of transporting light (Orelma et al., 2020). Due to this capability, they are present in our daily life in multiple applications such as communication, display, monitoring, or sensing systems (Senior et al., 2009).

They mainly consist of a core made of an optically transparent material with a high refractive index (r1), covered by a cladding made of a lower refractive index material (r2) (Reimer et al. 2021). This combination creates a waveguide for light to travel, and the cladding reduces the radiation loss into the surrounding air (Senior et al., 2009). To determine how good a waveguide is, a photodetector can be use to measure how much light arrives to the end of it. The light intensity values, measure in dBm, can be use to determined the attenuation. This concept refers to the amount of light that scaters as it “travels through a medium due to absorption or scattering of photons” (Mini Physics 2021). The lower the attenuation value, better the quality of the fiber.

For different purposes, such as sensing or light actuation, the amount of light that scatters can be control by creating macro bendings of the fibers, manipulating the cladding with micro perforations or removing it completely to make the fiber more reactive to external stimuli (Reimer et al., 2021).

As market existing products, Glass optical fibers (GOFs) have very high transmission and low attenuation loss and are mainly used for long-distance communication (Sanghera et al., 2002), but are fragile and expensive. On the other hand, Polymer optical fibers (POFs) are easy to handle, flexible, and cheap but better for short-range communication due to their considerable attenuation loss. They are mainly used for lighting applications and optical sensors (Zubia et al., 2001).

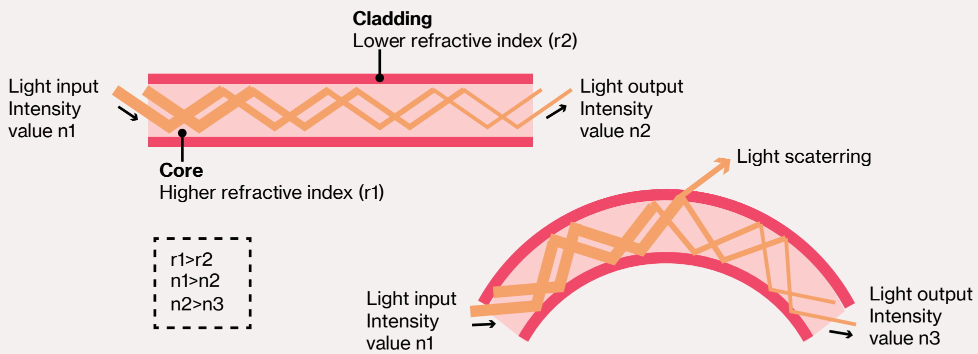

Figure 10 Optical fibers

Optical waveguide
Physical structure that guides electromagnetic waves in the optical spectrum. Optical waveguides can be classified according to their geometry: planar, strip, or fiber waveguides (Tong, 2014).

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POF
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GOF
Glass optical fibers (Sanghera et al., 2002).

BOF
Bio-based optical fibers (Orelma et al., 2020).

Core
Center of the fiber, optically transparent material with a high refractive index (Reimer et al., 2021).

Cladding
Cover of the fiber, material with a lower refractive index (Reimer et al., 2021).

Refractive index
Measure of the bending of a ray of light when passing from one medium into another (Encyclopaedia Britannica, 2021)

Light intensity
Photometric quantity. In this thesis it will be measure in dBm.

dBm
Decibel-milliwatts is a unit of level used to indicate that a power level is expressed in decibels (dB) with reference to one milliwatt (mW).

Scattering of light
Is the phenomenon by which a beam of light is redirected in many different directions when it interacts with a particle of matter (Senior et al., 2009).

Light attenuation
Refers to the reduction of light intensity as it travels through a medium due to absorption or scattering of photons (Mini Physics, 2021).

In the case of presented research, the focus will be put on novel bio-based optical fibers developed by the BIOPTICS team as an alternative to GOFs and POFs, thus it is relevant to understand the concept of bio-based materials. The next section introduces the concepts of Bio Design, Bio-Materials, and Cellulose in particular.

2.3 Bio Design

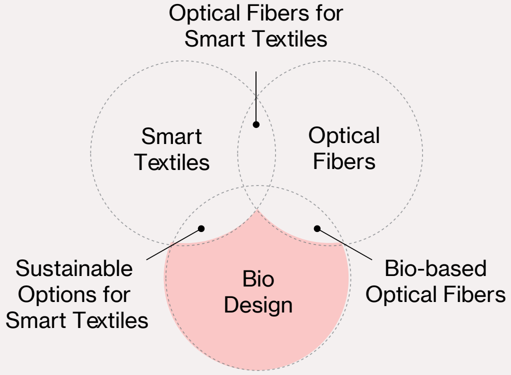


Figure 11 Background research

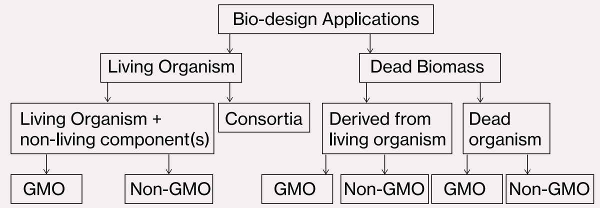


Figure 12 Bio-Design applications (Esat et al., 2018)

The observation of nature has always inspired humans in the creation of new technical solutions, which in the realm of design, has been called Bio-Inspired Design, meaning "the application of knowledge of biological systems in research and development for technical inventions and innovations" (Farzaneh et al., 2018). The term can be used to indicate design "of", "for" and "with" biology (Lee at al., 2020). In recent years, Bio-Design has emerged as an extension of Bio-Inspired Design, incorporating "the lifelike properties of living or once living organisms and their processes and their reappropriation to human-facing contexts and industries." (Esat et al. 2018, p. 1031). Biological systems not only inspire, but now they are part of the creation process and according to Est et al, Bio-design applications can be divided into Living Organism and Dead Biomass (Figure 12).

To better understand the dead biomass applications, it is possible to correlate it with the categories of bio-materials presented by Lee et al.(2020) in their report "Understanding "bio" material innovations" (Figure 13). According to them, materials that are "wholly or partly derived from biomass, such as plants, trees or animals" are called Bio-Based materials. In the case of this project, cellulose is a bio-based material derived from tree biomass, meaning that the project BIOPTICS is a bio-design application.

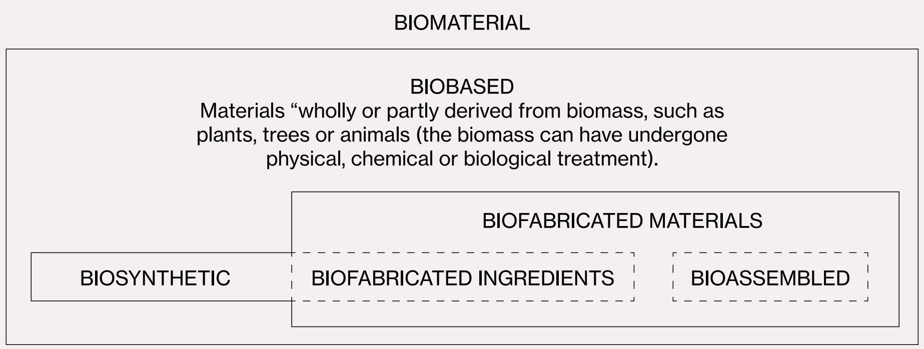


Figure 13 Biomaterial cathegories (Lee et al., 2020)

Cellulose

As an important structural component of the primary cell walls of green plants, cellulose is the most abundant organic polymer of Earth (Klemm et al. 2005), with a global production of ≈1.5 × 1012 tons per year (Reimer et al., 2021). Throughout human history, it has been used from construction material, clothing, paper, manufactured foods, pharmaceuticals, cosmetics, to as an energy source (Klemm et al., 2005). Because of its availability and renewability, its demand is increasing for environmentally friendly and biocompatible products, gaining popularity as an alternative to fossil-based materials.
Globally, its main production comes from wood and can be processed to manufacture products that are "light, soft, hard, breathable, colourful, 3D-printable, absorbable, filterable, noise, and heat-insulating, or extremely durable" (Kataja et al., 2018).

This project will use the following types of synthesized cellulose:

Carboxymethyl cellulose (CMC) used in powder format, is the most common water-soluble derivative of cellulose. Its main qualities are high viscosity, nontoxicity, and is hypoallergenic (Kataja et al., 2018).

Methyl cellulose (MC), similar to CMC, this powder is also soluble in water at low temperature. When heated, MC solutions solidify and shapes can be controlled (Kataja et al., 2018).

Once dried, these types of cellulose interact strongly with water, getting swollen and softened.

Cellulose bio-based materials in general can provide new solutions with a lower carbon footprint in comparison with fossil-based synthetic materials, and respond to global trends such as veganism and the war against plastics (Lee et al., 2020). Therefore, it can offer more sustainable solutions for smart textiles, which will be discussed in the next section.

Figure 14 MC 10% Gel

2.4 Sustainable options for Smart Textiles

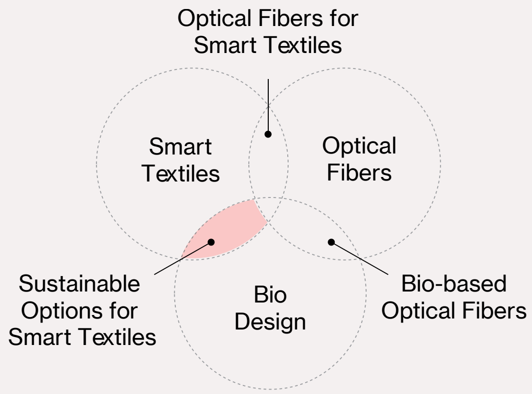


Figure 15 Background research

The development of smart textiles and eTextiles, capable of interacting with the environment through seamless integration of electronics into textiles, holds opportunities but also arises a new problem of waste management.
Currently, both the textile and electronics industries are facing a waste crisis. Globally, the fashion industry is responsible for 10% of global carbon emissions (European Parliament, 2021), and during 2020, e-waste became the world's fastest-growing domestic waste stream (UN's Global E-waste Monitor, 2020).

Therefore, it seems urgent to have eco-design guidelines for the development of new smart and eTextiles materials, such as reducing the diversity of materials in a product, reducing the weight, and prioritizing the use of renewable and recycled materials (Köhler, 2013).
In their review about end-of-life (EOL) solutions for smart textiles, Veske & Ilén (2021), identified three main tracks. The first one proposes Smart Textiles Services (STS), where smart textiles products are mainly rented instead of personally purchased, tackling the excess amount of clothing consumption. Secondly, the eco-design concept can support the integration of environmental aspects into smart textiles product design.

In particular, Köhler (2013), proposes 3 waste preventative eco-design approaches for eTextiles:

- Harnessing the inherent advantages of smart materials for sustainable design.
- Establishing open compatibility standards.
- Labelling the e-textiles to facilitate their recycling.

The case of integration of solar cells flexible panels into textiles for energy harvesting (Figure 16), is an example of harnessing its inherent advantages for smart textiles that need to be supplied by electrical powers (Ilén et al., 2021).
The third track is more general and presents different tools, methods and guidelines to support EOL solutions. For the perspective of integration for example, smart textiles researchers like Laura Devendorft (Wu et al., 2020), have been exploring traditional textiles techniques for reutilization of materials, proposing new methods of adhesive-less circuitry to disassembling or mending smart textiles.

Considering the eco-design approach, having a focus on the creation of bio-based smart textiles could give new alternatives to the industry, where adaptive, biocompatible, biodegradable and renewable materials could substitute metals and plastics.

Figure 16 Sun-Powered Textiles (Ilén et al., 2021)

From the aforementioned approaches, this thesis focuses on the utilization of cellulose-based optical fibers as a new renewable functional material with sensing and actuating capabilities. To understand how they could be used for the creation of new smart textiles, the next section introduces how traditional plastic and glass optical fibers have been used in combination with textile substrates.

2.5 Optical Fibers for Smart Textiles

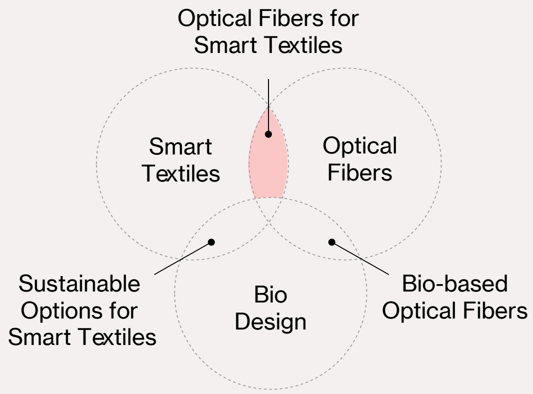


Figure 17 Background research

Optical Fibers, particularly POF, are thin, long, strong, flexible, lightweight components that can be easily manipulated and behave similarly to some plastic monofilaments normally used in the textile industry like nylon. These features make optical fibers a suitable material to be embedded into textile composites to create smart textiles based on light transmission. First, light works as an actuator, allowing the design of different dynamic visual patterns that can change according to a code. Designers, artists and researchers such as Joanna Berzowska (Sayed et al., 2010) and Malin Bobeck (Bobeck, 2021) have explored with different weaving and knitting techniques how to create these soft and flexible light interfaces that can be used in various contexts like arts (Figure 18), performance, or light therapy in clinical practice (Gong et al., 2019).

On the other hand, movement, pressure or contact can affect the light scattering from the fiber out, enabling it to create sensors by measuring the light intensity variations of the light entering and coming out of the fibers with a photodetector (Figure 19). A woven optical fiber sensor integrated into a seat for detecting seat occupancy (Haroglu et al., 2017) or the grounding stone of eTextile research, “wearable motherboard” - a vest in which POFs are spirally integrated into the tubular woven structure to form a penetration sensing component are some examples of its uses (Gopalsamy et al., 2019).

According to Gong el at. review (2019), the main applications in healthcare as wearables are heartbeat, respiratory, gait, and wrist pulse monitoring, using different integration techniques such as weaving, encapsulation, and gluing.

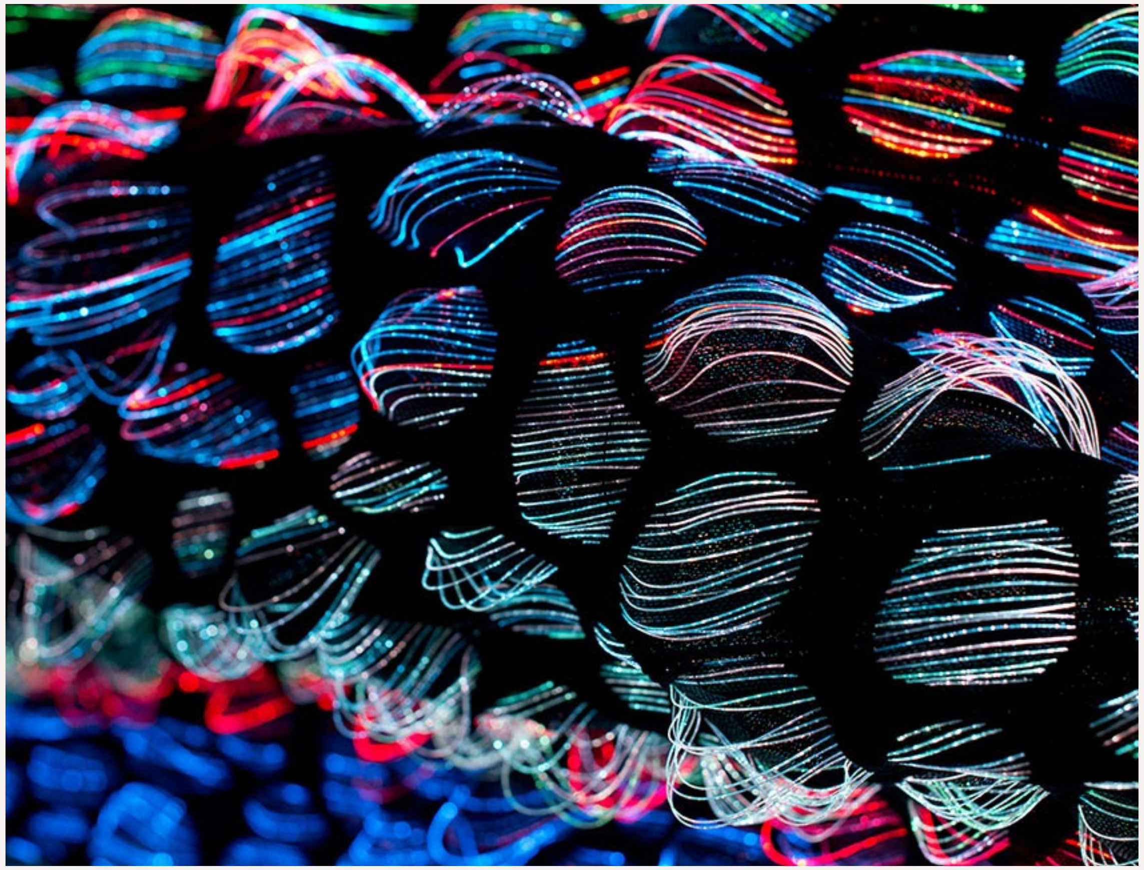
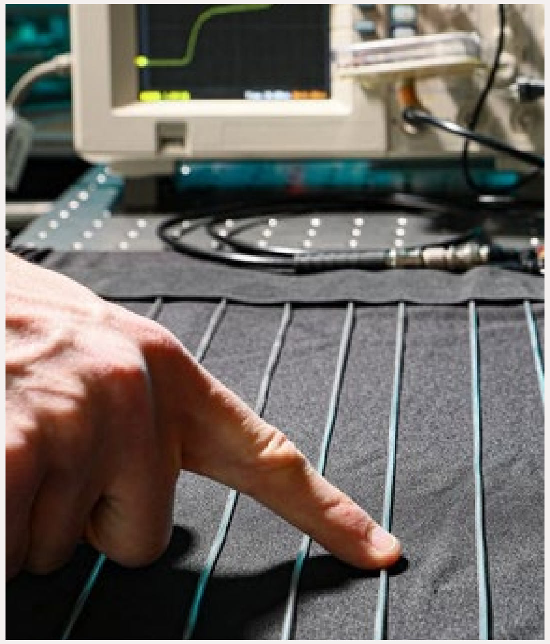


Figure 18 Malin Bobeck, 2021

Figure 19 Flexible fibre sensor (EPFL, 2020)



Even though exciting, the use of optical fibers for smart textiles has its downside. Traditional POFs are made with fossil-based materials like PMMA, PS or polycarbonate (Reimer et al., 2021). Through use and degradation, these materials can form microplastics, which can lead to impairment of health and the environment (Zubia et al., 2001). Due to these reasons, it is crucial to seek for more sustainable options, such as the one developed by the BIOPTICS team.
In the next section I will discuss its technical details and fabrication methods.

2.6 Bio-based Optical Fibers

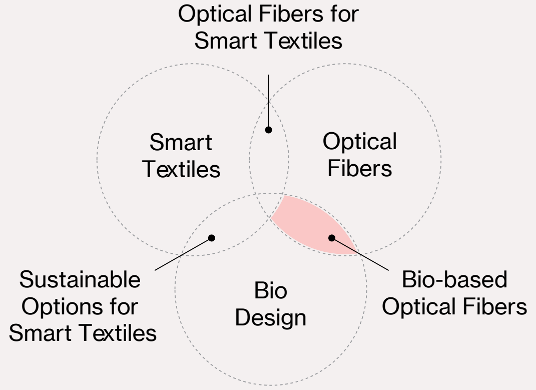


Figure 20 Background research

In response to sustainability concerns and the rise of cellulose used in optoelectronic devices (Reimer et al., 2021) the project BIOPTICS, is focused on the development of new biocompatible and biodegradable cellulose-based optical fibers (Hynninen et al., 2021, Orelma et al., 2020).
First, Orelma et al. (2020) had demonstrated the creation of optical fibers from regenerated cellulose as core (higher refractive index) and cellulose acetate as cladding (lower refractive index). Dry-jet spinning and water were used to create the core, while the cladding or shell was produced by coating the core with cellulose acetate dissolved in acetone (Figure 21).
This process resulted in a material with easy tenability, high-temperature resistance, and biocompatibility, and has proven to work as a water sensor.

Secondly, Hynninen et al (2020), have studied Methylcellulose-based optical fibers, which proved to be competitive among other biopolymeric optical waveguides. In this research, they also included gold nanoclusters to create a fiber composite with a luminescent property.

Both regenerate cellulose and methylcellulose fibers share qualities that prove them to be good and better alternatives to GOFs and POFs.
First, cellulose is a renewable and biodegradable material, and one of the most abundant polymers on earth. Its availability and environmental friendliness make it a better alternative to fossil-based fibers (Senior et al., 2009).
Secondly, its biocompatibility and nontoxicity enable the design of systems in contact with the human body, like pressure sensors (Reimer et al., 2021).
Finally, porous cellulose is an active material, capable of taking water or gas inside and reacting to them, thus, being an active material itself (Orelma et al., 2020). This opens the possibilities for the creation of new monitoring systems like humidity or ph sensors.

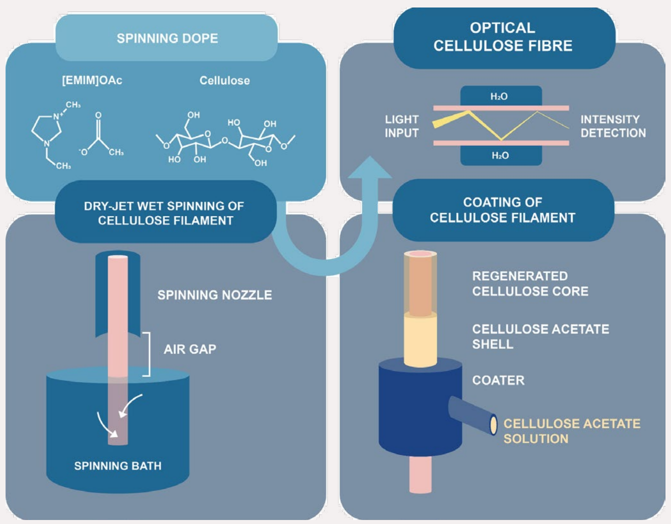
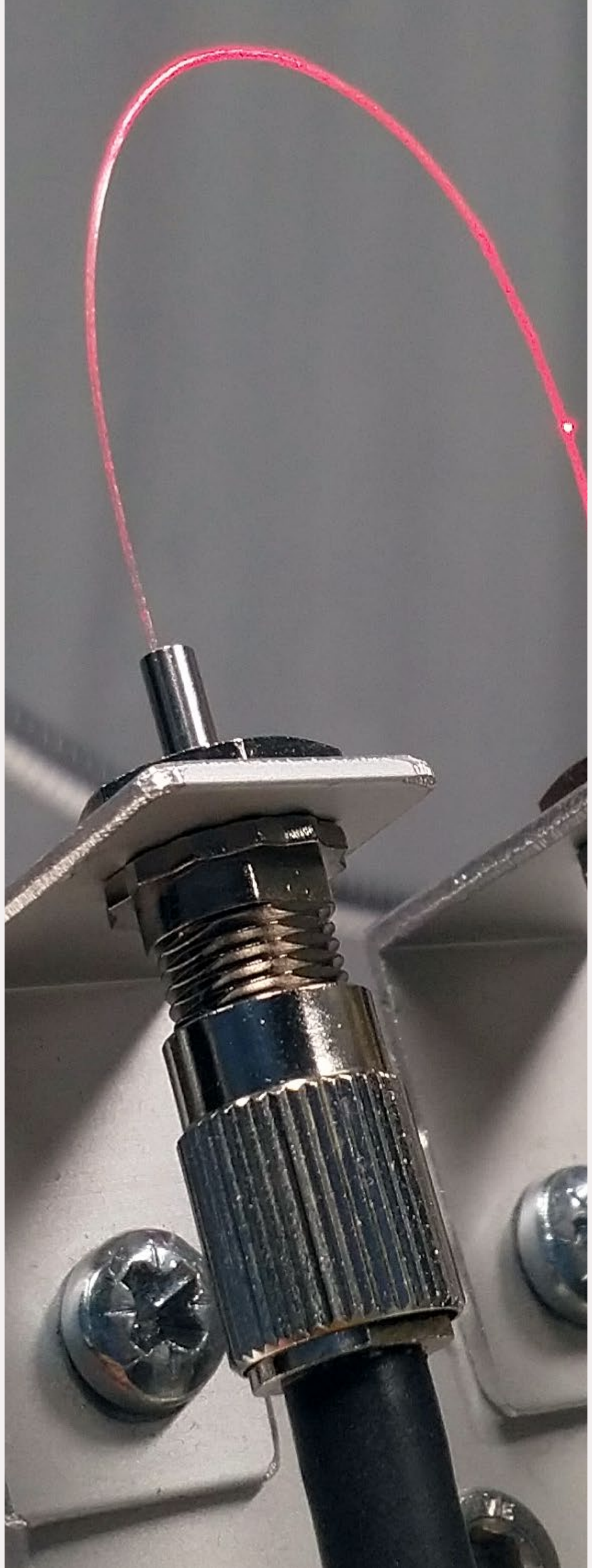


Figure 21 BOF production method (Orelma et al., 2020)



Cellulose-based optical fibers

- Optical waveguide for light transmission
- Active material. Takes water and gas inside and reacts to them.
- High strength
- Flexible
- High temperature resistance
- Easily chemically modifiable materials
- Can be integrated in many biopolymer matrixes
- Easily manageability
- Biocompatible
- Biodegradable
- Possible to add nanomaterials for luminescence, strength and conductivity

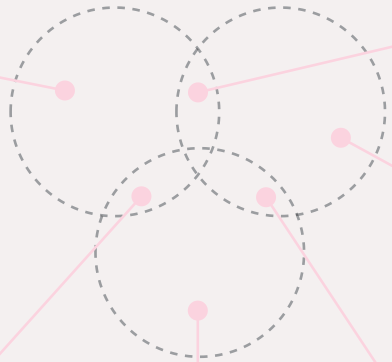
(Orelma et al, 2020 & Hynninen et al, 2020)

Thus, bio-based optical fibers enable versatile functionalities to be applied in smart textile development. They also offer more sustainable alternatives to the use of plastics and metals composites for light transmission, like POFs or LED strips, in clothing or textile products.
In the next section I will conclude the background chapter by summarising the key insights, learnings and technical concepts, which will guide the practice-based exploration process.

Figure 22 BOF conected to red laser

02 Background Research

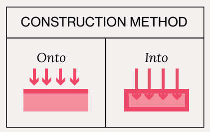
Summary background research



Smart Textiles

Smart textiles are fiber-based structures capable of interacting with environmental conditions or stimuli by reacting to them through sensing and reacting mechanisms (Ilén 2015).

SENSES →	HUMAN BRAIN →	MUSCLES
INPUTS →	PROCESSING →	OUTPUTS
Sensors Take information	*Microcontrollers* Read and process the information. Give instructions.	*Actuators* React to the information
e.g. Light sensor	*e.g. Arduino Lilypad*	*e.g. LED strip*



Sustainable Options for Smart Textiles

End-of-life (EOL) solutions for smart textiles (Veske & Ilén 2021):

1. Smart Textiles Services (STS), where smart textiles products are mainly rented instead of personally purchased, tackling the excess amount of clothing consumption.

2. Eco-design concept can support the integration of environmental aspects into smart textiles product design.

3. Tools, methods and guidelines to support EOL solutions.

Bio Design

Bio-Design has emerged as an extension of Bio-Inspired Design, incorporating "the lifelike properties of living or once living organisms and their processes and their reappropriation to human-facing contexts and industries." (Esat et al. 2018, p. 1031).

Bio-based material
Materials that are "wholly or partly derived from biomass, such as plants, trees or animals" (Lee et al.2020)

Cellulose
Important structural component of the primary cell walls of green plants, cellulose is the most abundant organic polymer of Earth (Klemm et al. 2005)

Optical Fibers for Smart Textiles

Optical Fibers, particularly POF, are thin, long, strong, flexible, lightweight components that can be easily manipulated and behave similarly to some plastic monofilaments normally used in the textile industry like nylon. These features make optical fibers a suitable material to be embedded into textile composites to create smart textiles based on light transmission.

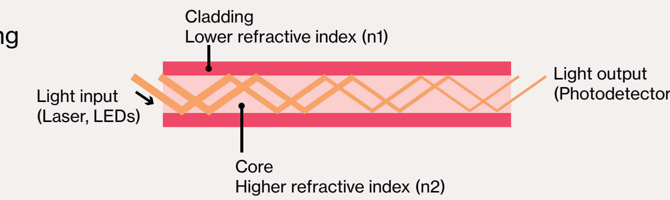
Actuation examples
Textile art
Performance
Light therapy

Sensing examples
Healthcare wearables such as heartbeat, respiratory, gait, and wrist pulse monitoring. (Gong el at. 2019)

Optical Fibers

Optical fibers or fiber waveguides are flexible and thin fibers (around 0.1 to 0,5 mm) made out of plastic or glass, based on a coaxial structure capable of transporting light (Orelma et al. 2020).

POFs: Plastic optical fibers
GOFs: Glass optical fibers
BOFs: Bio-based optical fibers



Bio-based Optical Fibers

In response to sustainability concerns and the rise of cellulose used in optoelectronic devices (Reimer et al. 2021), Orelma et al. (2020) and Hynninen et al. (2021) had demonstrated the development of new biocompatible and biodegradable cellulose-based optical fibers.

Characteristics BOFs

- High strength
- Flexible
- High temperature resistance
- Easily chemically modifiable materials
- Can be integrated in many biopolymer matrixes
- Easily manageability
- Biocompatibility
- Biodegradable
- Active material (takes water and gas inside and reacts to them)
- Possible to add nanomaterials for luminescence, strength and conductivity

03

METHODOLOGY

Can we integrate functionalized cellulose into textile structures for the creation of a bio smart-textile based on light transmission?

By doing so, does the integration enable sensing and actuation capabilities?

Can these new insights inform practice-based creative exploration for the creation of new smart textiles?

The research approach and methods were chosen to answer the research questions and took into consideration the stage of the research project BIOPTICS and my role as a designer in the interdisciplinary team. According to the Technology Readiness Level model (Mankins, 1995), by January 2021 the development was still on "TRL 1: Basic principles observed and reported", meaning that the project was on a basic research level, with very constrained samples in terms of optimization, scale, and production.
As a designer, my work was to contribute to TRL 1 and TRL 2: technology concept formulated, bringing new insights about the possibilities of integration into textiles to create new smart textiles structures, and collaborate with the team to identify changes, improvements, and possible contexts of use for the novel cellulose fibers. Textile prototypes helped to "enhance the collaborative innovation process by capturing different knowledge flows and different perspectives" (Niinimäki, 2019, p.3) and to communicate the project to a broader audience.

Therefore, as a material innovation project, and based on my motivations and own experience, *Practice-based Research* was chosen as the main research approach "in order to gain new knowledge partly by means of practice and the outcomes of that practice" (Candy, 2006). The obtained creative outcomes were then analyzed as data, because of their value as representations of implicit knowledge (Schön, 2017) unified with recently gained technical and scientific knowledge.

To organize the work stages, the *Double Diamond Design Council's framework* for innovation (Design Council, 2007) was used, following the stages of Discovering, Defining, Developing, and Delivering. Since the research project was in the very initial phase of material innovation, this framework helped to first understand the possibilities, study the state of the art, the material itself, and naturally, define the design proposal. The aim was to avoid jumping into proof of concepts too soon and ending up in a commonplace.

Since the project is not in a user-center stage, the main ethical consideration was related to the data collection at the lab and the intellectual property of the outcomes.

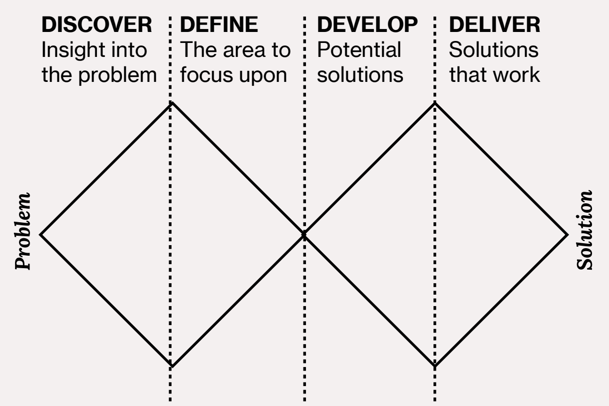


Figure 23 Double Diamond framework (Design Council 2007)

Data collection

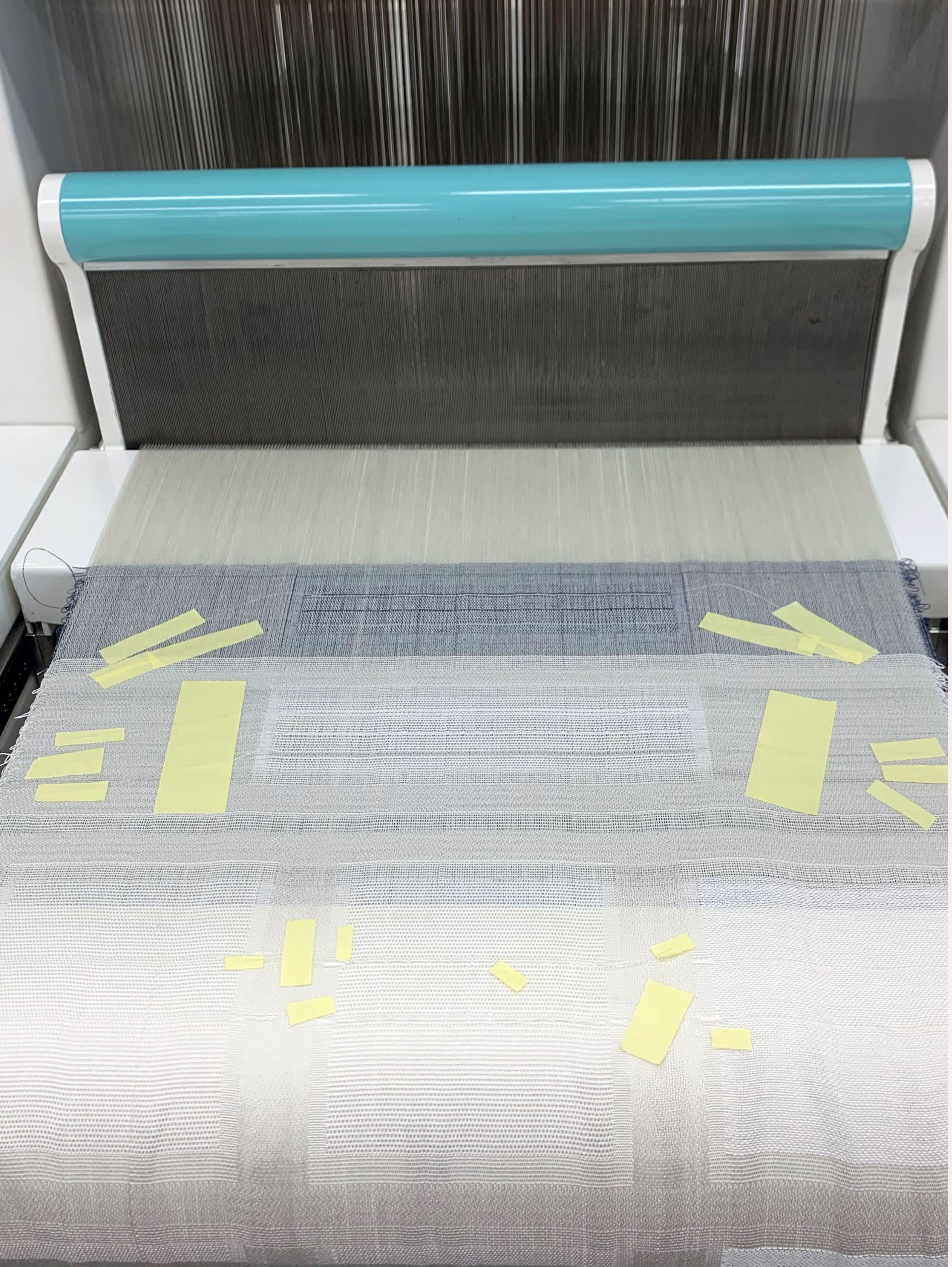
Brainstorming session: Creating the space to share the outcomes of the research with the whole team in an ideation session was fundamental to join the knowledge from the different fields (Niinimäki, 2019), which could not be achieved just with meetings. The session was guided with visual and tactile material to start the discussions, and was recorded and later transcribed, to then debrief the contents and propose some paths to continue working.

Hands-on textile prototyping: Creating physical prototypes was fundamental for the ideation process, giving tactile, visual, and functional cues about the materials and their possibilities (Giaccardi, 2019). Different fabrication techniques were used, such as weaving, knitting, and 3D printing. The work was documented with pictures, videos and personal notes. The documentation supported reflection in and on action during the prototyping process, and provided mnemonic support in the data analysis phase.

Data analysis

Subjective evaluation: Due to the reflective nature of the practice-based research approach (Schön 2017), textile samples were touched and handled constantly to obtain subjective qualitative data regarding their physical properties like softness or flexibility for example, which informed the decision making process (Bishop, 1996).

Laboratories analysis: As a collaborative project between material science and design, methods for the pursuit of scientific enquiry were also included (Peralta et al., 2010). The samples were measured in a controlled environment at the photonics laboratory to gather quantitative data, giving more in-depth information about their behavior and functionality. The data collection sessions were conducted by Ari Hakkonen, photonics expert at VTT.



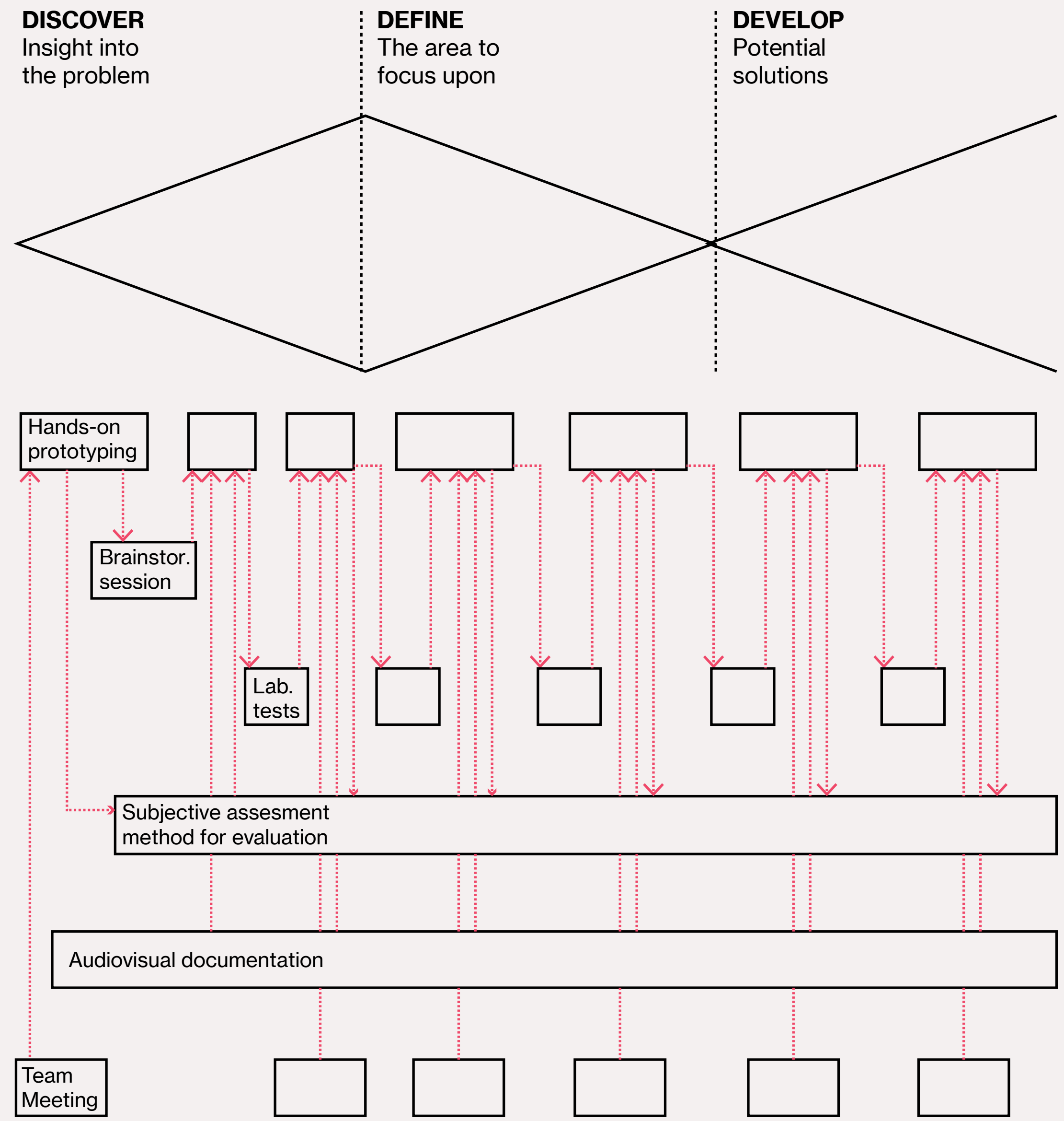
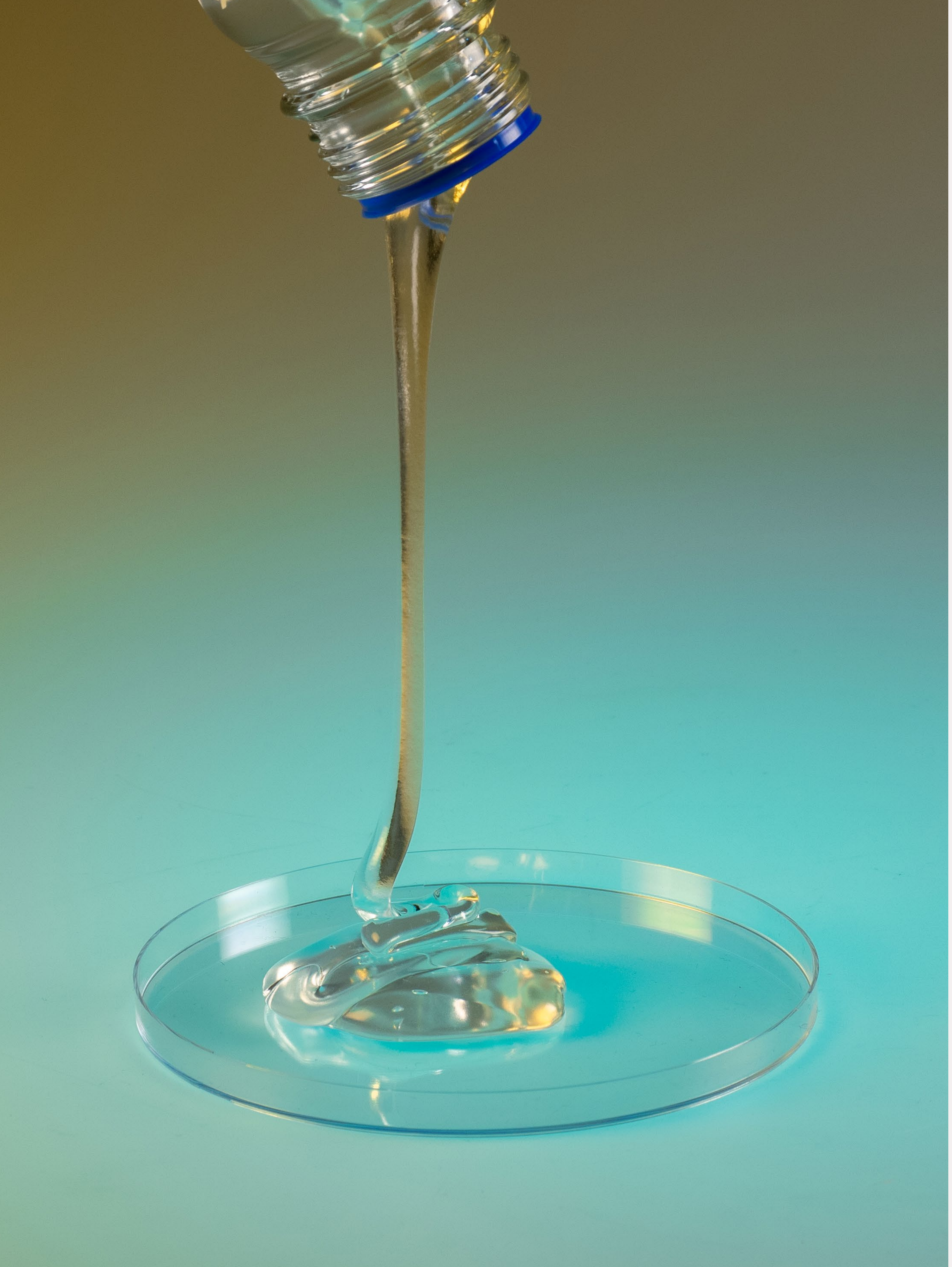


Figure 24 Double diamond framework and methods

The Deliver phase will correspond to the thesis writing and discussion.

04

Process



4.1 Phase 1_Discover

The design process started by the first stage of the double diamond framework called "Discovery". The aim was to understand the work context, get to know the team's expectations, and discover the material itself both from literature and a hands-on perspective. According to Barati et al. 's mapping tool for designing underdeveloped smart material composites (Barati et al., 2015), this stage corresponds to the initial "Property level", which answers the question "what a material or future product and their properties are" (p. 121). Since the BIOPTICS project was on a fundamental science level, the main challenge of this stage was to work with an under-developed cellulose-based optical fiber. Besides the optimization, there were only a few very small samples available for me to try, and they were still quite fragile. For the hands-on textile prototyping then, I focused on materials with similar characteristics like POF and other formats of functionalized cellulose, such as MC or CMC gels, that I could manipulate through different fabrication methods.

The insights of this stage helped to answer the first research question:

Can we integrate functionalized cellulose into textile structures for the creation of a bio smart-textile based on light transmission?

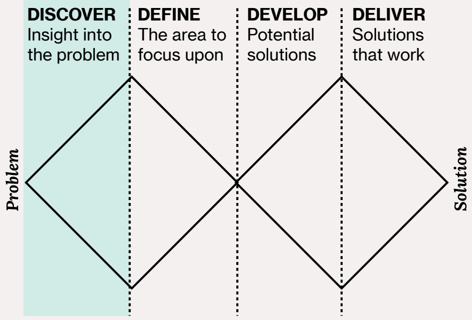


Figure 25 Discover phase

Brainstorming session

My participation in the project started by reading about optical fibers and joining the team in meetings, where they explained their progress so far in the material development. Nevertheless, these very technical insights were not enough for me to understand the full scope of the project. To start working on a proposal on how to integrate the material into textiles and on which of its properties to put the focus, I lead an ideation session to create a conversation about "dreams of future materials and scenarios of future applications" (Niinimäki, 2019, p. 1780), including material properties, users, interactions, formats of the material and different contexts. To guide it but keep it open enough, I created ideation cards based on the literature and their previous insights. I used 6 categories with different options each. Every participant (5), took one random card from each category and had to come up with a narrative using the concepts. The session was structured so that everyone had 20 minutes to work individually and then share their ideas, ending with an open conversation about the topics that arose. To complement, I included inspirational images (without descriptions) and some materials to bring some physical ideas. For documentation, the session was recorded and later transcribed, to then debrief the contents and propose some paths to continue working.

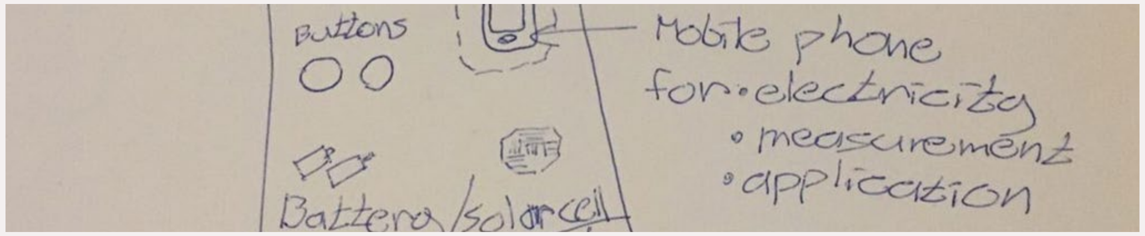


Figure 25 Brainstorming session drawing

Scale of Textiles	Place	Interaction	Characteristic	Output	Sensing
Small Medium Large	Inside the body Outside the body Object Outside space Inside space	Data collection Touch Play Inform	Flexible Biocompatible Translucent Luminescence Biodegradable	Light Movement Shape changing Degrade	Humidity Pressure PH Oxygen Temperature

Figure 26 Ideation cards cathegories

Participants
Ville Hynninen
Olli Ikkala
Nonappa Nonappa
Ari Hokkanen
Aayush Jaiswal

Moderator
Sofia Guridi

Example of response

Ville Hynninen
Luminescent / Outside of body / Sensing pressure / Degrading / React light

"Sleeve with an integrated pressure sensor, which can guide a person to do a correct movement for example in physical rehabilitation. It could change color to show to the person if the movement is right or wrong (visual feedback). For the biodegradable part, it would be that it is not generating microplastics."

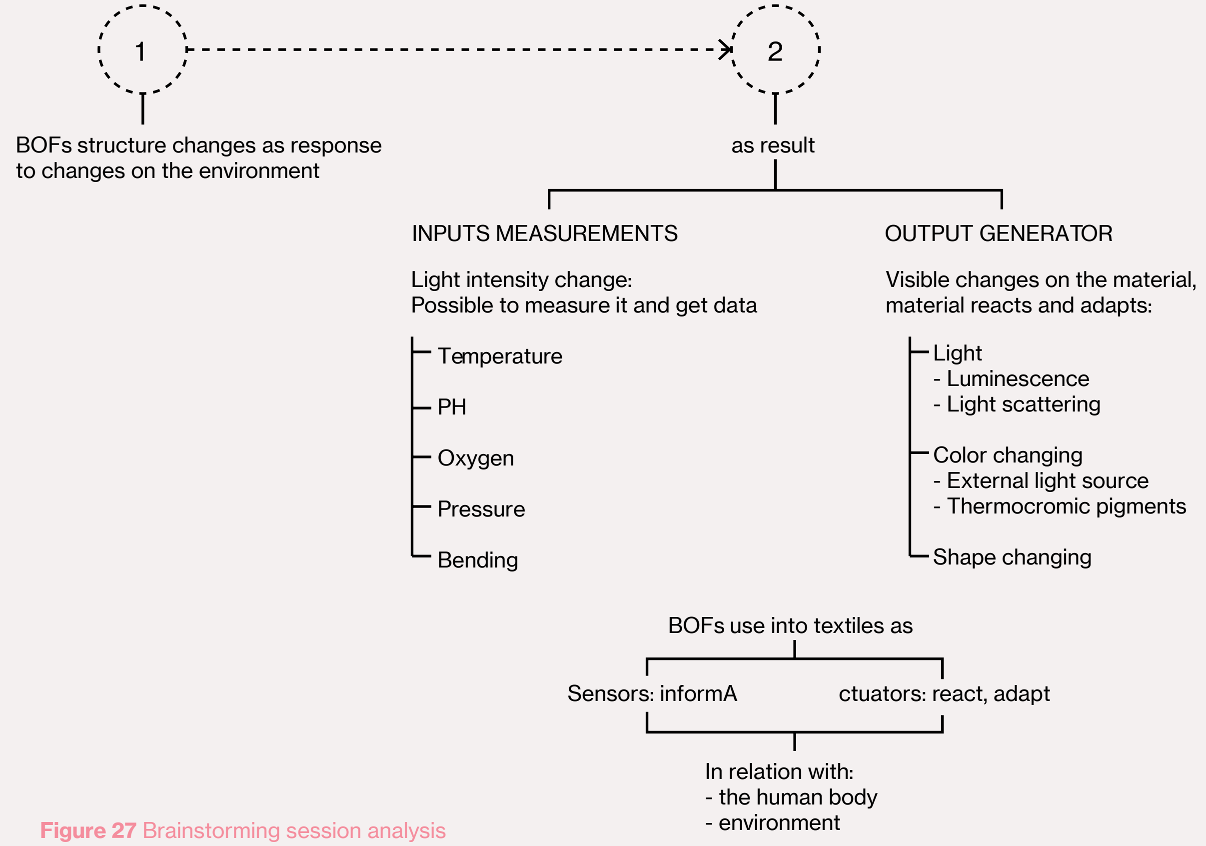


Figure 27 Brainstorming session analysis

The brainstorming session was successful, firstly because it went back to different ideas that came during the meetings, but in a more concrete manner, helping to put concepts together and develop ideas on top of them. For example, understanding under which physical phenomena a BOF could be used for sensing bending movements. Secondly, from my perspective as a designer, this experience was very beneficial to better grasp the technical concepts and be able to ask about topics I didn't fully understand. For example, once Ville mentioned that the fiber could change color based on movement, the concept of mechanoluminescence came out for the first time and I could understand it better. The exercise even inspired them to brainstorm new technical solutions to, for example, create a shape-changing optical fiber.

Considering that one of the main challenges of interdisciplinary collaboration is the use of a common language (Langella 2021), the experience proved to be valuable to bring our different knowledge closer, and create a fluid conversation despite me not managing all the scientific concepts so confidently.
Even though the exercise inspired the team members to create narratives related to the material, this was intended with the purpose of verbalizing the potential of it but not to define a context of use yet. Having context-related fixation in this early stage of the design process would have narrowed down the possibilities, limiting the emergence of more innovative ideas regarding the material development.
The debriefing then was focused on the properties of the material itself and posible textile functionalities that could be explored like sensing or actuating, which helped to define the variables to consider for the following prototyping stage.

Hands-on prototyping

Coming from a design background and considering the practice-based approach, prototypes during the research process were viewed not only in “their role in evaluation but also in their generative role” (Lim et al. 2008, p.1) enabling reflection on the design activities when exploring the design space. They worked as sketches throughout the whole process, helping to communicate, frame, refine, and discover possibilities.

The initial prototypes were low-fidelity ones, focused primarily on “design exploration and communication and less on formal design evaluation” (Lim et al. 2008, p.6) and did not follow strict guidelines. The aim was to connect technical, tacit and haptic knowledge with the use of the cellulose material to give space for unexpected results. As mentioned previously, because the cellulose-based optical fibers were not fully ready and just fragile small samples were available (around 5 cm) , I focused on similar characteristics materials like POF and other formats of functionalized cellulose proven to transmit light, such as MC or CMC gels, that I could manipulate through different fabrication methods.

At the end of each experimentation, laboratory tests and observations were made to answer one main question “Does the integration method allow the cellulose material to keep its light transmission properties when added to a textile structure? “, meaning, if there was an optical waveguide or not integrated into the textile.

The chosen materials and methods for integration to explore were based on the brainstorming results, literature, and embodied knowledge gained through my previous experience as a smart textile designer and practitioner.

Cellulose Materials	Integration Methods
MC Optical Fibers CMC Optical Fibers CMC Gel CMC + Glycerol films	Weaving Knitting 3D Printing

Figure 28 Guidelines prototyping Phase 1

Optical waveguide
Physical structure that guides electromagnetic waves in the optical spectrum. Optical waveguides can be classified according to their geometry: planar, strip, or fiber waveguides (Tong 2014).

Figure 29 Bio-based optical fibers

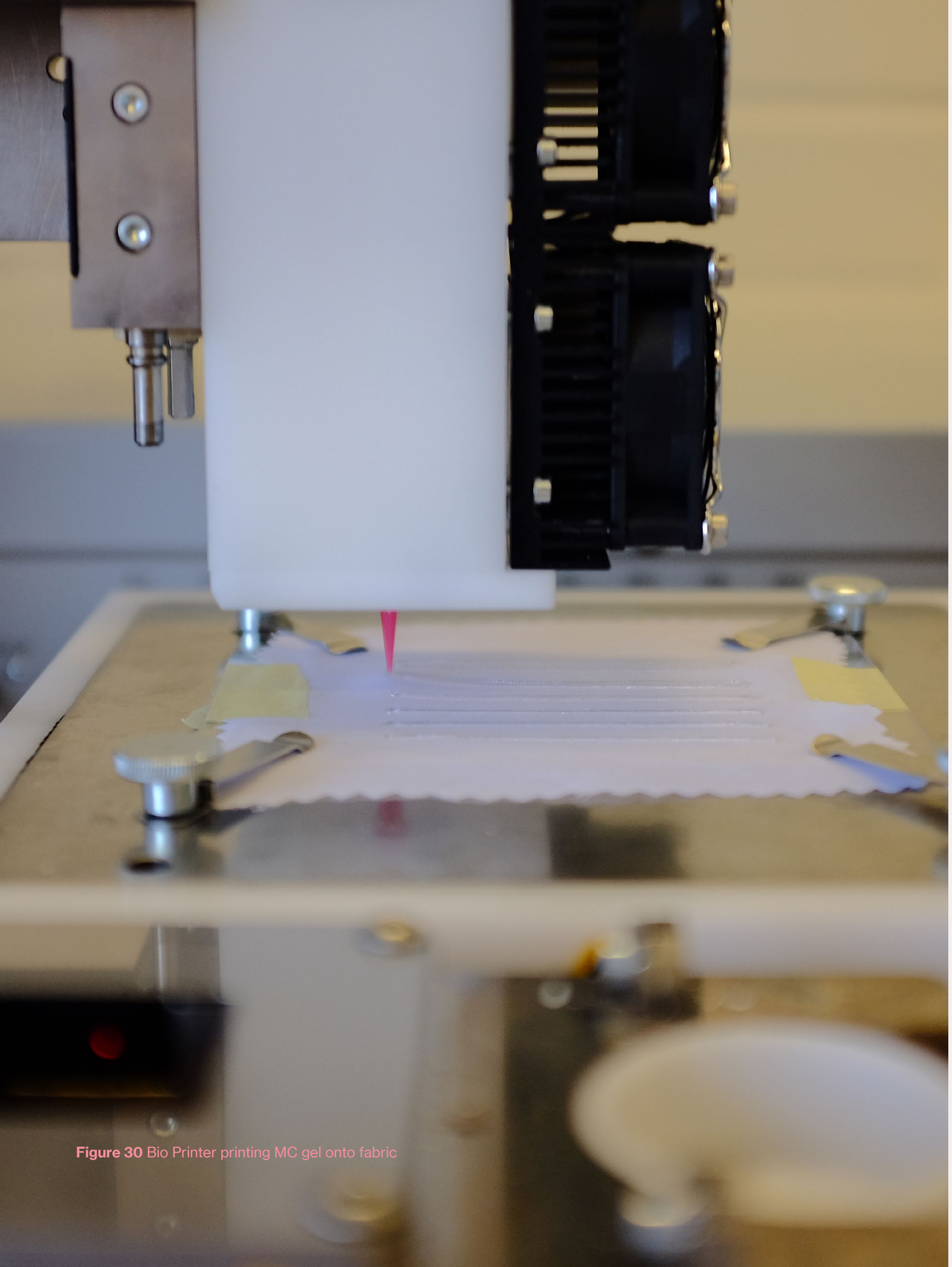


Figure 30 Bio Printer printing MC gel onto fabric

The three methods of integrations used were the following:

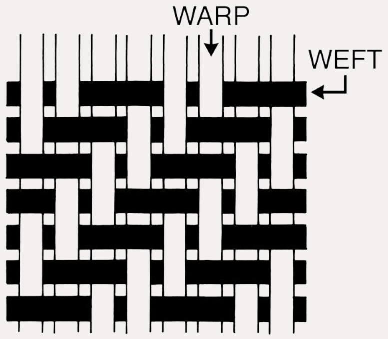


Figure 31 Woven structure

Weaving
As a textile fabrication process, weaving is based on passing two or more sets of yarns, strands, or strips of material over and under one another (Thompson et al. 2014). The fabrics then are composed of warp yarns running lengthwise and weft yarns running widthwise. The three principal weave structures are plain, twill and satin. Woven fabrics are usually more rigid than knits but can include elastomeric yarns to make them stretchy.

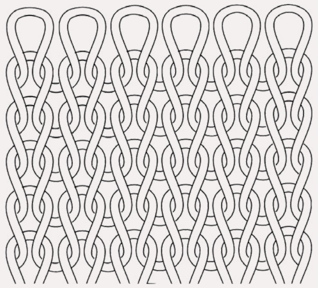


Figure 32 Knitted structure

Knitting
Knitting is a versatile textile construction method based on interloping continuous lengths of yarns. The loop structure that is created, allows yarns to move freely, even under tension, resulting in stretchy fabrics (Thompson et al. 2014).

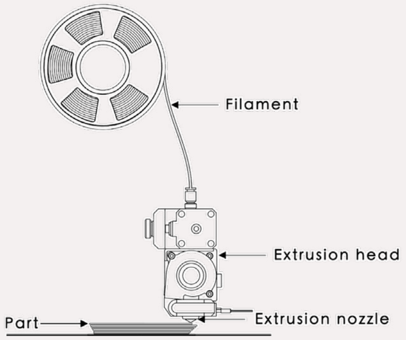


Figure 33 3D printing (Hsiang Loh et al., 2020)

3D Printing
3D printing is an additive manufacturing method used to create three-dimensional volumes. A computer-operated nozzle extrudes material that is stacked on layers to create specific volumetric shapes (Shahrubudin 2019).

Photonics lab testings

With the samples ready, Ari Hakkonen at VTT was in charge of setting the photonics instruments for measurements and making sense of the data collected. My participation during these sessions was relevant to discuss results and ideated while we worked doing the measurements.

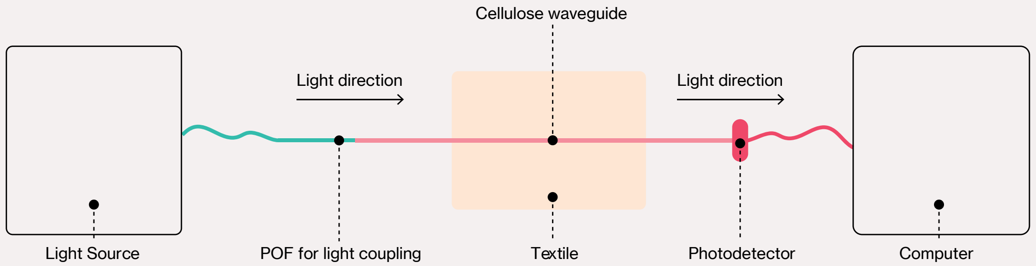


Figure 34 Photonics laboratory setup for sample's testing

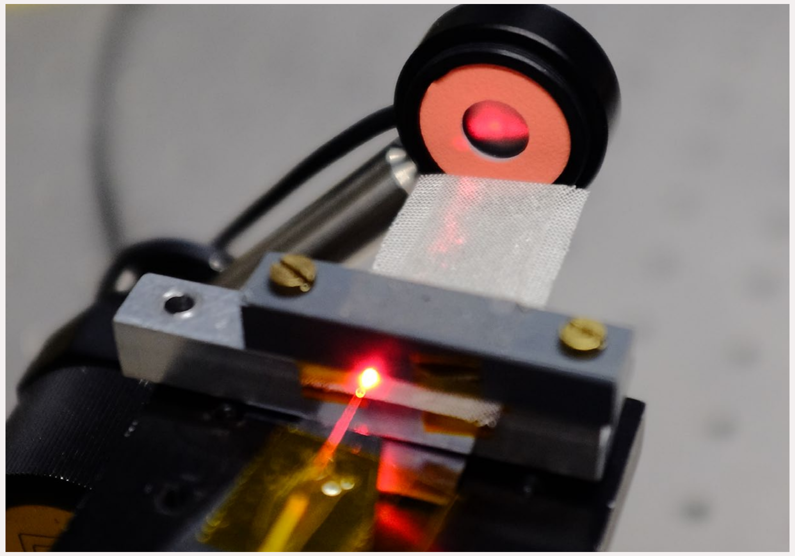


Figure 35 Laser, cellulose waveguide and photodetector

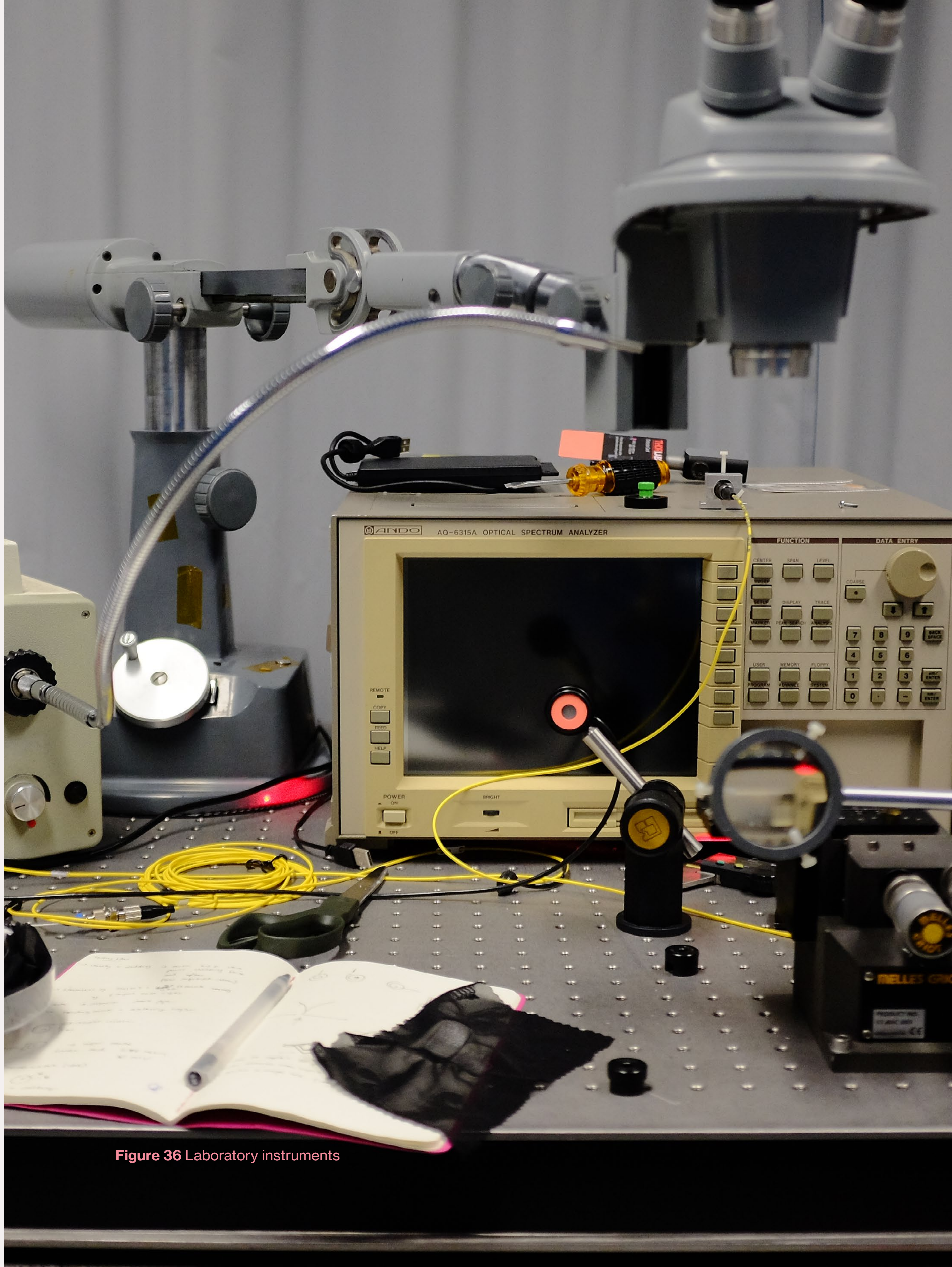


Figure 36 Laboratory instruments

The following results are the ones where an optical waveguide was obtained, even to a lower degree.

1.

Method of integration	Weaving / CAD loom and TC2 XS hand-operated Jacquard loom
Light Transmission material	POF 0,5 mm
Textile materials	Cotton, Polyester, Wool Yarns
Light source for testing	3V LED lights
Comments	For the first experimentations, cotton, wool, and polyester yarns were mixed together with POF to understand how the material behaves in different woven structures, and if it was possible to control the light output using patterns.
Observations	→ Its is ***possible to integrate*** the POF into a woven structure → POF adds ***stiffness*** to the fabric, behaving similarly to nylon monofilaments of the same thickness. → 0,5mm POF is flexible but not enough to have one continuous fiber, when bending the fiber to go for the upper line, too much light scatters the fibers. Each weft POF has to be cut to the width and place individually which makes the process slower. → By using patterns and multilayered structures, it is possible ***to control where the light is showing***. → Light patterns will be determined by the "horizontality/verticality" of the fiber. → Fading light effect can be achieve by using mohair yarns.

Figure 37 Basket weave using POFs, wool and mohair yarns

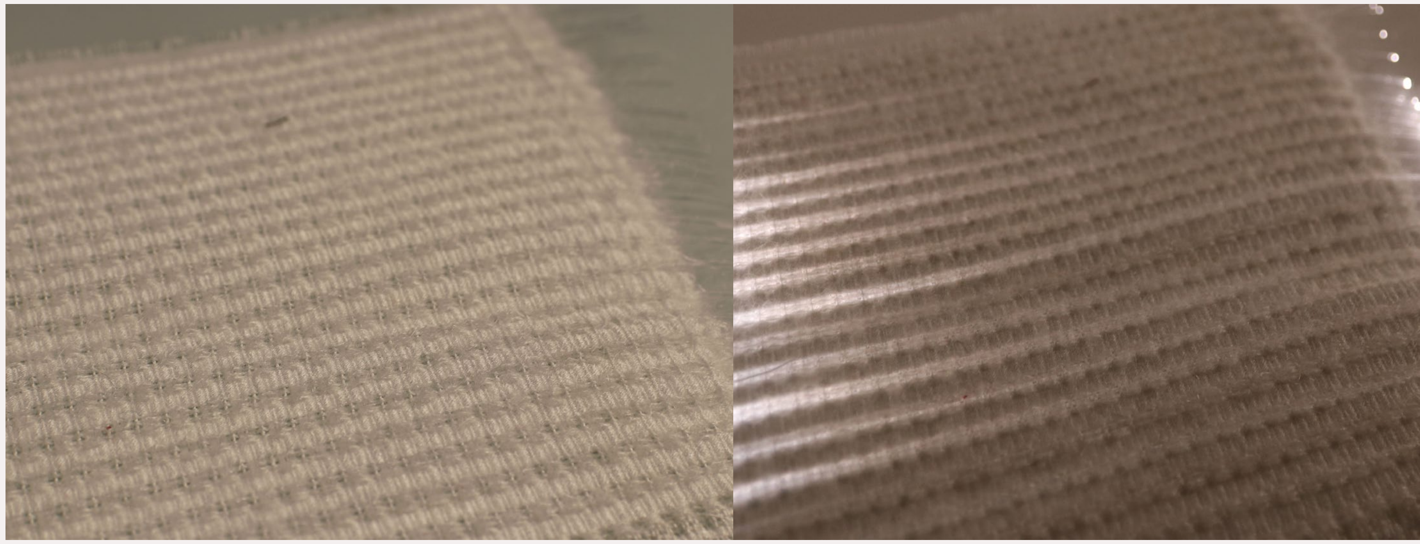


Figure 38 Double weft patterned weave using POFs, cotton and PU yarns

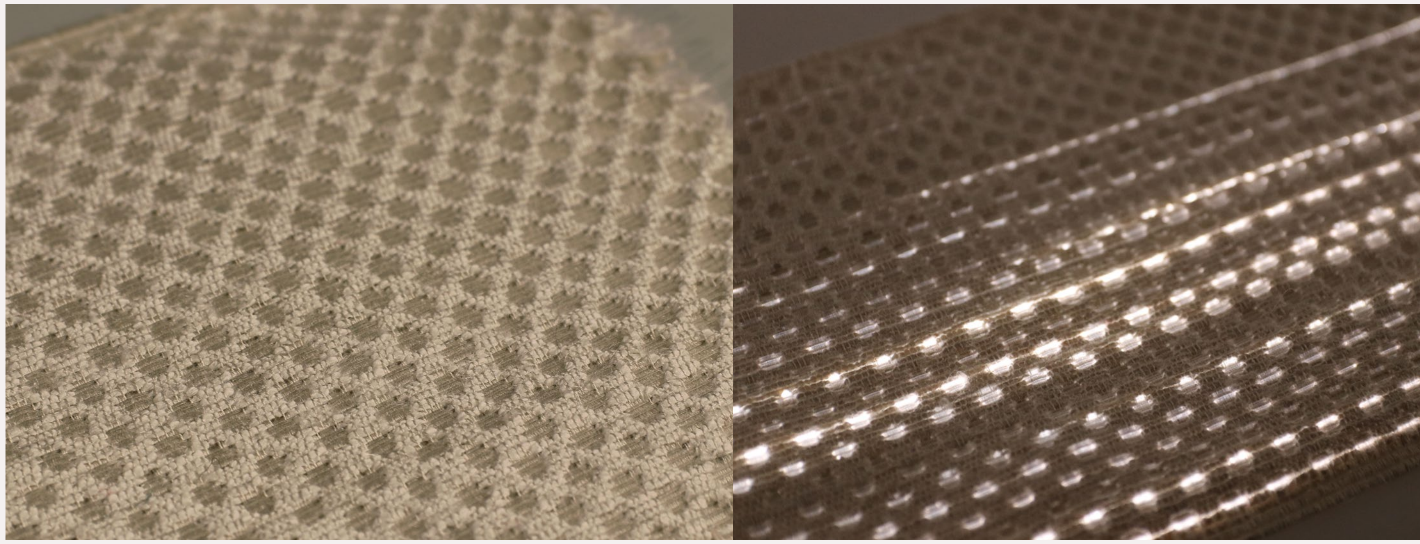


Figure 39 Multilayer patterned weave using POFs and mohair yarns

2.

Method of integration	Weaving / TC2 XS hand-operated Jacquard loom
Light Transmission material	CMC Fiber 320 nm VTT (without cladding)
Textile materials	Cotton
Light source for testing	Red laser 635 nm and Infrared 1050 nm
Comments	Once the BOFs were ready to be manipulated, simple woven samples were made to understand how the material behaved with this integration method. The amount of material available was limited to a small quantity because of the small-scale lab production of it. The used CMC fibers were first tested at the photonics laboratory and proved to have good attenuation values to transport light efficiently at least for 10 cm.
Observations	— The integration of the fibers into the textile structure is ***possible but they are fragile*** and manipulation needs to be very gentle. Too much bending results in the breaking of the fibers. — The used BOF does not have cladding to prevent light scattering in touching points. — It is possible to observe ***deformation of the fibers*** in the crossing points of the warp yarns, which could increase the amount of light scattering from the fiber out.

Figure 40 Simple weave 5end satin using BOF and cotton yarns

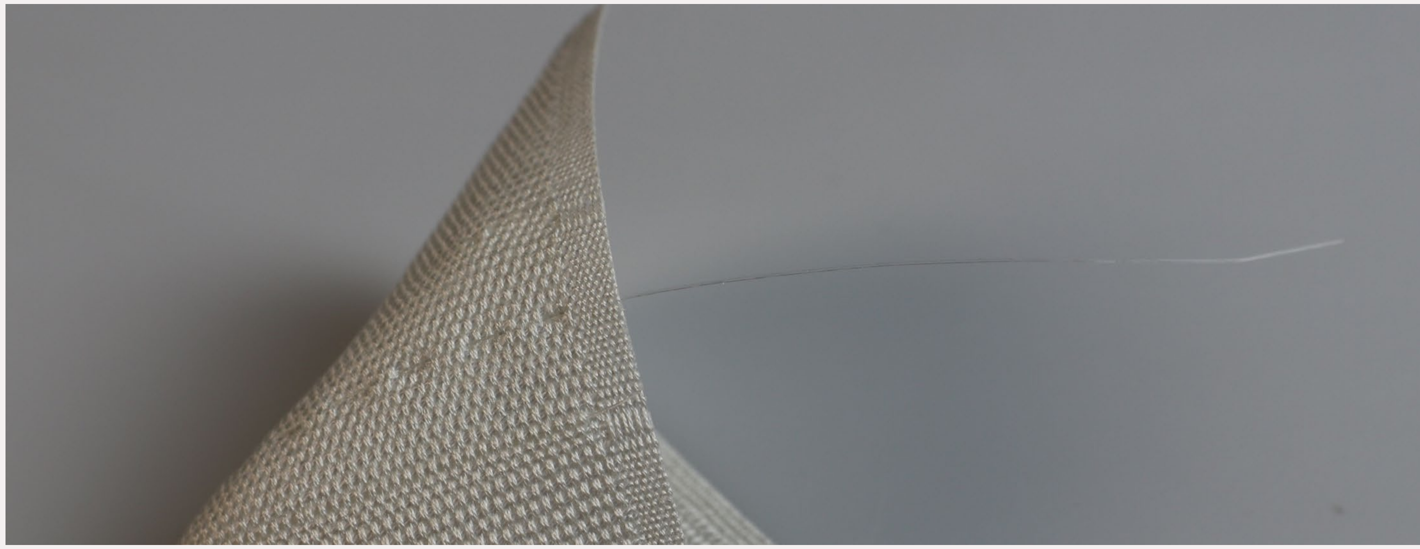


Figure 41 Cotton and BOF sample connected to red laser

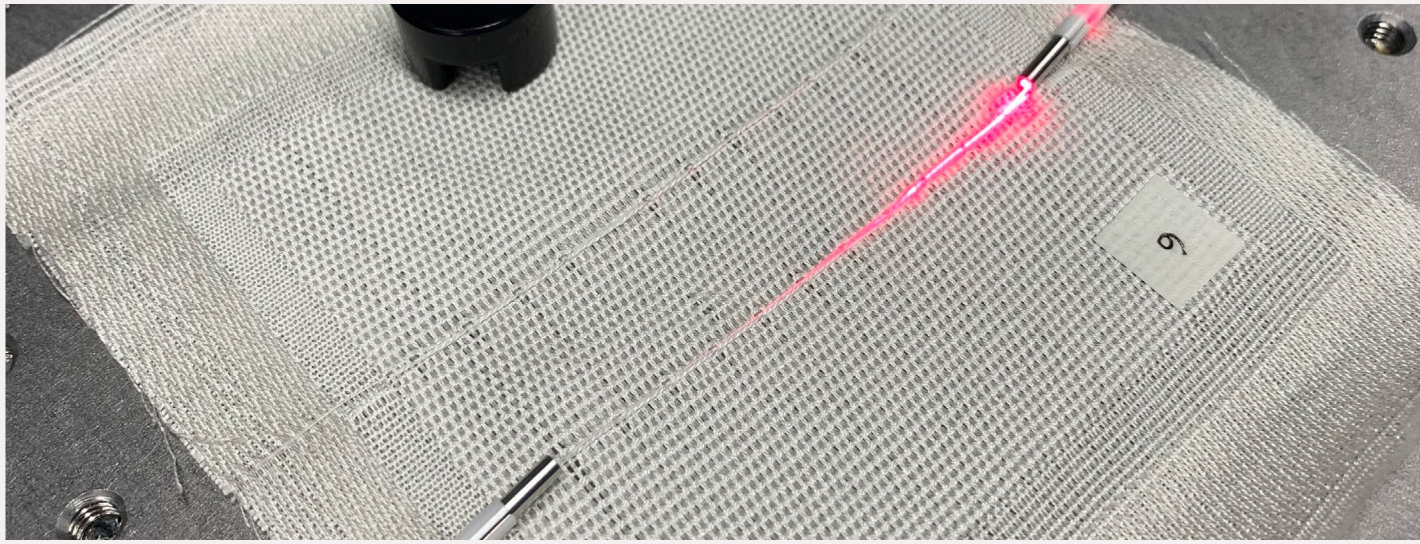


Figure 42 BOF fiber deformed due to warp yarns

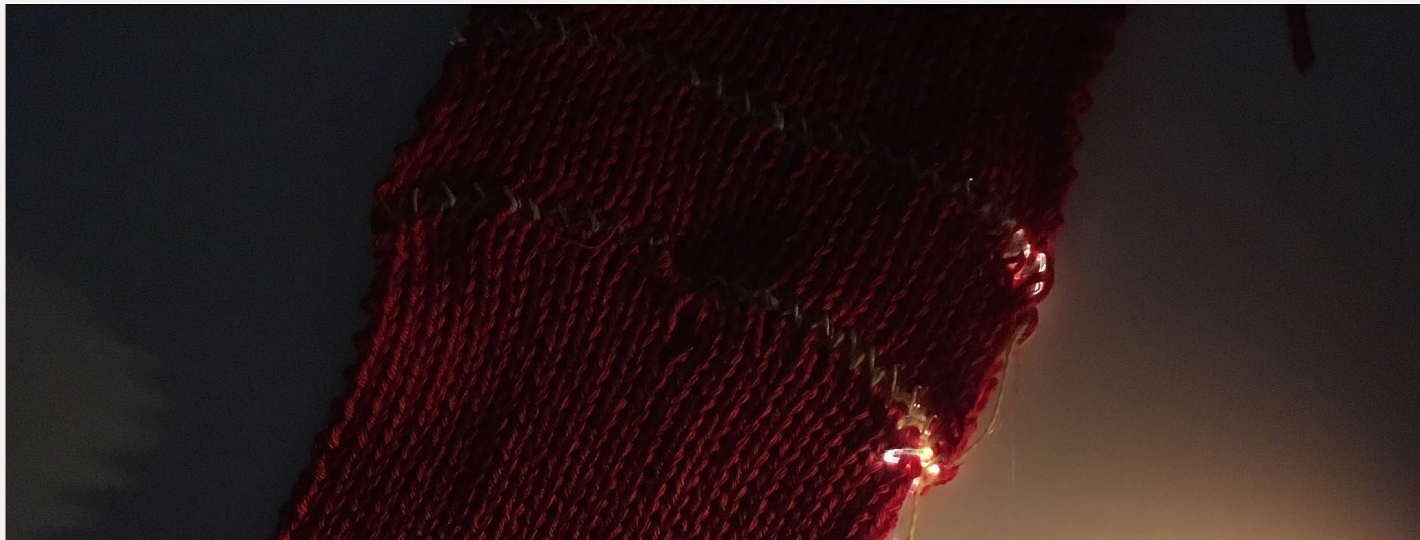
3.

Method of integration	Knitting / Hand-operated 8GG Stoll machine
Light Transmission material	POF 0,25 mm
Textile materials	Wool yarns
Light source for testing	3V LED lights
Observations	— A ***thinner POF*** was chosen to lower the stiffness of the fiber itself but still, the inherent friction of the knitting process was too much and ***it broke*** at some points. — Different knit structures and machine settings were tried, following recommendations from literature, but in all of them, ***the light scattered after a few loops.*** The bending of the POF was too much. — The method seems to work but needs more research and prototyping to find the correct settings and structure for more efficient light transmission through the POF. — BOFs would need to be stronger and longer than the current ones to integrate them into knitting.

Figure 43 Knitted samples using POFs and wool yarns

Figure 44 Floats samples connected to light

Figure 45 Cardigan sample connected to light



4.

Method of integration	3D Printing / Bio Printer VTT
Light Transmission material	MC (50 mg/ml) Gel
Textile materials	Cotton organza, Cotton canvas, Polyester Ripstop
Light source for testing	Red laser 635 nm
Comments	A BioPrinted designed especially for biomaterials was used to 3D print MC gel, which is the same material used by Ville Hynninen (Tampere University) in the development of BOFs. The aim was to see if it was possible to create planar waveguides on top of the fabric and explore the possibilities of the method to reproduce complex shapes. Woven fabrics made out of cotton and polyester were used as a base. This stage was done in collaboration with Marie Gestranius, a researcher at VTT, and intensive work was needed to determine the correct settings (speed, pressure, infills, material, bubble control) for correct printing.
Observations	— It is ***possible to 3D print cellulose on top of fabric***, but since after drying it loses most of its volume, the process is more similar to 2D printing. — Base fabric needs to be able to absorb some of the gel but then more layers are needed so MC is still on top for the light to travel and reach around 100 um. — For maintaining the light attenuation values of the gel, room temperature drying is recommended over the use of an oven. — As the print dries, the fabric tends to contract. The fabric then needs to be held on the edges until fully dried. This process can also be controlled to create 3D volumes. — ***Light coupling is very challenging.*** Some tests were done trying to melt a MC fiber to the MC print but more work is needed to achieve good results. — 6 layers printed onto cotton organza ***did work as planar waveguides***, but just for a short length of 5 cm. The result is promising but more work is needed.

Figure 46 Straight lines onto cotton organza

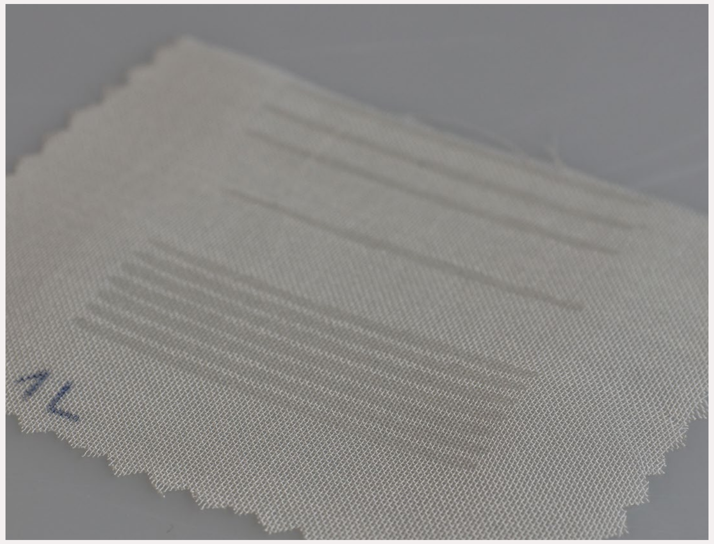


Figure 47 Complex pattern onto cotton organza

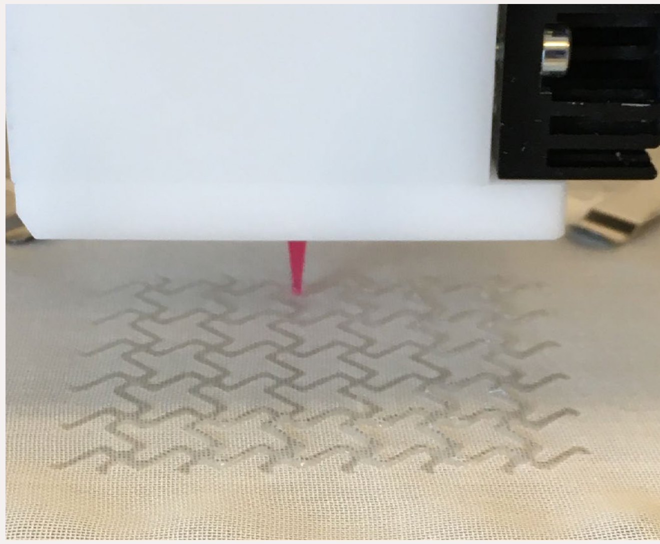
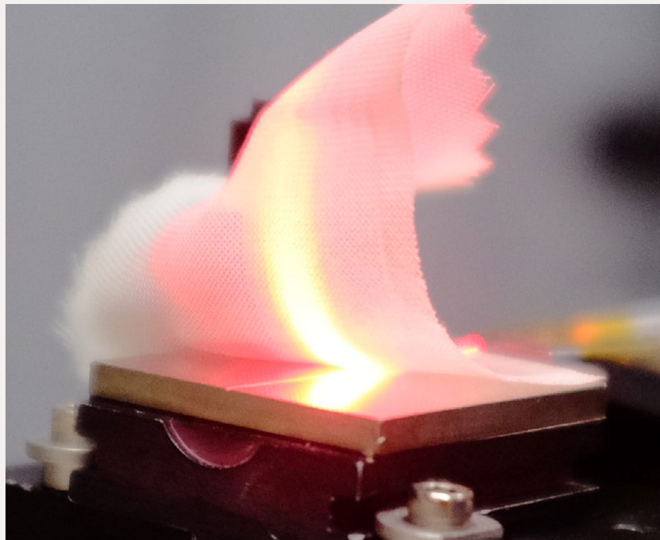


Figure 48 Rectangles onto cotton canvas

Figure 49 Print pealing of from polyester ripstop

Figure 50 Coupling between print and BOF

Figure 51 MC waveguide onto cotton canvas



5.

Method of integration	Weaving / TC2 XS hand-operated Jacquard loom
Light Transmission material	CMC + Glycerol (3%) 130 nm films
Textile materials	Cotton yarns
Light source for testing	Red laser 635 nm
Comments	After reviewing the results of the 3D printing, I thought it would be interesting to keep exploring with planar waveguides. The team had previously measured the attenuation values of MC and CMC films and the results were close to the values of CMC optical fibers. After making some CMC films together with Aayush Jaiswal at VTT, I noticed that they were not flexible enough to be integrated into textiles so we added a plastifier (Glycerol). The final films were flexible, maintained the attenuation values, and could be cut and shaped as desired. Attenuation values: CMC fiber 320 nm no cladding: 1,6 dB/cm CMC + Glycerol film 130 nm cladding no : 1,8 dB/cm
Observations	— Its is ***possible to integrate*** the films into different single layer woven structures. — Due to having a bigger area than the optical fibers, the ***light output area is bigger*** and creates a very interesting visual effects. — The material is ***easy to produce, flexible, and easy to handle.*** — The material ***can be cut in different shapes*** (straight lines, curves)

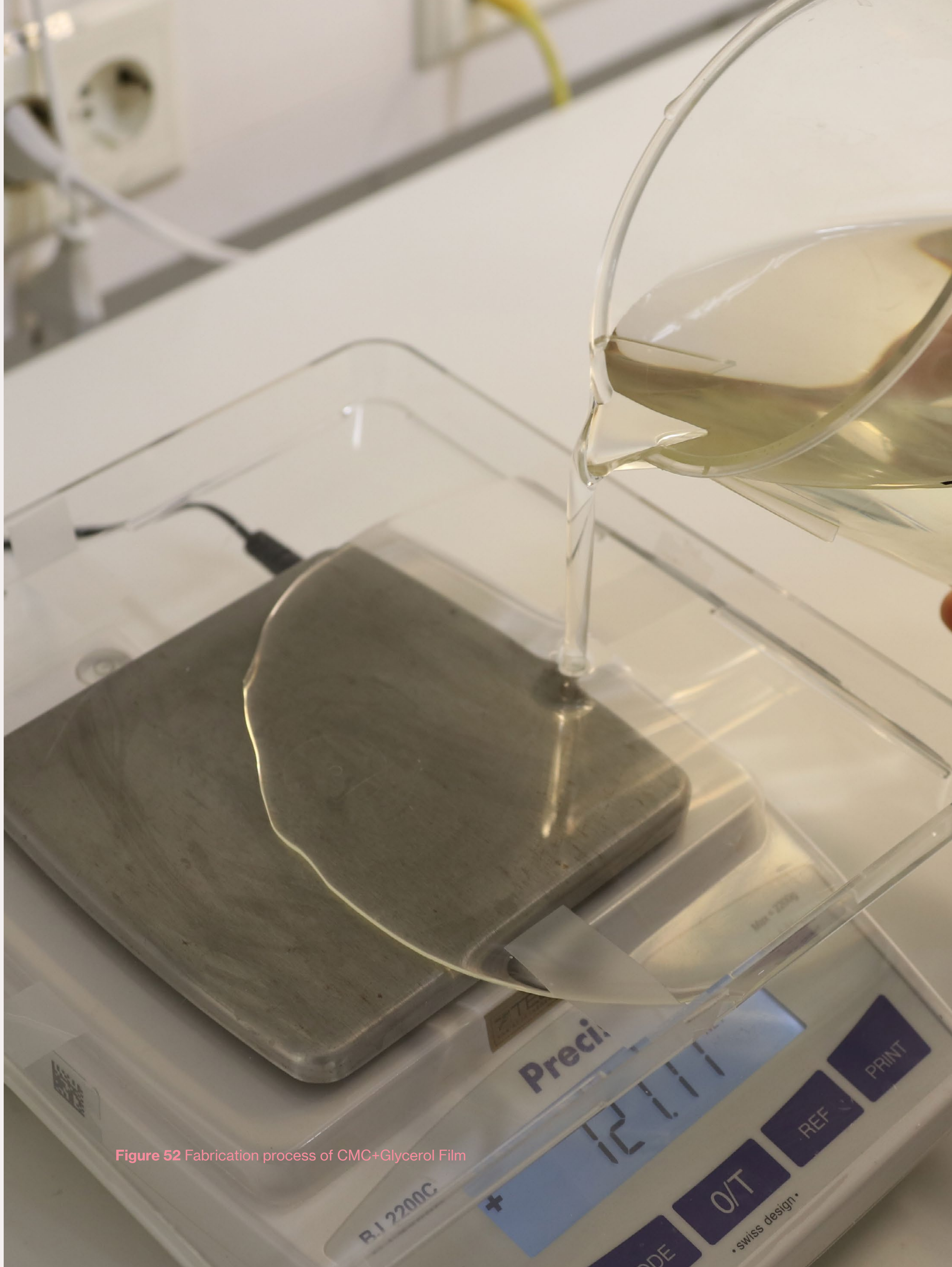


Figure 52 Fabrication process of CMC+Glycerol Film

Figure 53 CMC + Glycerol film

Figure 54 CMC + Glycerol 0,5 cm film woven into 5end satin structure

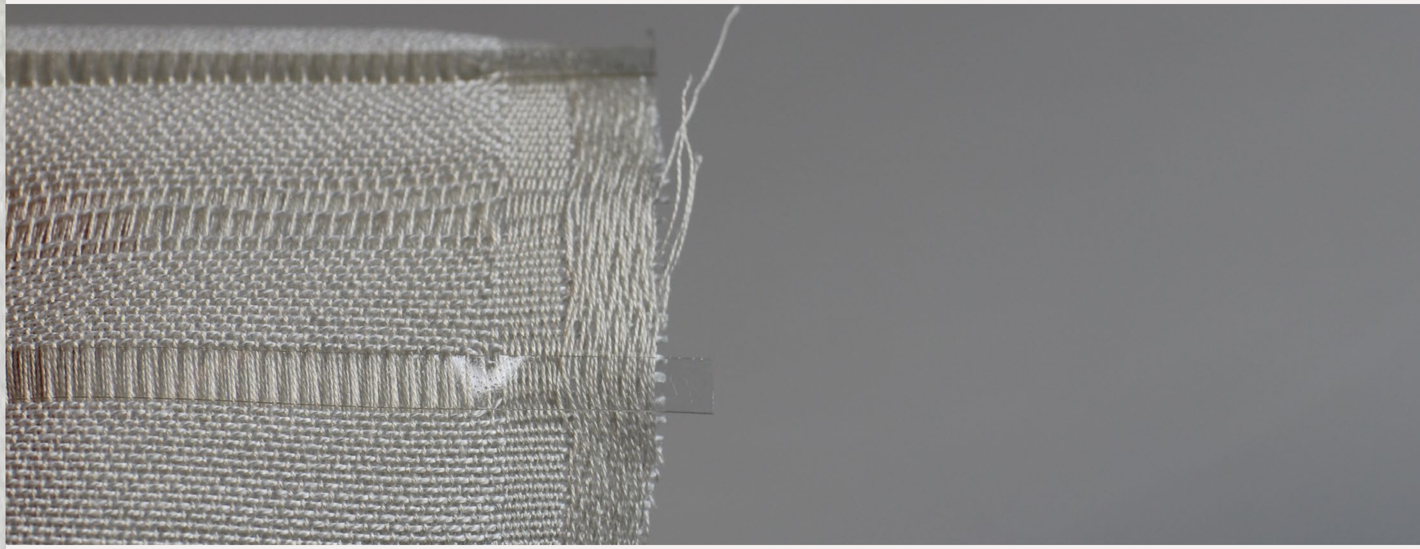


Figure 55 CMC + Glycerol 0,5 cm film woven into 5end satin structure

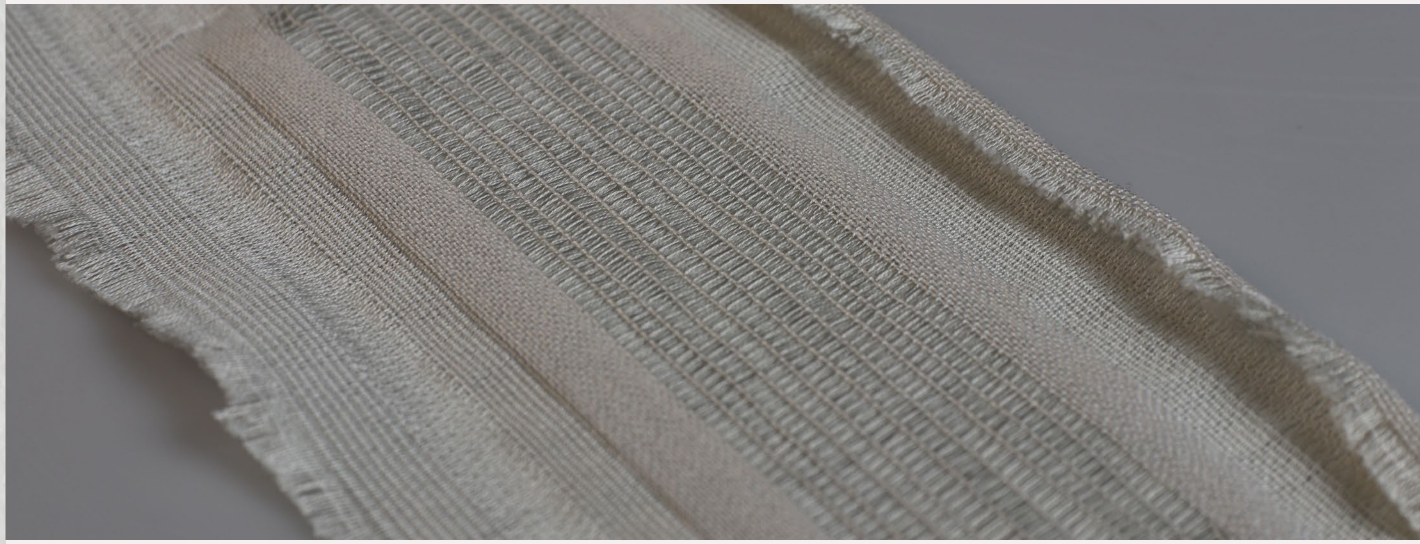
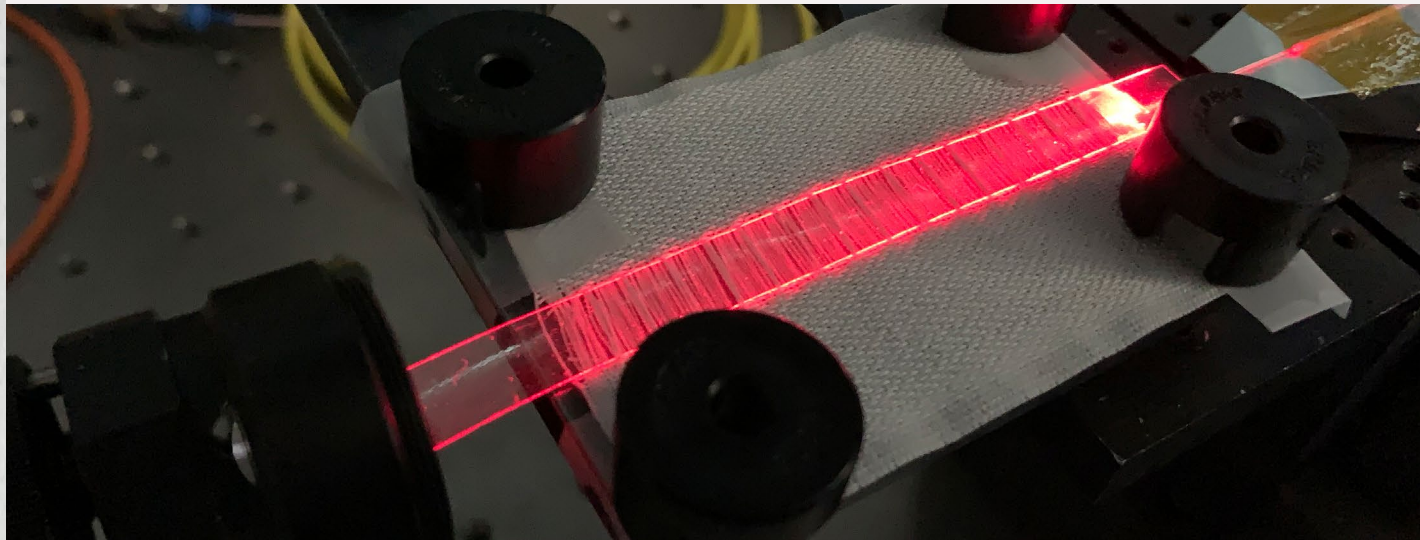


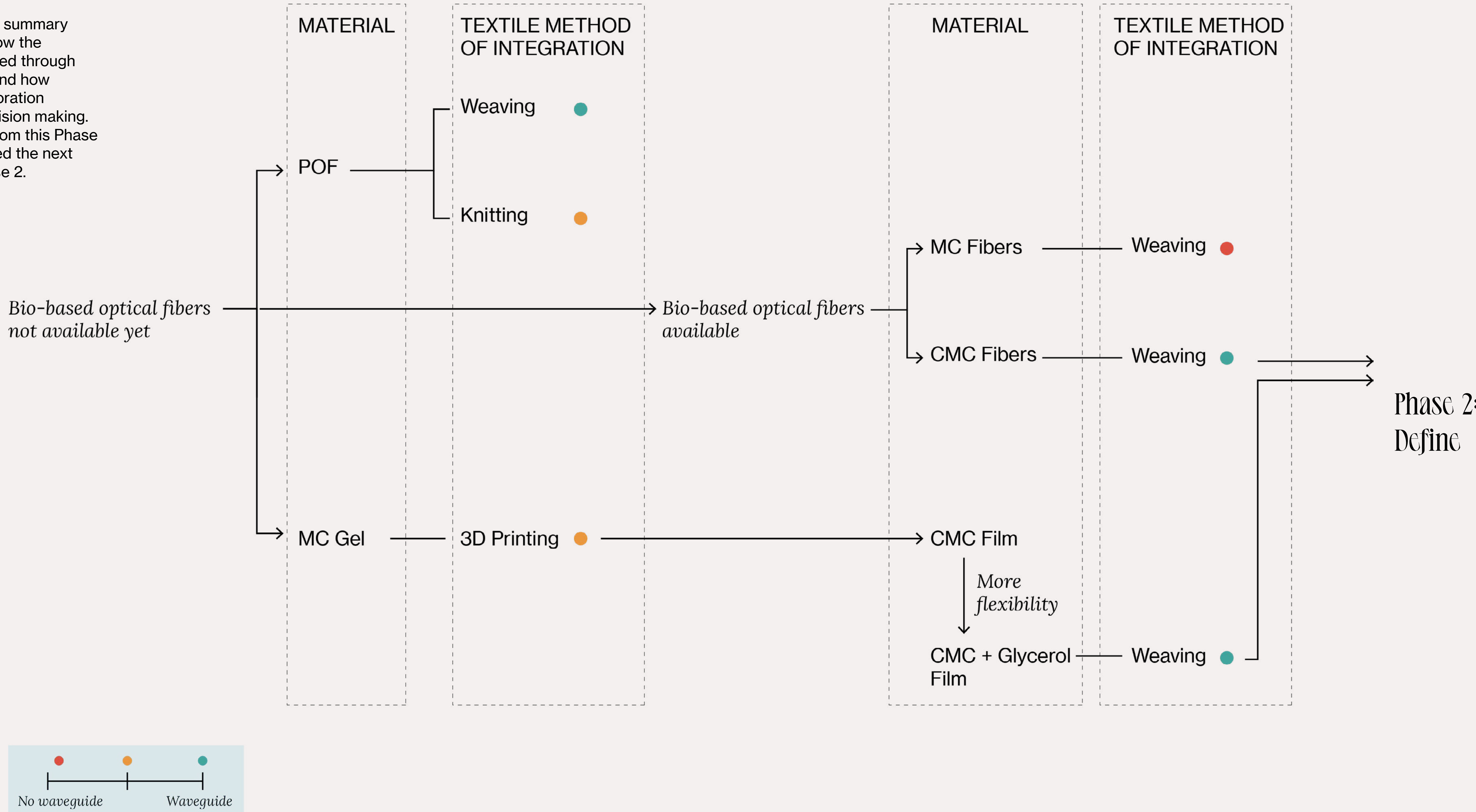
Figure 56 CMC + Glycerol 0,8 cm film woven samples connected red laser



RQ1
"Can we integrate functionalized cellulose into textile structures for the creation of a bio smart-textile based on light transmission? "

Summary
Phase 1: Discover

The following summary represents how the Phase 1 evolved through prototyping and how material exploration informed decision making. The results from this Phase will determined the next "Define" Phase 2.



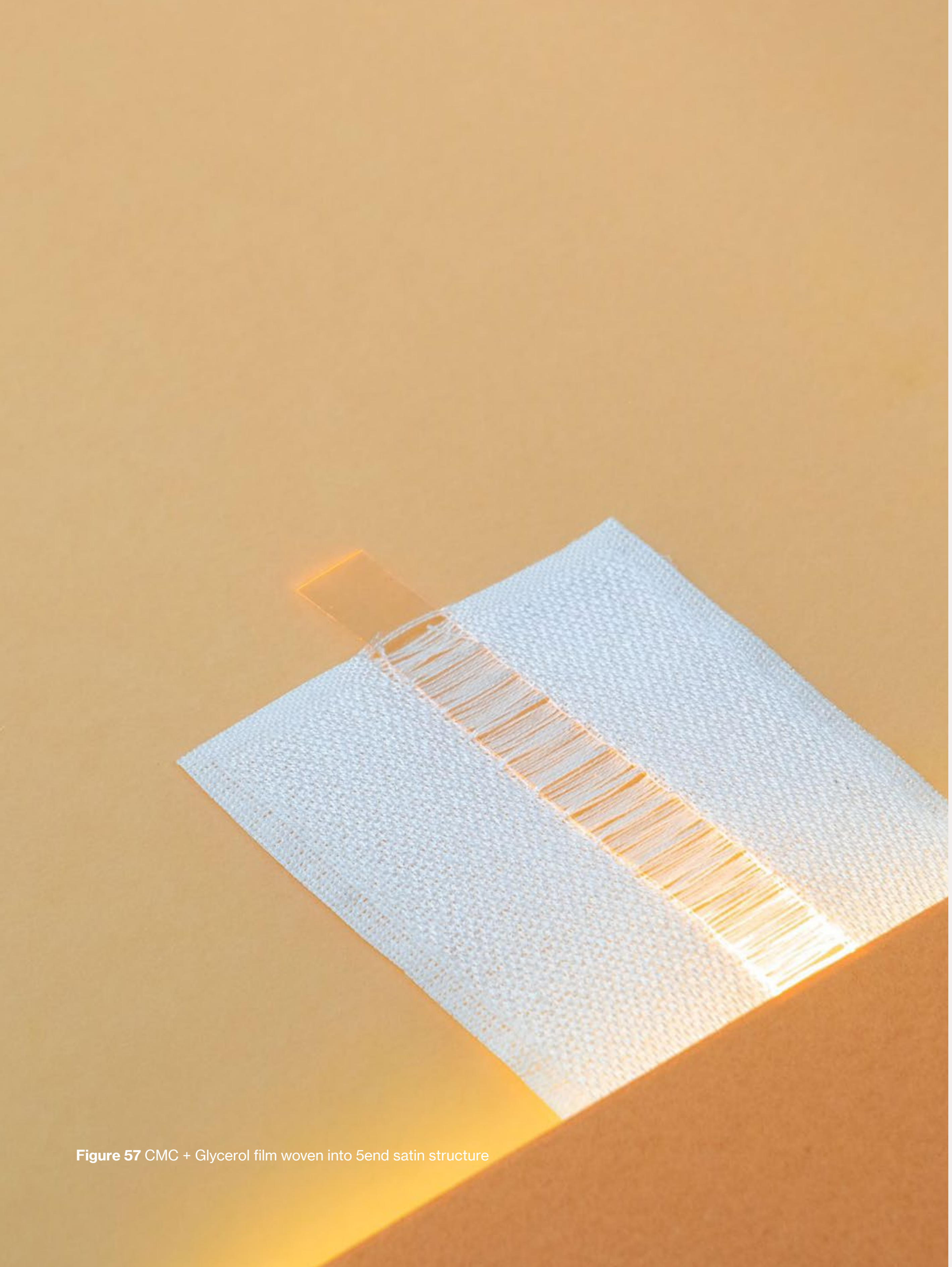


Figure 57 CMC + Glycerol film woven into 5end satin structure

4.2 Phase 2_Define

With the insights gathered from the Discovery Phase 1, I focused on the fabrication methods, materials and variables I would like to keep exploring, reducing the scope of research. Knowing that the CMC can be integrated into textile structures for light transmission, this phase aimed to answer the next research question:

"How does the integration enable sensing and actuation capabilities?"

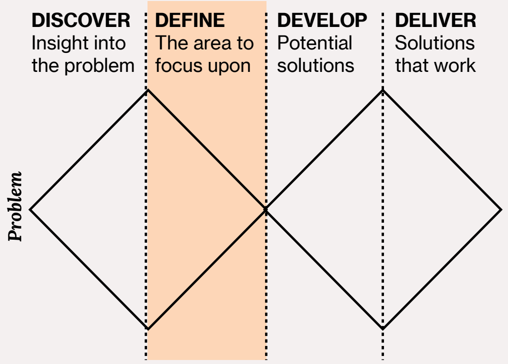
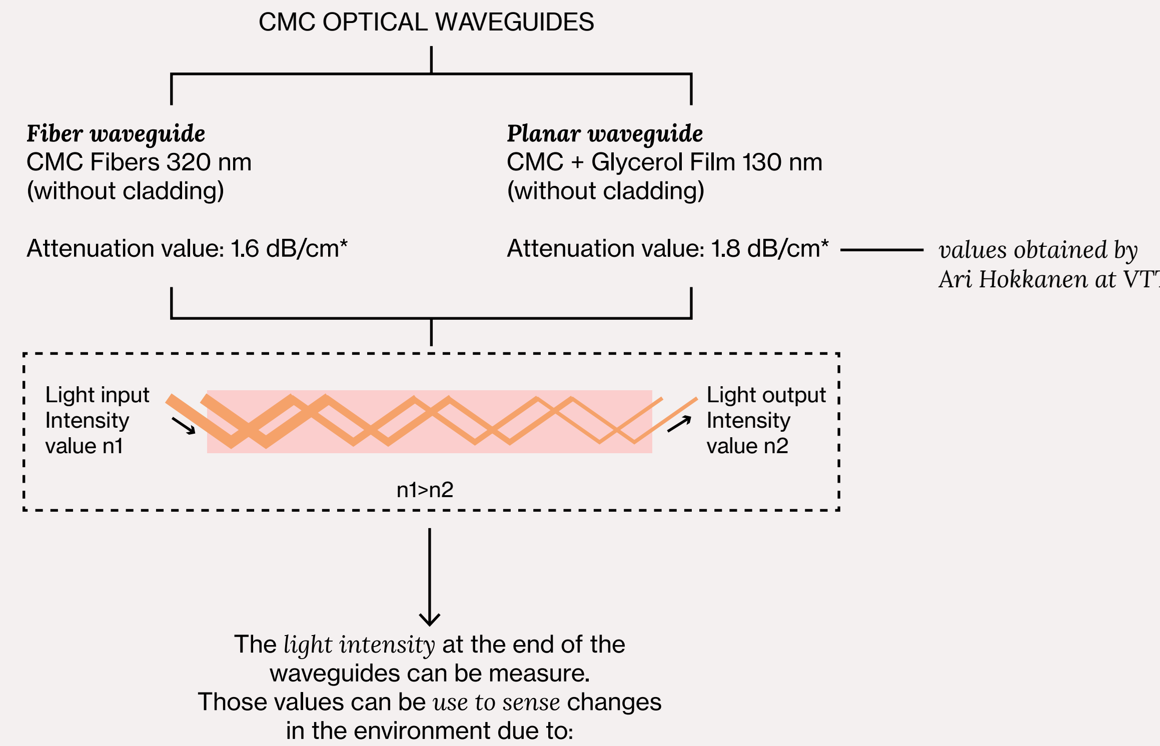


Figure 58 Define phase

Actuation and sensing capabilities

To explore the feasibility of using the cellulose waveguides as actuators and sensors for smart textiles, understanding of its behaviour is needed. As explained in the background chapter, optical fibers (GOFs, POFs or BOFs) transport light and the cladding layer prevents the light to scatter in its longitudinal direction. Due to the initial stage of the BOPTICS research, the available CMC fibers and CMC films dont have yet a cladding layer, which will be included in further work. This means that they can still transport light and work as light actuators, but they are more reactive to external stimuli. Even thought this could present a problem, it can be use in our advantge to measure changes in the environment.

Therefore, the sensing will work based on the amount of light scatering out of the waveguides (fibers and planar). The scatering can be cause by the amount of contact points between the material and external sources such as human skin, yarns or water. It can also be cause by deformation of the waveguides due to bending or swelling. (Figure x) To determine the amount of light scaterring, the light intensity is measured in dBm at the beginning and end of the waveguides.



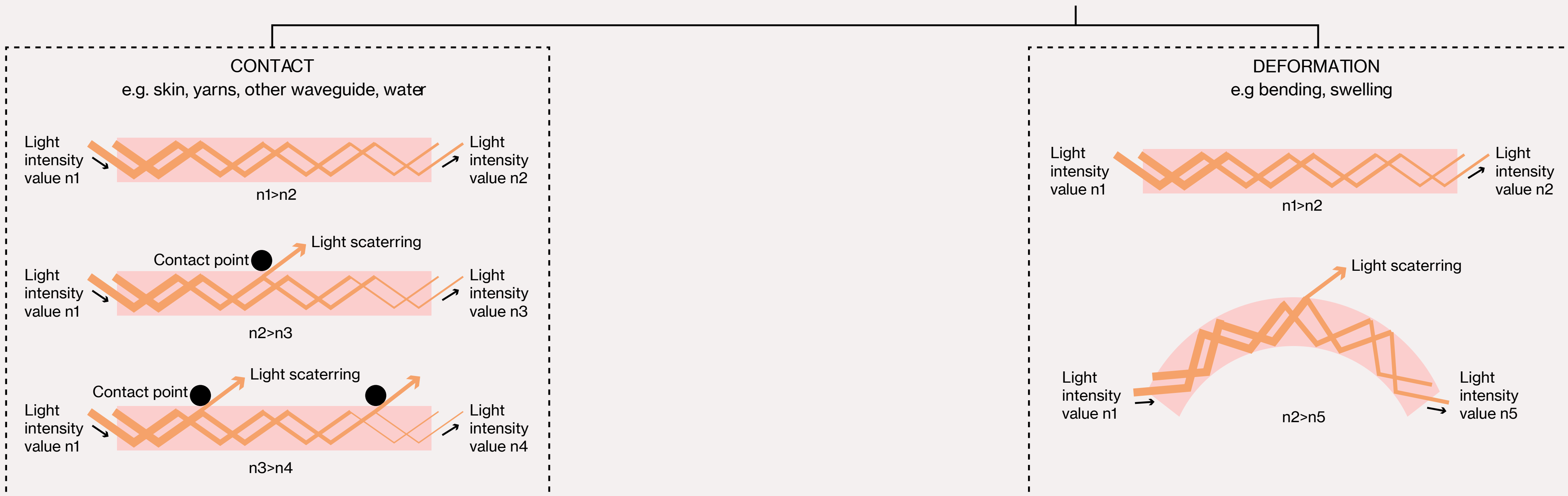


Figure 59 Optical waveguides sensing

Figure 63 Samples phase 2

Optical Waveguides	Integration Methods	Actuation	Sensing
CMC Optical Fibers CMC + Glycerol Films	Weaving	Light	Touch Bending Humidity

Figure 64 Guidelines prototyping Phase 2

Hands-on textile prototyping

Considering the previous insights, the most successful and interesting results were achieved with CMC Fibers and CMC + Glycerol Films, weaving as a method, and light output actuation. These materials and integration methods were chosen to design new samples, to be tested as possible touch, bending, and humidity sensors, which were options discussed during the brainstorming session.
Variables were defined to explore how the integration method could affect the behavior of the cellulose films and fibers. Three different simple woven structures were chosen (plain weave, satin, and 12x2 floats). For the case of humidity sensing, it was also important to compare how the textile yarns affected the sensing, so cotton and polyester yarns were chosen as contrast based on their capacity to absorb and repel water.

The size of the samples was defined by the maximum length of 10 cm for the fibers and films, which was adequate for lab testing with a photodetector. Longer samples would have resulted in too much scattering and not enough light at the end to measure.
All the samples were done in a TC2 XS Jacquard loom with mercerized cotton warp yarns.

Variables

CELLULOSE MATERIAL		CMC Fiber 320 nm				CMC + Glycerol Film 130 nm			
WOVEN STRUCTURE		5x1		12x2		5x1		12x2	
WEFT YARNS		Cotton	Polyester	Cotton	Polyester	Cotton	Polyester	Cotton	Polyester
INITIAL VALUE	Resting State								
SENSING	Touch								
	Bending								
	Water Drop								

Figure 60 Samples variables

Samples sizes

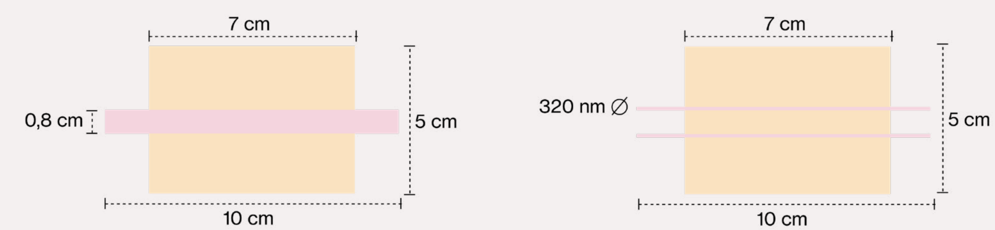


Figure 61 Samples design

Woven structures

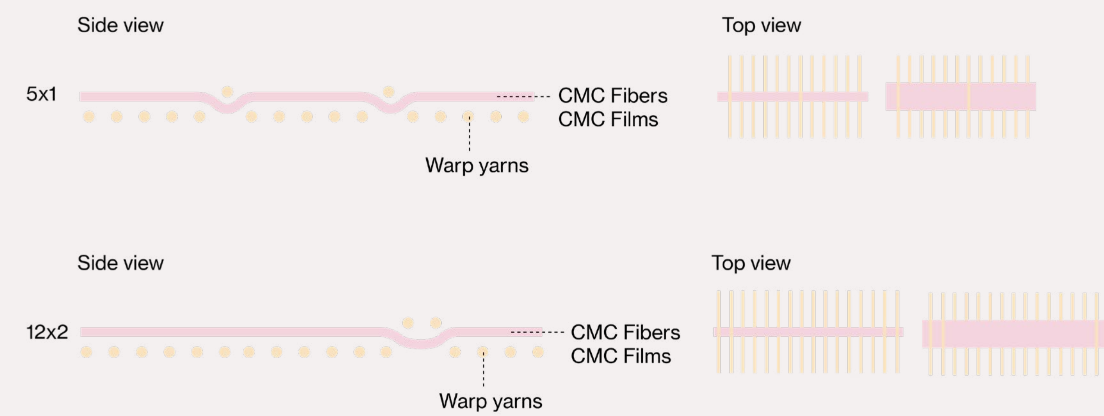


Figure 62 Woven structures

Photonics laboratory tests

With the samples ready, Ari Hakkonen at VTT was in charge of setting the photonics instruments for measurements and making sense of the data collected. My participation during these sessions was relevant to discuss results and ideated while working doing the measurements.

To keep the samples in place and get constant results, magnets were use to maintain the positions and garantee a good light coupling with the laser source.
As light source, a 637 nm red laser was used for the pictures but and infrared light of 1050 nm was use for the measurements since it gaved better readings.

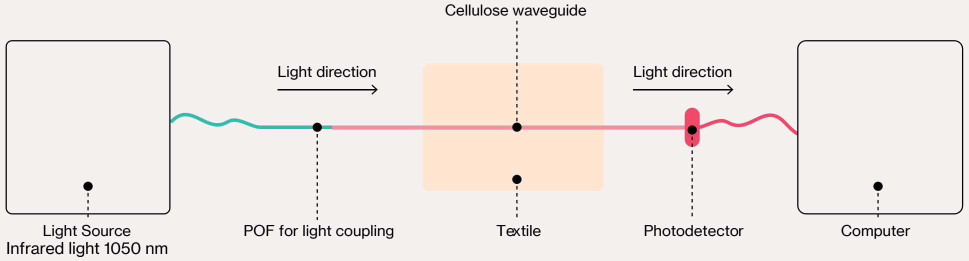


Figure 64 Photonics laboratory setup

Resting state *Touch 250 grs* *Bending 1,5 cm radius* *Water drop*

CMC Fiber

CMC + Glycerol film

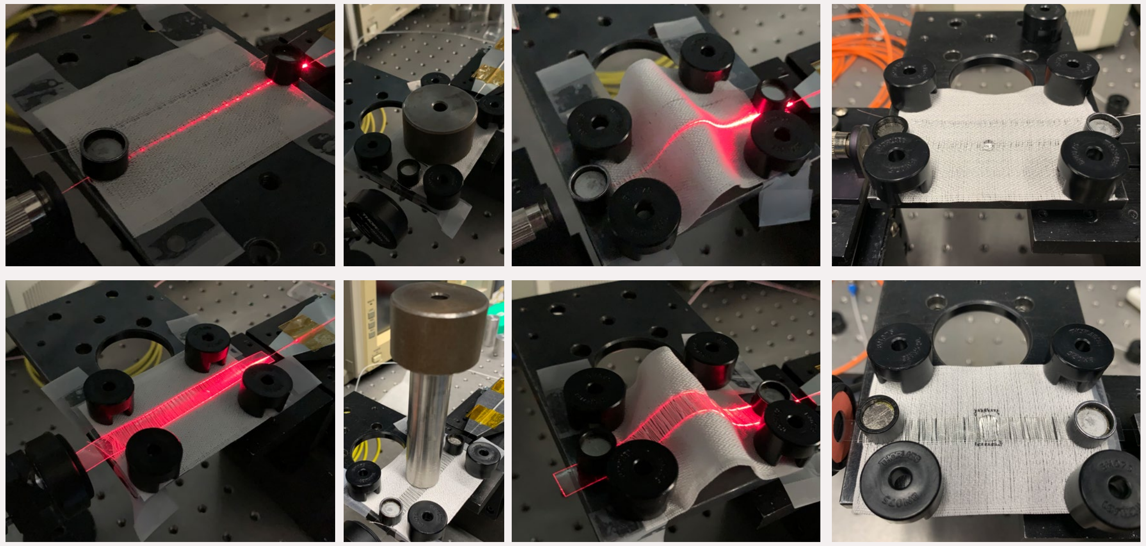


Figure 65 Photonics laboratory setup

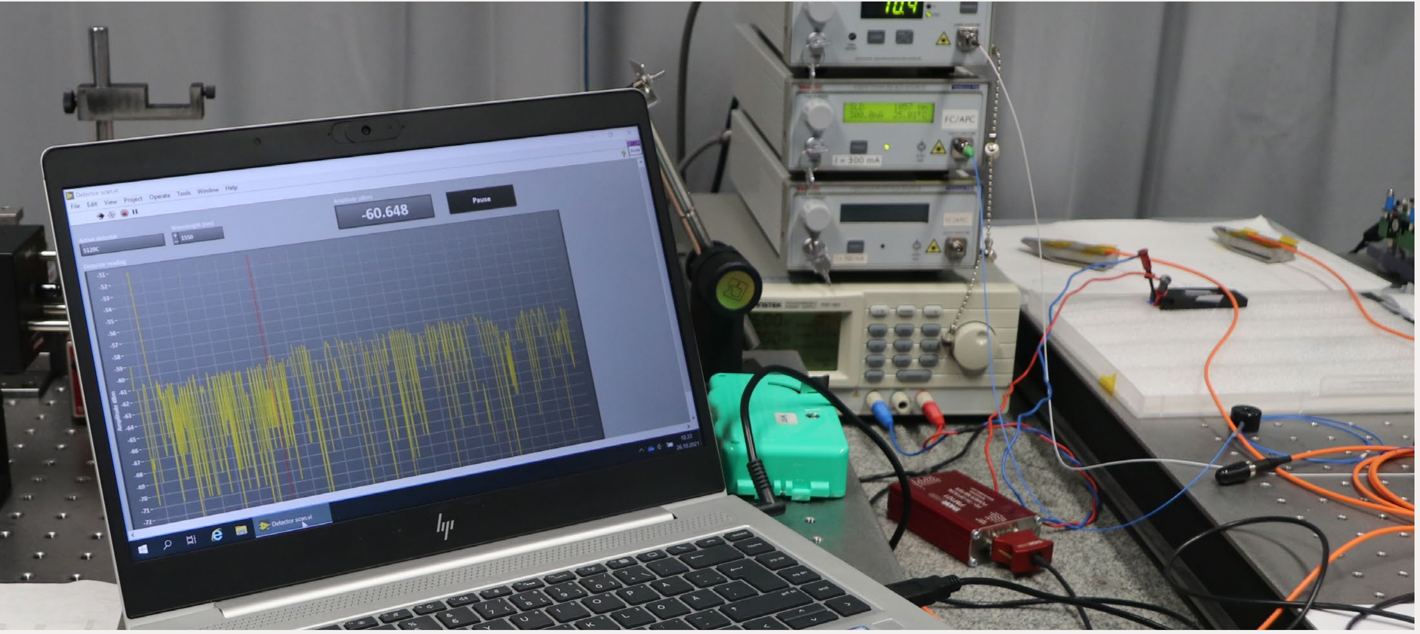


Figure 66 Photonics laboratory instruments

Results

The sensing was tested by compairing the initial value of the light intensity when the samples were in resting state with the values measured after touching, bending or moist the samples. For each case, 6 measurements were done to get average values, and the light coupling was optimized after each time.
In all cases, changes of these values were observed, meaning that the samples can be used as sensors.

For example:
Sample 1
Resting state light intensity: -37 dBm
Touching light intensity: -46 dBm (average)
Touching sensing range: 9 dBm

CELLULOSE MATERIAL		CMC Fiber 320 nm				CMC + Glycerol Film 130 nm			
WOVEN STRUCTURE		5x1		12x2		5x1		12x2	
WEFT YARNS		Cotton	Polyester	Cotton	Polyester	Cotton	Polyester	Cotton	Polyester
INITIAL VALUE	Resting State	-37 dBm		-28 dBm		-8 dBm		-9 dBm	
SENSING	Touch	8 dBm		1 dBm		0,2 dBm		1,7 dBm	
	Bending	7,8 dBm		5 dBm		0,5 dBm		1,5 dBm	
	Water Drop			11,6 dBm	13,4 dBm				15 dBm

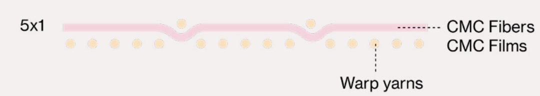
Table 1 Results laboratory tests

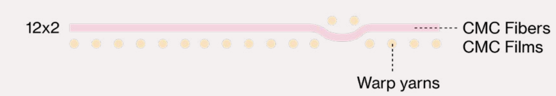
- All samples worked as ***light output actuators***.
- ***Changes in the light intensity values were observed*** in all the samples when applying weight (for touch), curving them (for bending) and adding water (for humidity sensing).
- ***CMC Fibers are more sensitive than CMC + Gly Films***, thus giving a bigger range of values between the resting state and the touch, benging and moist. This could be explain by the fact that light travels on the surface, therefore is more reactive to external stimuli.

CELLULOSE MATERIAL		CMC Fiber 320 nm				CMC + Glycerol Film 130 nm			
WOVEN STRUCTURE		5x1		12x2		5x1		12x2	
WEFT YARNS		Cotton	Polyester	Cotton	Polyester	Cotton	Polyester	Cotton	Polyester
INITIAL VALUE	Resting State	-37 dBm		-28 dBm		-8 dBm		-9 dBm	
SENSING	Touch	8 dBm		1 dBm		0,2 dBm		1,7 dBm	
	Bending	7,8 dBm		5 dBm		0,5 dBm		1,5 dBm	
	Water Drop			11,6 dBm	13,4 dBm				15 dBm

Table 2 Results laboratory tests

- In the same 10 cm lenght, the ***area of the CMC film strips is bigger*** than the CMC fiber (8 cm2 versus 0,0032 cm2). For this reason ***more light can travel*** and the light intensity value is higher.
- ***Woven structure does affects the light intensity***, specially in CMC fibers. In the case of the CMC fibers, the attenuation is higher in the 5x1 structures. In the case of the CMC + glycerol films, the attenuation is higher in the 12x2. This could be explain by the amount of surface contact generated by the warp yarns interlacing.





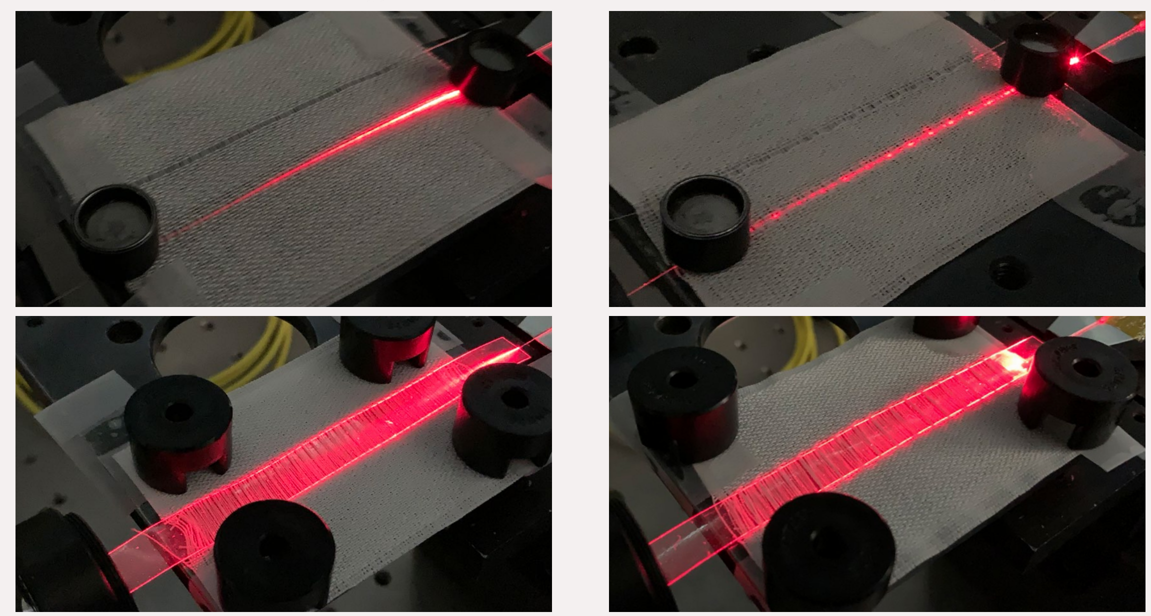


Figure 67 Samples connected to red laser

CELLULOSE MATERIAL		CMC Fiber 320 nm				CMC + Glycerol Film 130 nm			
WOVEN STRUCTURE		5x1		12x2		5x1		12x2	
WEFT YARNS		Cotton	Polyester	Cotton	Polyester	Cotton	Polyester	Cotton	Polyester
INITIAL VALUE	Resting State	-37 dBm		-28 dBm		-8 dBm		-9 dBm	
SENSING	Touch	8 dBm		1 dBm		0,2 dBm		1,7 dBm	
	Bending	7,8 dBm		5 dBm		0,5 dBm		1,5 dBm	
	Water Drop			11,6 dBm	13,4 dBm				15 dBm

Table 3 Results laboratory tests

CMC fibers are more sensitive to touch than CMC films.
In the case of ***fibers***, the ***5x1 woven structure gives a bigger range*** of values between the resting state and touching than the 12x2 structure. For the films, the behaviour is the opposite. This could be explain by the contact surface, the amount of touching points and the amount of light on the surface of the waveguide.

CELLULOSE MATERIAL		CMC Fiber 320 nm				CMC + Glycerol Film 130 nm			
WOVEN STRUCTURE		5x1		12x2		5x1		12x2	
WEFT YARNS		Cotton	Polyester	Cotton	Polyester	Cotton	Polyester	Cotton	Polyester
INITIAL VALUE	Resting State	-37 dBm		-28 dBm		-8 dBm		-9 dBm	
SENSING	Touch	8 dBm		1 dBm		0,2 dBm		1,7 dBm	
	Bending	7,8 dBm		5 dBm		0,5 dBm		1,5 dBm	
	Water Drop			11,6 dBm	13,4 dBm				15 dBm

Table 4 Results laboratory tests

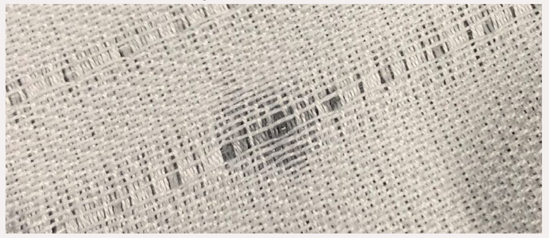
Samples work as bending sensors, but not perceivable change was noted when changing the curve radius. More exaggerated curves could be explore.

CELLULOSE MATERIAL		CMC Fiber 320 nm				CMC + Glycerol Film 130 nm			
WOVEN STRUCTURE		5x1		12x2		5x1		12x2	
WEFT YARNS		Cotton	Polyester	Cotton	Polyester	Cotton	Polyester	Cotton	Polyester
INITIAL VALUE	Resting State	-37 dBm		-28 dBm		-8 dBm		-9 dBm	
SENSING	Touch	8 dBm		1 dBm		0,2 dBm		1,7 dBm	
	Bending	7,8 dBm		5 dBm		0,5 dBm		1,5 dBm	
	Water Drop			11,6 dBm	13,4 dBm				15 dBm

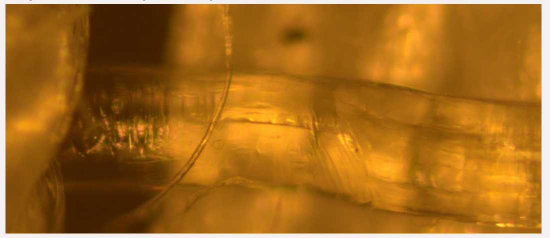
Table 5 Results laboratory tests

- In the case of the humidity/water sensing, the ***cotton and polyester yarns make the recovering of the CMC from wet to dry slower,*** in comparison with CMC fibers alone.
- Since polyester doesn't absorb the water, the ***water drop stays on the surface for longer*** time before evaporate. This makes the fiber/film to be in contact with water for longer, increasing the attenuation in comparison with the cotton samples.
- ***CMC fiber swells and changes diameter***
- ***CMC film swells and melts with the cotton yarns***

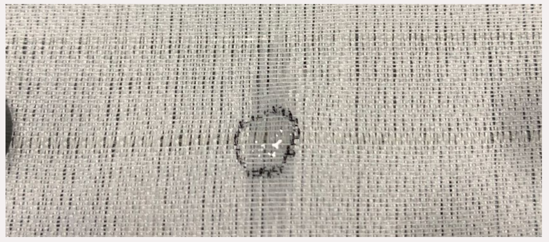
Water drop in CMC fiber + cotton sample



Deformation of CMC fiber



Water drop in CMC fiber + cotton/polyester sample



Deformation of CMC film

Figure 67 Humidity sensing samples

Summary
Phase 2: Define

RQ2
"How does the integration enable sensing and actuation capabilities?"

CELLULOSE-BASED OPTICAL WAVEGUIDES

CMC Fibers 320 nm
CMC + Glycerol Films 130 nm

↓

Films are more flexible, resistant and easier to handle than the current fibers which brake easily and deform with the warp yarns.

CMC + Glycerol films are good alternative for prototyping while CMC fibers get developed

TEXTILE INTEGRATION METHOD

Weaving

↓

Weaving structures do affect the amout of light scaterring from the waveguides.
The amount of touching points between the waveguide (fiber or film) and the warp or weft yarns determines the changes on the light intensity.

Weaving structures can be use to create different sensing mechanisms

ACTUATION

Light

↓

Both films and fibers work as light actuators since it is possible to see the light scattering in their lenght.
Since the film can be cut, in different widths, its is possible to control the area of the waveguide.

Possible to create different shapes for light actuation using films

SENSING

Touch
Bending
Humidity

↓

As an active material, CMC reacts to external stimuly.
By touching or alterating the shape of the fibers and films, a difference in the light intensity can be detected, making them suitable for sensing.
The results show mainly a change of state between Resting and "Activated", for example no-bending and bending, but the material needs to be better researched and optimize to detect degrees of change.
For example, how much it is bending.

Sensing change of state

→ Phase 3: Develop

Figure 69 Creative exploration

4.3 Develop

"Can these new insights inform practice-based creative exploration for the creation of new smart textiles?"

As a final step for this project, the insights from the focus phase led to a creative exploration of possible textile sensors and light actuators based on the integration of CMC.
Taking the laboratory testing results into account, the focus was centered on using CMC + glycerol films. Compared with the small amount of fragile CMC fibers, the film's easy production method provided me with a big amount of stronger and more flexible material for testing. In the future, the films can be changed by the fibers maintaining the results close enough due to their similar behaviour and attenuation values.
Using the gained material knowledge and also the insights regarding the textile integration, I present small textile sensors and two garments as proof of concepts. The aim is not to propose a defined solution for a context-base brief, but to use prototyping methods and visual documentation to communicate the potential of the new material and explore new solutions directions.

The aim of this phase was to answer the last research question.

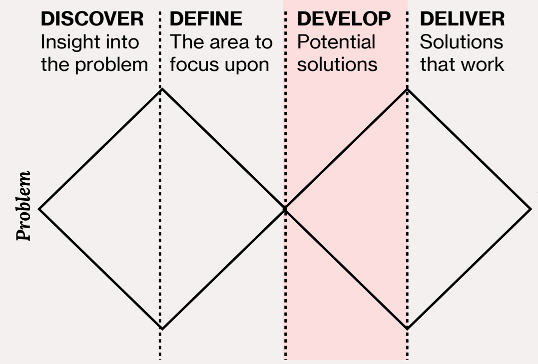


Figure 68 Develop phase

Visual research

Together with the technical information, a visual research was included related to the evocative qualities of the material and a personal approach to smart textiles narratives.
In terms of the material, the main characteristics that I decided to communicate were:

- Biodegradable
- Biocompatible
- Transparency
- Lightness
- Softness
- Flexibility

For the narratives, personally I believe that smart textiles can have a powerful impact on wellbeing, as soft, light and delicate materials close to our bodies. They can provide us with valuable information about our vital signs and also be an interface to communicate with digital environments in a softer and more gentle way than using hard screens. When looking for online images related to smart textiles, the main visual references show elastic fabrics, tight to the body products, blue lights and electronics-inspired patterns. These visual and haptics decisions bring a sense of energy, high level performance, sports and science fiction-like aesthetics that makes them not easily relatable with daily life.
In contrast, I decided to develop a proof of concept prototype that would evoque feelings of wellbeing, rest, warmth and calm, aiming to explore how smart textiles and wearable technology could feel more approachable.

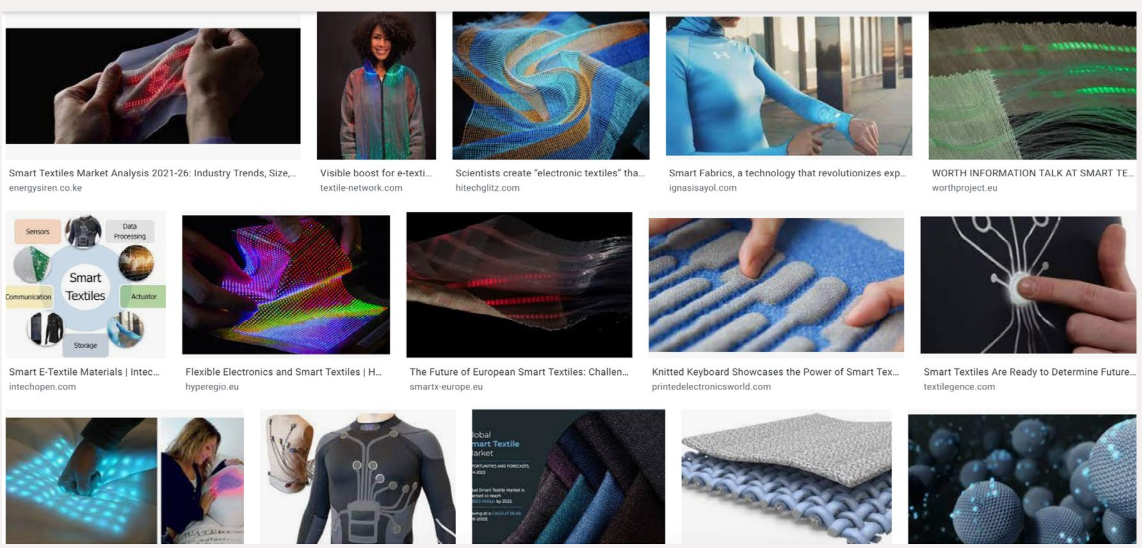


Figure 70 Visual references

Color palette and material selection

Due to the relevance of the light output in the development of the new smart textile samples, the color of the light itself was the main guide for the color decisions.
CMC and MC can only transmit wavelengths from the red to infrared spectrum of light, meaning that if white light is connected, just oranges-reds will be visible and the blue light will get absorbed. This characteristic was well suitable with the concept of warmth, so the color palette was built on pink and orange tones with hints of green and red for contrast.

The yarn selection was defined by the aim to create light and, if possible, translucent textiles. A TC2 Jacquard Loom was used, which defined the already existing warp, mercerized white cotton in this case, so more decisions were made regarding the weft yarns. Having the sustainability aspect as an umbrella, mostly cotton yarns were use to create mono-material samples, except for the use of a polyester yarn to explore with shrinking structures and mohair to test how the light would interact with more hairy yarns, to increase the feeling of comfort and lightness.
Multiple samples were made to test colors, yarns and graphic effects.

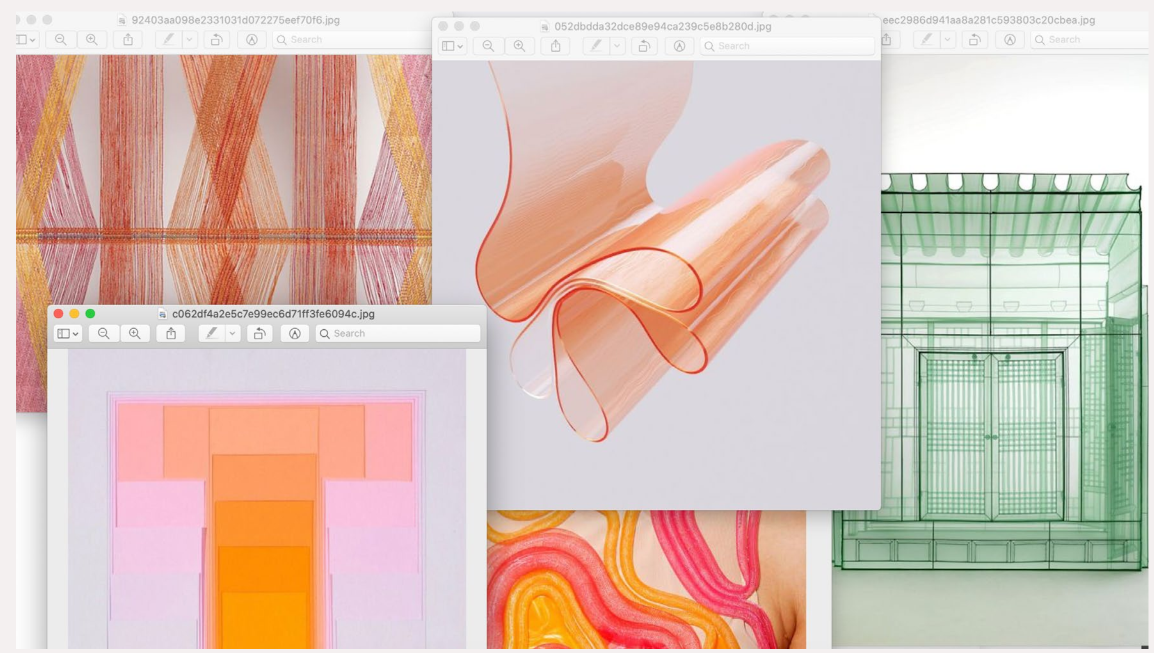


Figure 71 Visual moodboard

Figure 72 Colors and materials exploration

Textile sensor samples using CMC planar waveguides

Small scale sensor samples were created with the focus on touch and bending, since the humidity sensing needs deeper research and testing to work properly.
Once ready, all samples were tested at the photonics laboratory together with Ari Hakkonen, to get results regarding the range of attenuation values changes.

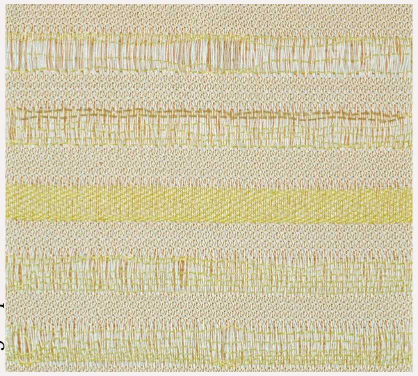
Optical Waveguides	Integration Methods	Actuation	Sensing
CMC + Glycerol Films	Weaving	Light	Touch Bending

Figure 73 Guidelines prototyping Phase 3

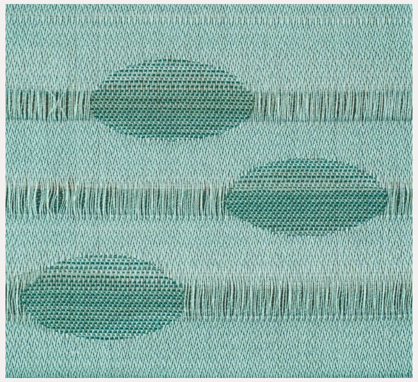
04 Process

Slider

Light pockets

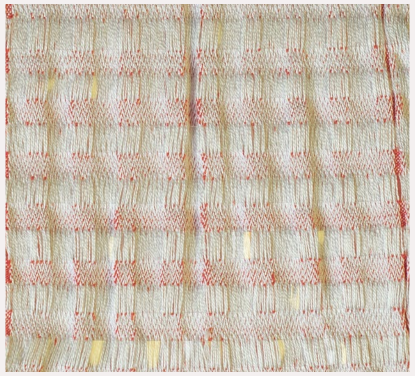


Push button



Bend sensor

Stretch sensor



Touch sensing grid

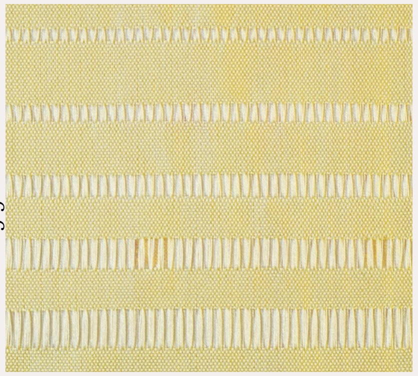
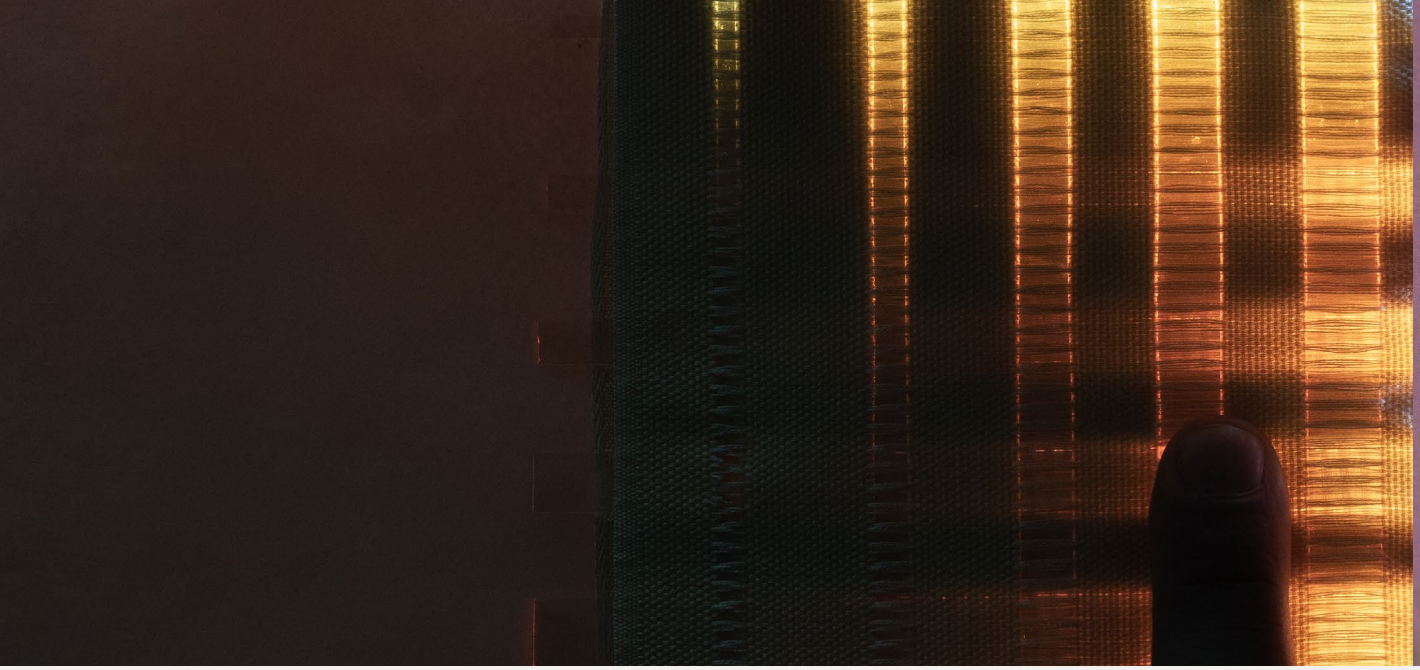
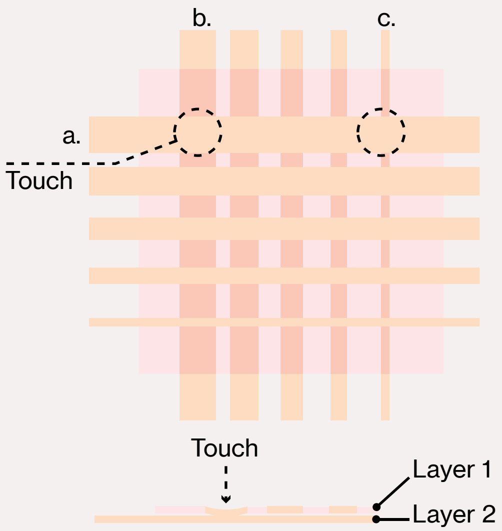


Figure 74 Bio-based smart textile samples





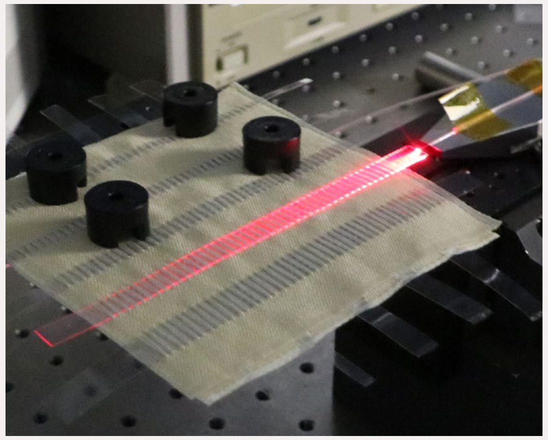


Figure 75 Touch sensing grid

Actuation
Light

Sensing
Touch sensing grid

Waveguide material
CMC + Glycerol film
17 cm x 0,2/0,4/0,6/0,8/1 cm

Textile materials
Mercerized cotton 38/2 white (warp)
Mercerized cotton Nm 70/2 yellow (weft)

Light source for testing
Infrared light 1050 nm

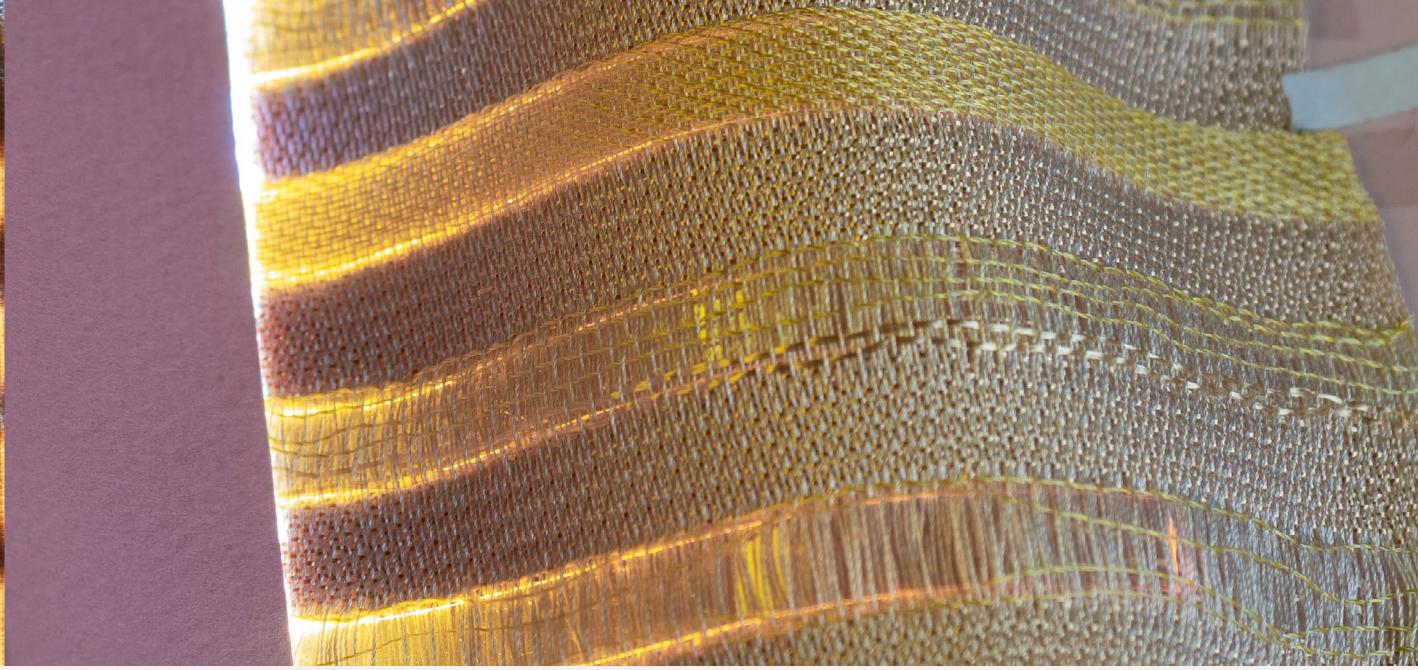
Woven structures
Simple weave 6x6.

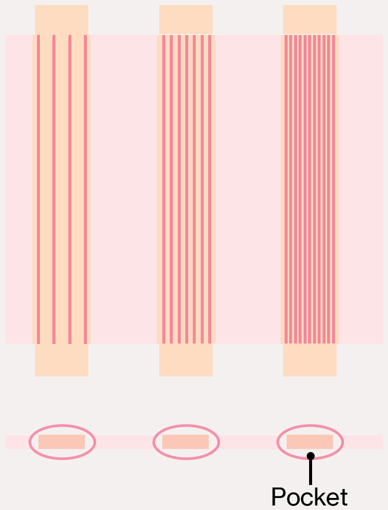
Working principle
Grid created by using CMC films in both X and Y directions. The sensor combines two layers with 5 strips of film of different width each, which will results in different light intensity values due to the size area. This could be use to determine in wich part of the grid is the touch been apply.

Light intensity value a,b > Light intensity value a,c

Light intensity values

Resting state intersection: -12,9 dBm
Touching intersection: -13,5 dBm





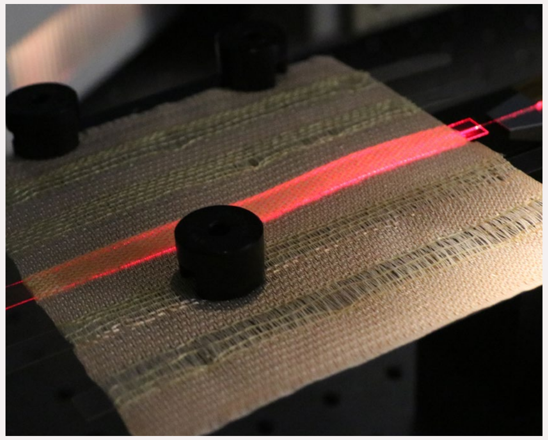


Figure 76 Light pockets sample

Actuation
Light

Waveguide material
CMC + Glycerol film
17 x 0,8 cm

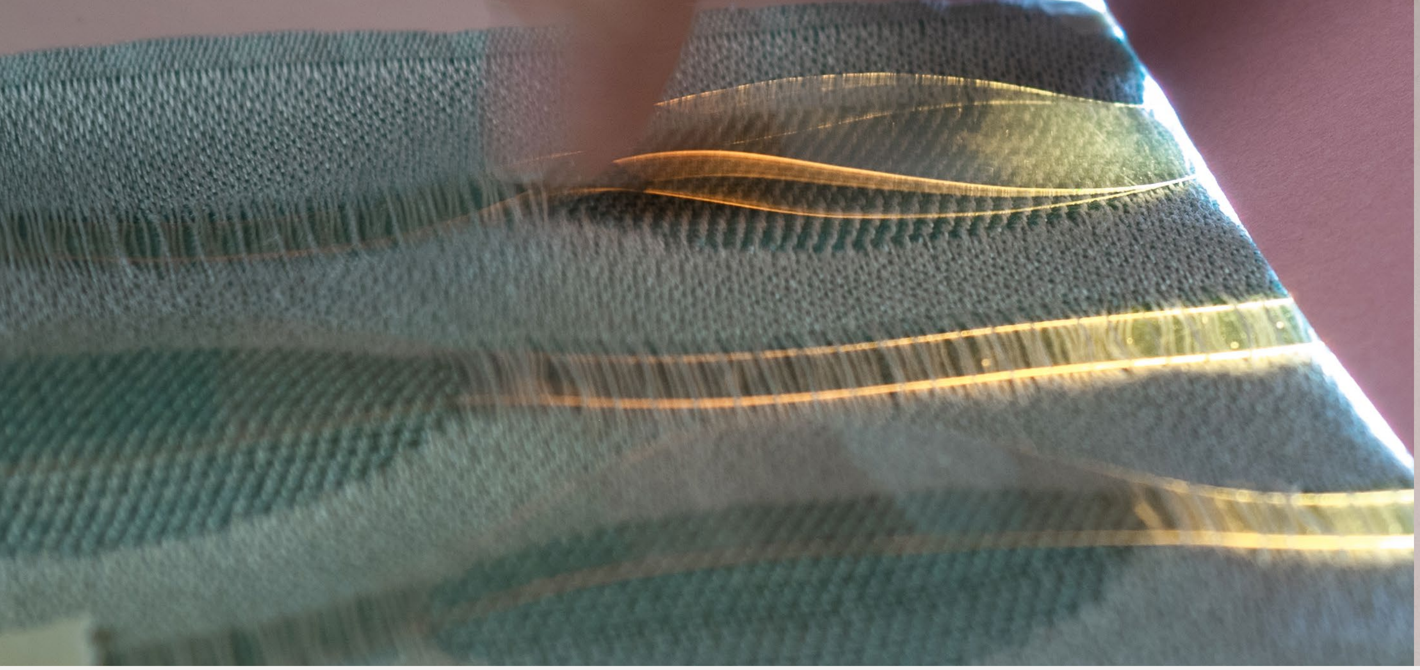
Textile materials
Mercerized cotton 38/2 white (warp)
Mercerized cotton Nm 70/2 yellow (weft)

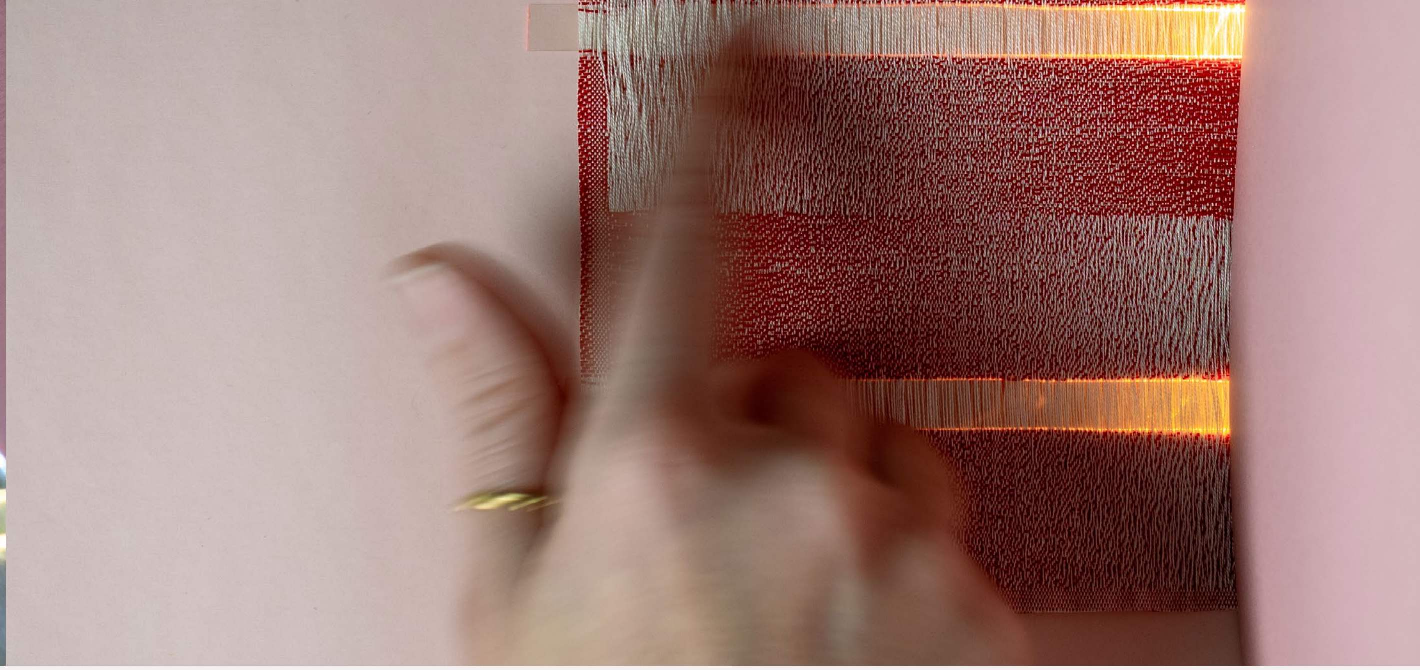
Light source for testing
Infrared light 1050 nm

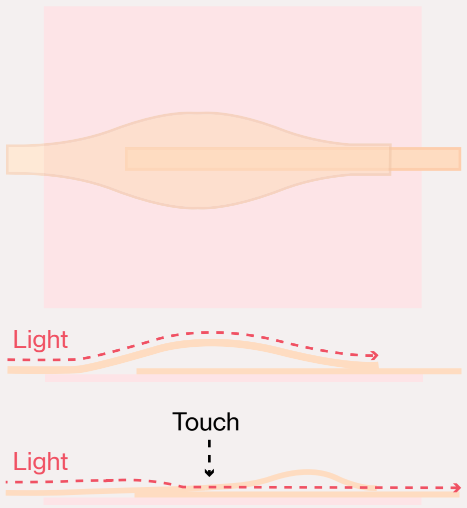
Woven structures
Pocket weave

Working principle
In previous samples, simple weave was used to integrate CMC+ glycerol films. In comparison, this sample explores the use of double weave structures to insert the film into a pocket instead of weaving into the warp yarns.
Three different densities were use to create the pockets, to see how this would affect the light output.

Light intensity values
Resting state: -11 dBm







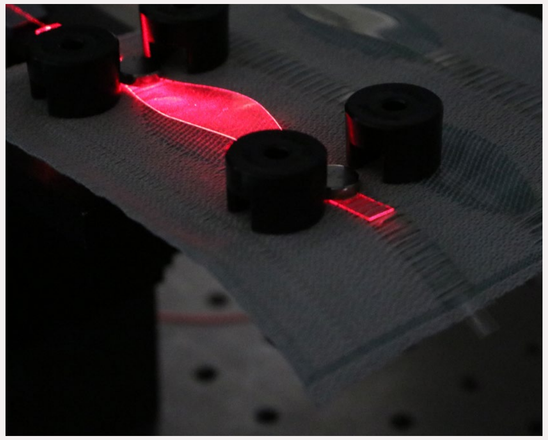


Figure 76 Push button sample

Actuation
Light

Sensing
Push button

Waveguide material
CMC + Glycerol film
Curve shapes

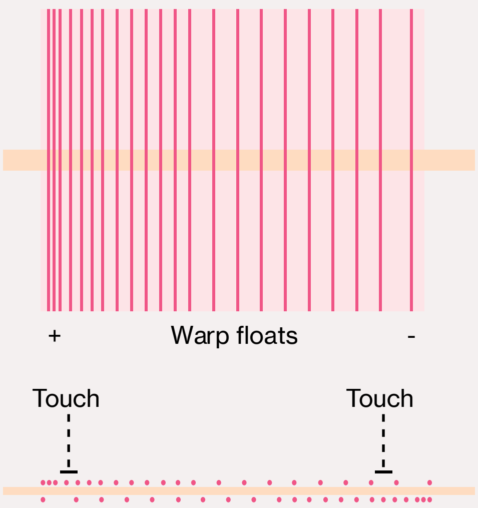
Textile materials
Mercerized cotton 38/2 white (warp)
Mercerized cotton 65/2 green (weft)

Light source for testing
Infrared light 1050 nm

Woven structures
Double weave and weft floats

Working principle
This sample was inspired by traditional electrical push buttons, where physical contact between two plaques allows the flow of electricity. In this case, instead of electricity, is the flow of light which is achieve by touching the weft floats of film, creating contact between two strips.
This sensor would enable sensing the states of 0/1, meaning, presence or absence of light at the end of the film place above.
Also, the curve shape of the film hints where should the touch be done.

Light intensity values
Resting state: -30 dBm
Touching: -23,7 dBm



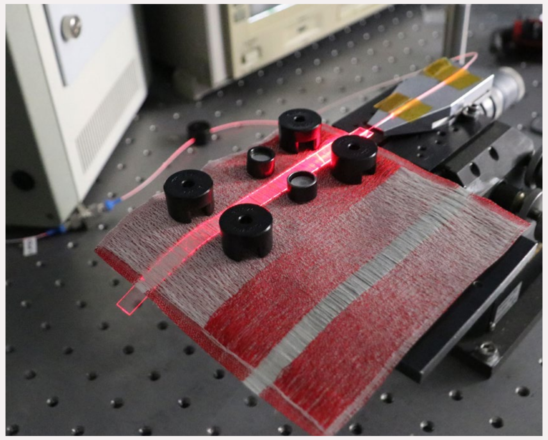


Figure 77 Touch sensing slider

Actuation
Light

Sensing
Touch slider

Waveguide material
CMC + Glycerol film
17 x 0,8 cm

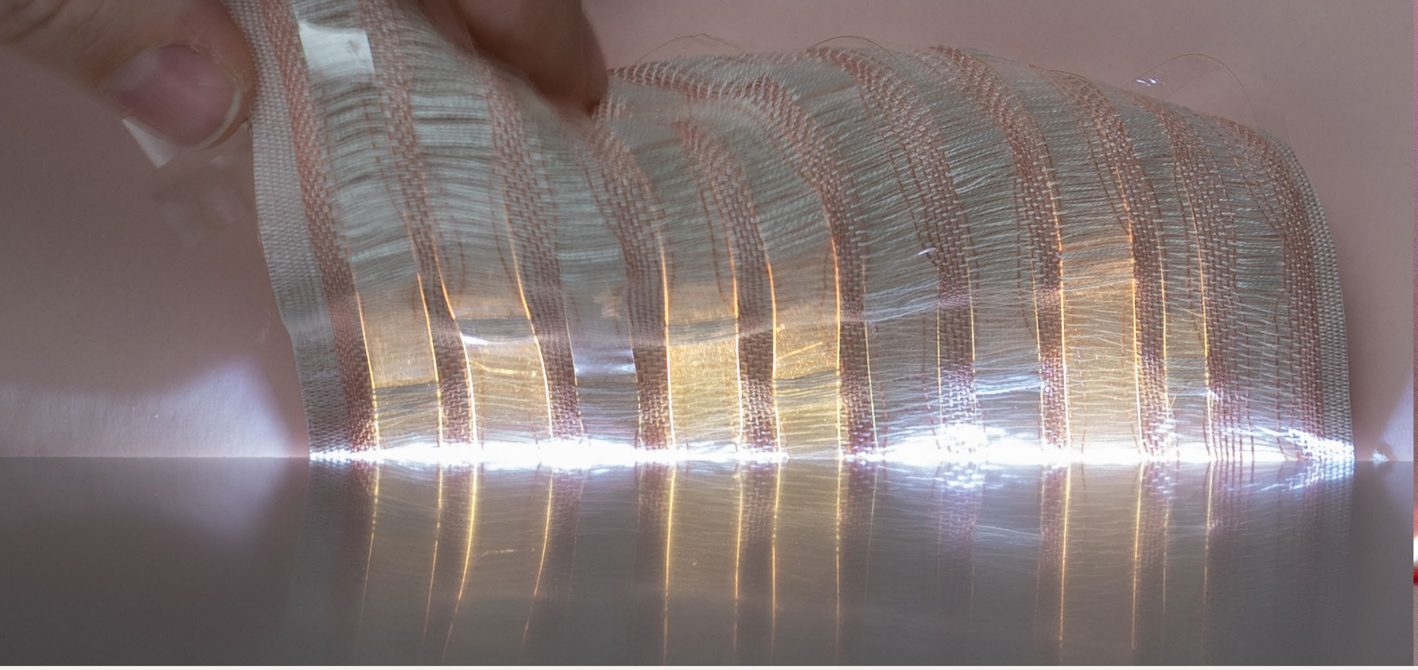
Textile materials
Mercerized cotton 38/2 white (warp)
Mercerized cotton Nm 39 red (weft)

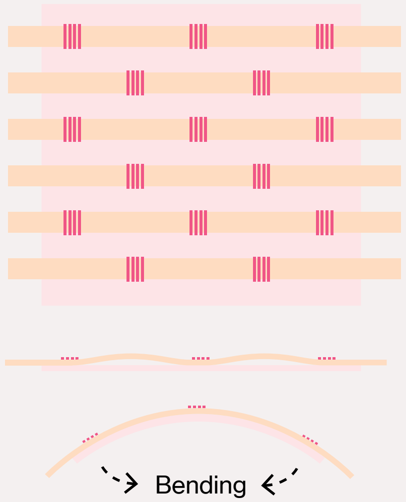
Light source for testing
Infrared light 1050 nm

Woven structures
Simple weave gradient pattern

Working principle
The pattern creates a gradient going from smaller to longer warp floats. Therefore, the amount of warp yarns going over the film increases from right to left (more white to more red). Following the principles of contact points, this sample aims to create a “slider”, with the light intensity changing in different degrees, as the finger touches the different areas of the “gradient”.

Light intensity values
Resting state: -12,9 dBm
Touching more warp area: -12 dBm
Touching less warp area: -11 dBm





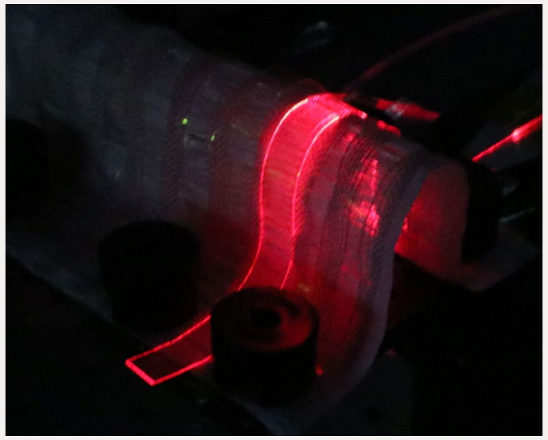


Figure 78 Bending sensor

Actuation
Light

Sensing
Bending

Waveguide material
CMC + Glycerol film
17 x 0,8 cm

Textile materials
Mercerized white cotton 38/2 (warp)
Mercerized cotton Nm 2/65 pink (weft)

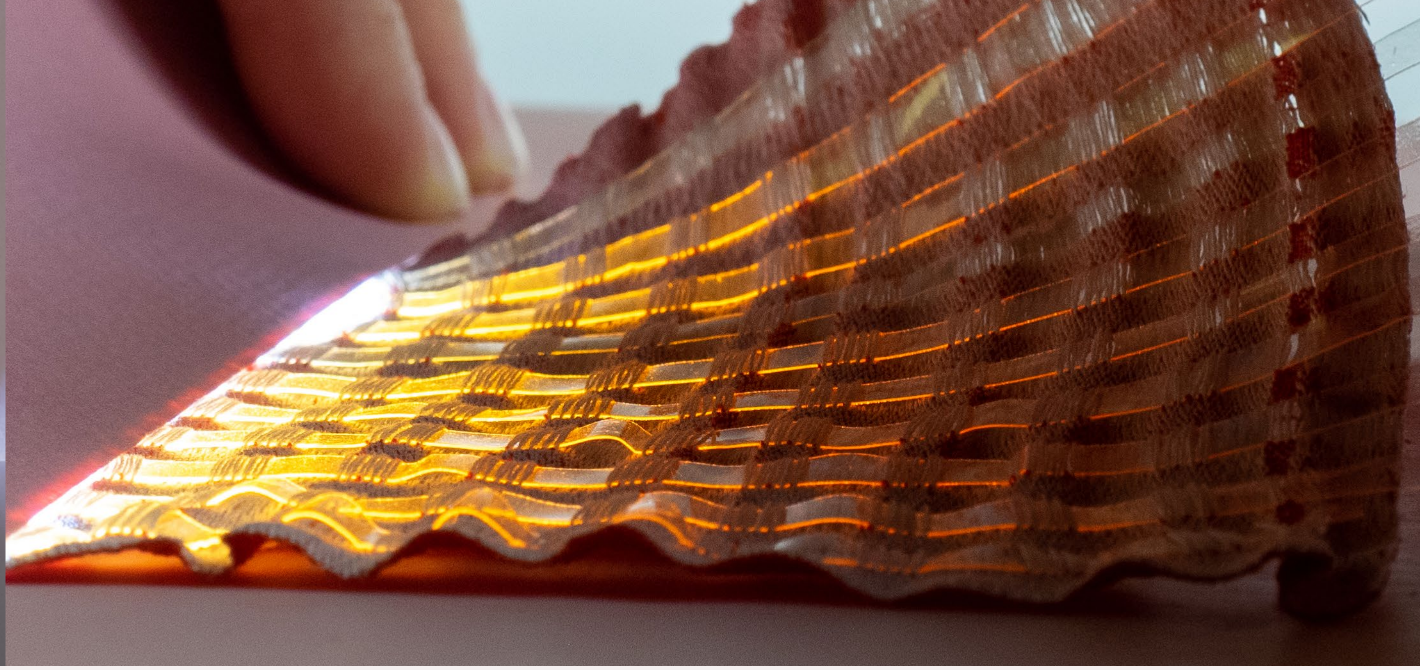
Light source for testing
Infrared light 1050 nm

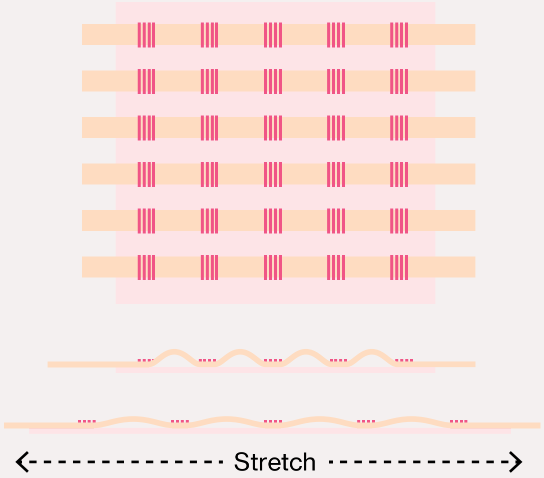
Woven structures
Simple weave with long floats

Working principle
This sample uses big floats of the film to control the amount of touching points. When the sample is straight, the floats create arcs. By bending the textile, these arcs get flatter, thus, creating more touching points between the film and the warp yarns underneath.

Light intensity values

Resting state: -12,5 dBm
Bending (radius 1,5 cm): -13,5 dBm





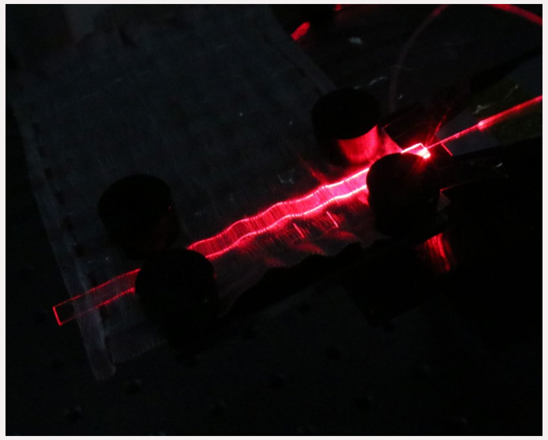


Figure 79 Stretch sensor

Actuation
Light

Sensing
Strectch sensor

Waveguide material
CMC + Glycerol film
17 x 0,5 cm

Textile materials
Mercerized cotton 38/2 Nm white (warp)
Daytona 100% PP 30 red (weft)

Light source for testing
Infrared light 1050 nm

Woven structures
Simple weave 5end satin with shrinking/stretch yarn

Working principle
The sample was made using a PP shrinking yarn. Once its taken out of the loom, heat is apply and the yarns shrink, reducing the size of the sample. Since the CMC film is not shrinking, little loops are created. The sensor then works by measuring the intensity value changes when stretching the sample and making the loops flat again.

Light intensity values
Resting state: -9,5 dBm
Stretch (around 2 cm more): -8,3 dBm

Smart Textile creative exploration

For the following creative exploration, light therapy textile wearables will serve as an inspiration of possible context of use for the novel bio-based smart textiles developed during this thesis.

In the medical context, the use low levels of visible or near infrared light has proven to be effective in the treatment of various conditions such as baby's jaundice (Maisels et al., 2008), seasonal affective disorder (SAD), sleep disorders, dementia (Mayo Clinic, 2021), postpartum depression (Swanwon et al., 2018), various types of cancer (Mordon et al., 2014), pain control, inflammation and healing of wounds amongst others (Hamblin et al., 2006). As explained previously in the background chapter, work has been done to investigate the integration of plastic optical fibers (POFs) into textiles structures for the creation of wearables. Profita et al. (2015) research showed an example of glasses, scarf, hats and hoods for light therapy purposes, where the light can be on the body of the user instead of coming from a fixed screen. This enables more freedom of movement and homogeneity of light delivery (Mordon et al., 2014).

Actuation
Light

Waveguide material
17 x 1 cm CMC + Glycerol film

Textile materials
Mercerized white cotton 38/2 (warp)
Mercerized cotton 65/2 pink (weft)
Astrokid Mohair (weft)

Light source for testing
Infrared light 1050 nm

Woven structures
Double weft fading pattern (cotton and mohair weft)
Simple weave 5end satin (film weft)

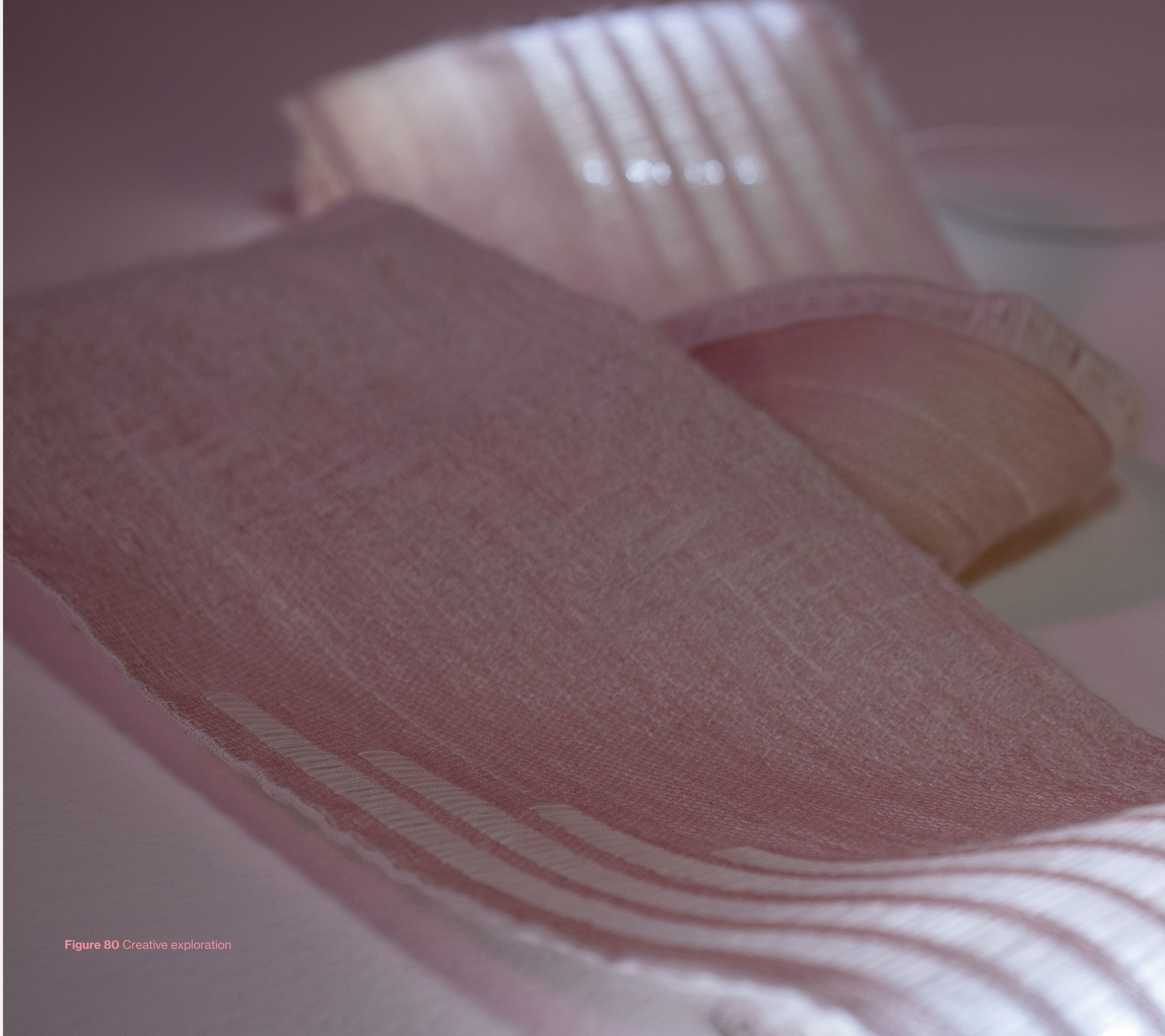


Figure 80 Creative exploration

Figure 81 Creative exploration

Figure 82 Creative exploration

Actuation
Light

Waveguide material
17 x 0,8 cm CMC + Glycerol film

Textile materials
Mercerized white cotton 38/2 (warp)
Mercerized cotton 65/2 pink (weft)

Light source for testing
Infrared light 1050 nm

Woven structures
Simple weave fading pattern (cotton weft)
Simple weave 5end satin (film weft)

Figure 83 Creative exploration

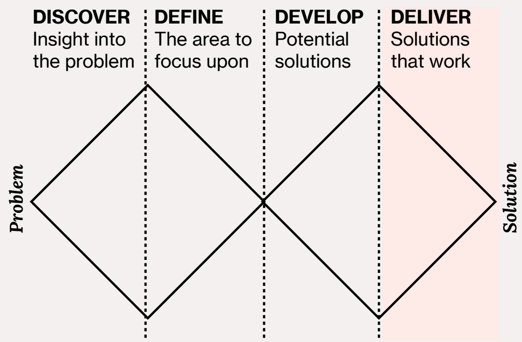
Figure 84 Creative exploration

Figure 85 Creative exploration

05

Discussion

The previous chapters presented the creation of novel exploratory samples of bio-based smart textiles. These textiles were a result of interdisciplinary work between design and material science through a practice-based research approach.
The following chapter represents the last phase from the framework: Deliver which corresponds to the thematic discussion of the results.



Biomaterials for smart textiles

The original goal of the BIOPTICS project was to create bio-based smart textiles samples; these were successfully achieved by integrating a cellulose biomaterial provided by the material science team. Based on the explorations, synthesized cellulose proved to be a versatile material for the creation of light-transmitting waveguides integrated into textile. One of the most interesting aspects of the cellulose used, CMC and MC, was the range of formats which were available for use in the experiments. Gel, fiber, and films enabled the use of 3D printing, knitting, and weaving, showing great versatility for the design of complex shapes, different thicknesses, and flexibilities. This enabled control of the light-transmitting properties, for example, on the width or shape of the glowing waveguide area or its degree of curvature.
As the materials were easy to handle and non-toxic, the process went smoothly and the prototyping swiftly due to the use of traditional tools, such as brushes, syringes, or embroidery canvases. Therefore, no strict laboratory

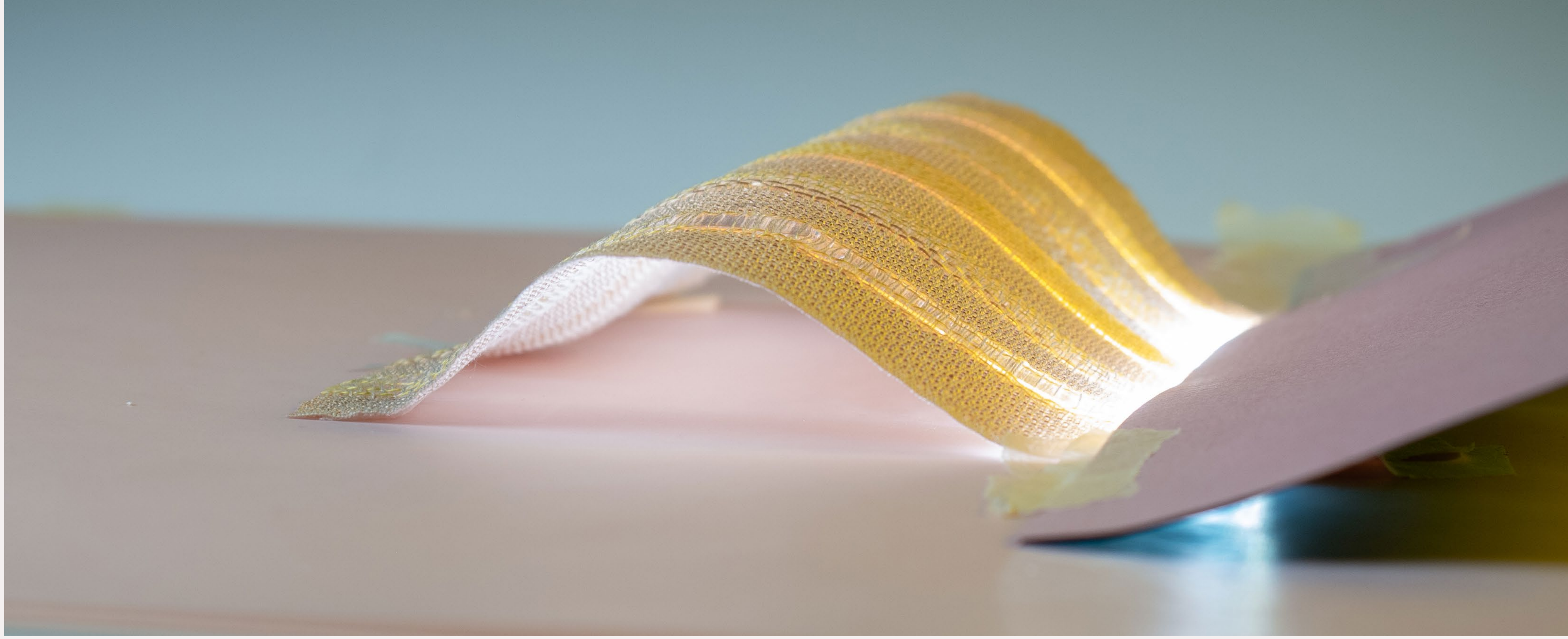


Figure 86 Sensor sample

conditions or supervision from a professional were needed, resulting in more spontaneous and intuitive exercises, such as testing different shapes of the films.
Since the samples were focused on the sensing and actuation part of smart textiles, it is exciting to think about ways of combining this technology with new developments for sustainable power sources, including integrated solar panels.

Novel smart textiles sensors

In addition to the bio-based aspect, one of the most interesting results was the capability of using the same functional material, cellulose, to create optical fiber waveguides or planar waveguides which can be applied for multiple purposes. The specific characteristics of CMC (translucent, flexible, light-transmitting, water-absorbing) provided the material with multi-functional properties and enabled its use as both sensors and actuators. This means that the material can simultaneously sense and react to the environment, which is not a common characteristic of other functional materials. For example, on touching the waveguide, contact is sensed and concurrently a change is seen in the light output. This could contribute to the aim of more ubiquitous integration of functionalized materials, improving the efficiency of smart textiles in terms of different variables, such as the number of components, weight, complexity, or cost.
On the other hand, the result shows the relevance of textile integration, meaning that different structures and the selection of yarns can affect the behavior of the functional material, thus amplifying the range of possibilities to control it. For 3D printing, the type of textile substrate and its capacity to absorb water can effect certain outcomes, such as determining the expansion of the cellulose gel print as well as its ability to bond to the fibers. Using dense polyester fabrics as the base had better defined but more brittle shapes in comparison with less dense cotton organza. In the case of knitting, the definition of the size and amount of loops determines the quantity of light scattered affecting the amount of light traveling to the end of the waveguide. Furthermore, less frictional methods, such as inlay, could contribute to less breakage of the fibers. Finally, weaving was the most explored integration method and although the work was limited to simple structures, meaningful insights were gained. Since the fibers and films were used as weft yarns, one of the most important parameters was the length of the weft floats. For example, plain weaves created more contact points and tighter structures, resulting in an increase of the light scattering, which in turn affected both the sensing readings and the light actuation. We also observed that multilayer structures can be used to hide the light in specific places, creating patterns that change the colors of the light output based on the colored yarns placed on top.

As shown, the role of textile knowledge was key and shows the importance of interdisciplinary work from the first stages of materials development, contributing to material behaviour understanding.

Accelerating the process

When starting the project, one of my personal concerns was how to achieve the goal to create new smart textiles if the cellulose fibers were still at a very initial stage.
This was accentuated by the fact that scientific research usually takes longer times than design projects, so the optimization of the fibers, even if promising, would take years before being ready to use.
Nevertheless, the final results show that design methods like prototyping, combined with haptic and tacit textile knowledge in an instinctive exploratory process, led to speed up the process of material development. First, material prototypes helped to visualize the discussed concepts, like textile sensors, generating some preliminary results even if the optical fiber material was not still optimized. For example, creating a small proof of concept of a woven humidity sensor gives hints to which variables need to be controlled, like the material of the textile yarns, and which characteristics of the optical fibers need to be improved, like water resistance.
On the other hand, the decision to work with alternative versions of the cellulose material, not only enabled the creation of prototypes to communicate what could be possible with the fiber optics, but more importantly, actually opened the way to discover new interesting formats of the material and promising processes. Even though challenging, 3D printing seems to be an integration method to keep exploring, and the use of films not only worked as an alternative but came up as a promising material with its own characteristics and benefits, particularly for light actuation.

These results show the impact that design methodologies can have in early stages of material research. Having focused on just using POF to simulate BOF, and not being involved with the material itself, would have limited innovation and new ideas.

Aesthetics and haptics properties

The use of design methods not only contributed to speed up the process and achieve functional samples, but also added an extra layer of information related to perceptive, emotional, and evocative qualities of the material. As a practice-based research, “thinking through the senses” (Nimkulrat, 2010, p. 75) was fundamental, so textures, colors and shapes guided the decision making and pushed the exploration to discover new ways of working with the material. For example, following the intuition of cutting the cellulose films in curve shapes had an appealing visual effect when connected to light, that drove experiments on how those shapes could be beneficial when creating a bending sensor or as indicator for a touch sensor. On the other hand, hiding the cellulose films into woven pockets to create a continuity in the texture of the smart textile, let to discover that light would expread in a different way, creating new interesting effects with the colors of the surrounding yarns.
The evocative qualities of the material as something biocompatible, soft and “friendly” also guided the decisions regarding the use of thin cotton yarns, and to try different structures that were translucent instead of dense and heavy, affecting the behavior of the sensors. Thus, during the whole process, both quantitative and qualitative data had equal relevance in the material development. The final results aim to inspire more designers and smart textiles experts to work with biomaterials not just by their functionality but also from its aesthetics and haptics properties, enriching the smart textiles experience with expressive narratives.

Figure 87 Hands-on approach

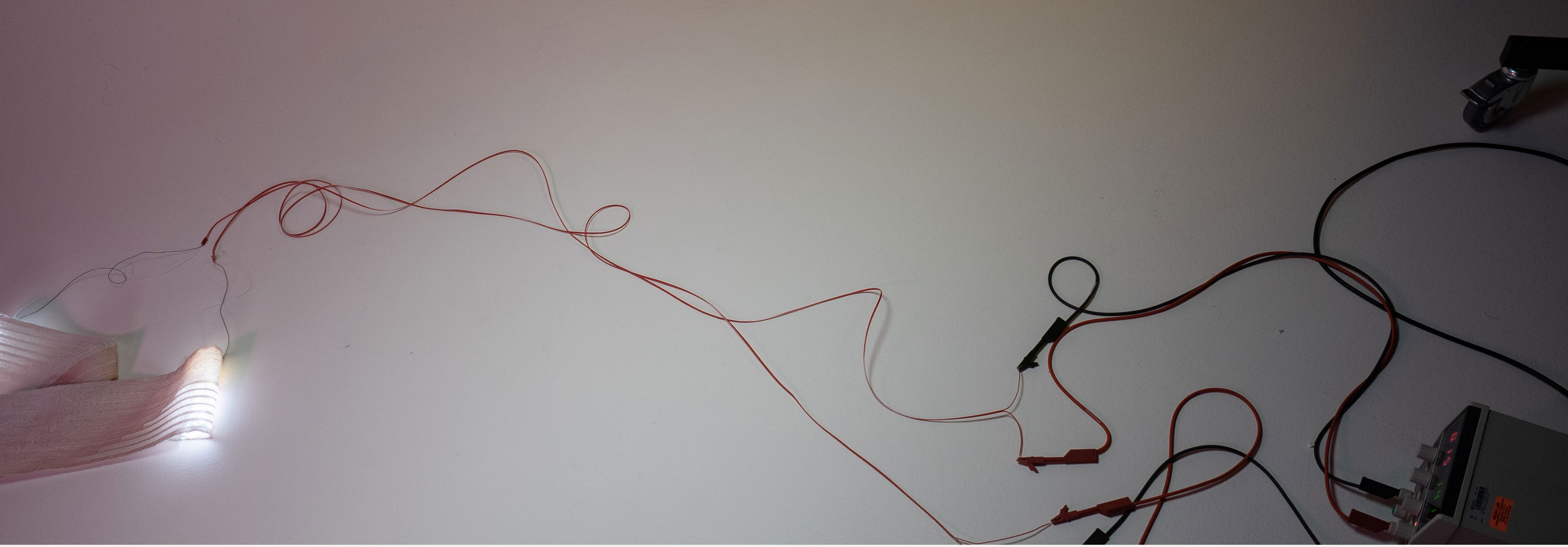


Figure 88 Creative exploration

Interdisciplinary tensions and learnings

The focus of this thesis research was on the development of novel bio-based smart textiles. Nevertheless, due to the interdisciplinary nature of the project, learnings were gained related to the teamwork dynamics.
The initial phase presented a challenge based on the lack of common understanding regarding my role as designer in the team. Initial conversations pointed my work direction into directly creating fabrics and clothing using alternative POFs. Due to the initial stage of the material development and my own motivations, I instead proposed to be more involved in the material research itself. To achieve this, I arranged working sessions at the lab with Aayush Jaisval, Ari Hakkonnen and Marie Gestranius. Working together with them making the material at VTT and testing it at the photonics laboratory created a positive work environment to ideate together about new prototypes, commenting on the results and building up the confidence to ask technical questions.
At the end of the project, my work enabled me to better communicate what I could bring to the research including creative prototyping methods and practice-based material explorations.
Finally, building a common language and trust in everyone's processes was essential for a positive work flow.

Limitations and further work

This thesis aimed to create new bio-based smart textiles using functionalized cellulose, following a creative experimental exploration. Therefore, certain variables were left out from the research scope. First, as the aim was to create waveguides for light transmission, other factors such as the washability and durability of the material were not considered. This is one concern which scientists have in mind, when they focus on experimenting with different coating and cladding options to solve those challenges. That also requires increasing understanding on the impact of the material in terms of sustainability.
Secondly, there was no intention to solve the issue of light source, the coupling and power supply. This research could later include professionals working on the energy field for smart textiles, such as Elina Ilen (Ilén et al. 2021) or Pauline Van Dongen (Smelik 2016), who are currently developing textile integrated solar panels.

Now that the proof of concepts exist, further research is needed to optimize the sensors, and to better understand the influence of the textile structures behaviour and the selection of yarns from the textiles perspective. Material experience methods (Karana et al. 2015) could also be interesting to apply, revealing more information about the sensorial, interpretative, affective, and performative levels, thus presenting the material to users in co-creation sessions.
As light is an important factor in this thesis, more research could be carried out regarding optics, light color and light perception, studying, for example studying in which way the color of the textile fibers affects the reflection.
Finally, the project will continue exploring a more context-based approach. Light therapy biodegradable devices for medical uses look promising and hope to contribute both to the field of smart textiles and wearable technology.

06

Conclusion

As a response to the upcoming waste management challenges of smart textiles development, this thesis presented novel ways of using functional cellulose for the creation of bio-based smart textiles. The practice-based approach and interdisciplinary work enabled to positively answer the initial research questions by following Discovering, Defining, Developing, and Delivering phases. The integration of functional cellulose gels, fibers and films into textile structures was possible using different methods such as 3D printing, knitting and weaving. The integration enabled humidity, touch and bending sensing, together with light actuation. Both the qualitative and quantitative data informed creative exploration for the creation of new bio-based smart textiles prototypes that serve as proof of concept to express the possibilities of the novel material.
The results showed that intuitive, embodied and tacit knowledge had an equal relevance than quantitative data in the research process, proving the value of design methodologies in technology driven projects.
Finally, this thesis presents an example on how contemporary designers with textile knowledge can have a role in innovative material development during the initial stages of research, with potential to contribute to our lives in the future.

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Figures