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The Design and Development of an Illuminated Polymeric Optical Fibre Knitted Garment

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The Design and Development of an Illuminated Polymeric Optical Fibre (POF) Knitted Garment

This paper presents a new design and development process for integrating illuminated Polymeric Optical Fibre (POF) into knitted garments, by incorporating POF directly into the looped structure. Fully-fashioned knitting is presented as a means of overcoming garment design restrictions in existing cut & sew illuminated POF. A key challenge this work addresses is the creation of more appealing and fashionable form-fitting illuminated POF garments. The resultant work, a tight-fitting knitted raglan sleeve jumper with a section of knitted POF demonstrates that new and appealing aesthetics can be achieved, with our new technique. This project builds on existing research into POF integration into fashion and textiles, whist challenging the existing view that POF cannot be formed into a looped structure when used for illumination purpose. In contrast to other research into the integration of POF into a knitted fabric, this project used a hand flat knitting machine to produce the knitted POF garment, as this type of machine balances the benefits of using handcraft techniques for challenging fibres, with the faster knitting speed better associated with using knitting machines.

Keywords: Polymeric Optical Fibre, POF, Smart Textiles, E-textiles, Illumination, Knitting

Introduction

Polymeric Optical Fibres (POF) have been used in textiles to enhance fabrics with smart properties. As a material for smart textiles, POF has a number of advantages. It is immune to electromagnetic interference and it is relatively low cost (Schwarz-Pfeiffer et al., 2015). Since POF is lightweight, flexible and in a fibre form, it is a good candidate for textiles integration. POF is typically used for signal transmission but it has also been used as a sensor, capable of measuring a range of variables such as temperature, strain and positioning. Several studies have demonstrated success in this application (Pirotte et al., 2010, Rothmaier et al., 2008, El-Sherif, 2005), particularly its use in health monitoring and other monitoring applications.

This paper focuses on POF for illumination, which has been used as garment embellishment and in light therapy applications (Quandt et al., 2017) and further explores its potential for additional aesthetic value. An interesting feature of POF is that the fibres require deliberate damage to the cladding along the lateral side of the fibres for the light to be emitted along the length of the fibre, as the light in undamaged POF is only visible from the end of the fibre. There are interesting characteristics to POF from a design perspective. As it is transparent, when integrated into the textiles structure, the illuminating element is somewhat hidden without a deliberate need to conceal it within the design. When not illuminated, the fabric retains the appearance of regular fabric. The creative application of POF is not new, researchers and designers have demonstrated its potential, utilising it in woven structures to create compelling textures (Bobeck, 2017, Tan, 2013a), and combining POF fabric with other textiles processes (Bai and Tan, 2013) e.g. screen-printing, to add further levels on complexity to the design.

There are however challenges to using POF within traditional fabric structures. While malleable, it is not as flexible as conventional yarns. In essence POF cannot be readily manipulated into tight loops, as a tight bend disrupts the transmission of light along the fibre and can result in fibre breakage. This physical limitation has been taken this into account in the design of POF fabrics, with researchers successfully integrating the fibre into a woven structure as a weft (horizontal) yarn, since the woven structure does not force the fibres into tight bends. Here the fibres are held in the textiles structure through its interlacement with the warp (vertical) yarns. In contrast, knitted fabric consists exclusively of small loops, hence the fibres tend to snap, disrupting the illumination in a conventional knit structure. To overcome this issue, inlay, a technique in which POF is interlaced between the knit loops rather than being pulled through the loops, has been explored as a means to integrate POF into a knitted structure (Kuang, 2016, Oscarsson et al., 2009, El-Sherif, 2005).

While these techniques successfully integrate POF into the textiles structure, they place restrictions on the garment design possibilities for the material. Woven POF fabric cannot be cut into a shaped pattern piece, as this would disrupt the transmission of light across the whole fabric also the fabric does not drape in the same manner as conventional fabric further limiting its potential. These features of POF make it difficult to produce a tight fitting POF garment along with other challenges, stiffness and the inelastic nature of the fibre which can also negatively impact on the garment's shape. Furthermore, inlayed POF restricts the extensibility of knitted fabric, since the extensibility of knitted fabric is enabled by its looped structure.

Literature Review

The literature helps illustrate the design potential for POF illuminating garments, as well as the limitations when using either woven or inlayed POF fabric. Woven POF is shown to be a more mature area of research when compared to knitted POF. Encouragingly, woven POF can be seen in mainstream products, designer garments such as the 'Tinkerbell' dress by Richard Nichol (Blanks, 2014) and Clare Dane's Met Gala dress by Zac Posen (Chi, 2016). As the research discussing integrating POF into a knitted structure is limited, the literature review also examined research into knitting through other high modulus/stiff yarns, helping to define the key factors to consider when developing and designing knitted POF.

Design Opportunities for Illuminated POF fabric

Designers and artists have used POF within the woven textiles to add harmonising illumination with the design aesthetic. POF has also been integrated into products for practical purposes. An interesting example is Fabrikk (2018), fashion accessories brand, who use woven POF in the lining of their bags to allow the user to see the contents of their bag more clearly The entire interior of the bag is illuminated by a single LED, as opposed to having a focused area of light. Large areas of illumination can be created by embroidering an array of LEDs all over the fabric, as seen in the garments by CuteCircuit (2013). However, when compared to woven POF, the array of LEDs has a TV screen like appearance, which has been criticized by some as 'visually jarring'.

Jacquard weaving has been used to create POF fabrics with illuminating patterns in the fabric (Gorgutsa et al., 2013). The work of artist Malin Bobeck (Bobeck, 2017) pushes this further, demonstrating how POF can be integrated into 3D textured fabrics, using different woven structures in combination with textiles techniques like tufting, to create immersive art pieces that encourage physical interaction. Bai and Tan (2013) use a number of applied process to modify the appearance of the illumination. In addition to jacquard weaving, laser engraving is another way to create glowing patterns and motifs. In contrast, screen-printing can be used to block illumination in areas of the fabric, while also acting as a decorative element when the POF fabric is used without illumination.

POF can also be woven with other materials to give fabric smart functionalities. Conductive material can be used to add touch sensing capabilities. Tan et al. (2019) used conductive thread together with POF in a woven fabric to create a touch sensitive illuminating fabric in a single process. As a result, the fabric retains the look and feel of a conventional woven fabric, since all the functional fibres are integrated into a single layered fabric, rather than having an additional layer of conductive material for the touch sensitivity.

Illuminating POF textiles highlight the design potential for the material. However, while these examples show the level of design complexity that can be achieved with POF textiles, they use relatively simple forms, as they are being applied to interior textiles products or large-scale artworks. In contrast, illuminating POF garments have a tendency to use plain woven POF fabric, potentially due to the difficulty with using the fabric in garment construction.

Design constraints for Illuminated POF garments

While POF presents clear design opportunities, there are some unique properties of POF fabric that can make its integration into the garment construction process more complex. POF illuminated garments have often used POF fabric with the POF running vertically. The reasons for this can be illustrated through an analysis of the dress Urban Glow (Tan, 2013b) (Fig. 1). In Urban Glow, the POF fabric is used for loose hanging sleeves. Since POF needs to be connected to a light source at the edge of the fabric, it is more practical to have the POF running vertically so that the light source can be concealed in the garment. Another reason for orientating the POF vertically is that the orientation of the fabric can affect the drape of the garment. This is seen in conventional pattern cutting. for example, cutting a garment on the bias (rotating 45 degrees from the warp or weft threads) results in a garment that drapes better over the curves of the body. For POF, the stiffness means that the woven fabric can fold easily in the direction parallel to the POF but cannot be folded in a direction perpendicular to it. Consequently, the fabric has to be orientated with POF running vertically in order for the fabric to be gathered and stitched to the dress. The impact of using POF horizontally can be seen in the E-textiles Salla Dress (Chen, 2017) (Figure 2), which uses POF inlayed horizontally across the knitted dress. The POF causes parts of the dress to protrude.

Figure 1. Urban Glow (2013) by Dr Jeanne Tan – A garment that utilises woven POF

Figure 2. E-textiles Salla dress (Chen, 2017)

When incorporating POF fabric into a garment, the connection to the light source must be considered during the pattern cutting process. One of the edges of the POF pattern piece must have loose ends of optical fibre, which can later be bundled and attached to the light source. As a result, the pattern piece cannot be cut in exactly the same way as regular fabric.

The pattern cutting constraints, coupled with the stiffness of the POF and the need to conceal the electronic components, means that creating tight-fitting garments is more challenging with POF fabric. In garment pattern drafting, a pattern for a tight-fitting garment will use curved lines to ensure that when constructed, the garment will fit the contours of the body. However, POF cannot be cut with a curved edge running parallel with the POF, since this would result in the some of the fibre being severed, and the light not being carried throughout the length of the fabric. At present, garment design is restricted to using POF in rectangular panels. In order to create the appearance of a curved seam for the, the adjoining fabric piece is designed with a curved edge, that is then placed on top of the POF fabric, acting as a frame (Wong et al., 2016). Unfortunately, this framing process results in excess fabric on the underside of the garment, potentially causing discomfort, or detracting on the appearance of the garment.

Opportunities for POF garment design using knit

The underlying thinking that has driven this project is the potential for knitting to address the pattern cutting constraints in the design of illuminated garments using woven POF, and the difficulty creating tight-fitting POF garments due to the POF's rigidity. Innovations in knitting technology have benefited the knit industry both in terms of the production process and the product, such is the case with seamless knitting and intimate apparel (Lau and Yu, 2016). The versatility of knitting has led to its use in high performance fabrics, for sportswear, footwear and other technical use cases (Power, 2018). Within the field of smart textiles research, computerised knitting machines are frequently used to produce textiles sensors (Ehrmann et al., 2014, Ou et al., 2019).

Knitting has the potential to address the pattern cutting constraints since knitted fabric can be knitted into the pattern piece shape, known as fully-fashioned knitting. Utilising fully-fashioned knitting in garment production has the benefit of reducing yarn costs, as no fabric cutting is required (Power, 2008). Knitting POF fabric into shape can allow for more tight-fitting garments to be designed, as knitting to shape reduces the amount of excess fabric that is present in the woven POF garments using the framing method. In addition to the benefit of using fully-fashioned knitting, the extensibility of typical knitted fabric lends itself to use in tight-fitting garments, since it can conform to the shape of the body.

Existing research has presented a technique for integrating POF into a knitted fabric, through the use of inlay. In this technique, the POF is interlaced between the knitted loops. Since inlay interlaces the POF between the knitted loops, rather than pulling it through the knitted loop, the POF is subjected to less force, reducing the amount of damage to the fibre.

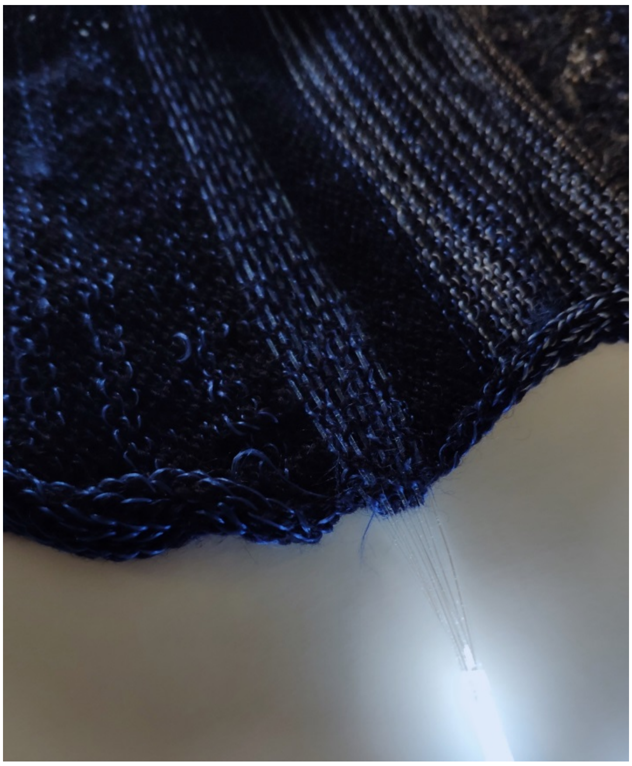

Figure 3. POF inlayed into a plain knit structure (Weft knitting)

Inlay has been used in warp knitting (Shindo, 2015), but more frequently in weft knitting (Kuang, 2016, Oscarsson et al., 2009, El-Sherif et al., 2000). Research using POF in weft knitting shows that POF can be integrated in segments (Fig. 3), or with a continuous POF in a serpentine shape. A challenge with continuous POF, is that each row must be spaced further apart to prevent damaging tight bends, making the all-over fabric illumination sparse.

While inlay has the advantage of preventing critical bending and can be employed in machine knitting, but this technique suffers from drawbacks. Inlay POF shares some of constraints as woven POF, i.e. poor draping qualities and pattern cutting restrictions, since the fabric structure is comparable to a woven structure. Another drawback is that the POF is not looped into the knitted structure in inlay, the fabric can shift along the POF, causing the fabric to gather in select areas, or potentially be removed from the knitted fabric if not secured.

Inlay limits the design possibilities of knitted fabric as inlay POF in weft knitted fabric can only forms straight horizontal lines, since the yarn feeders move horizontally. While it is possible to insert a yarn vertically into the knitted structure, as demonstrated in the work by Albaugh et al. (2019), in which a yarn is inserted into the knit structure vertically to act as a tendon actuator. However, this technique has the same disadvantages as inlay since the fibres aren’t well secured in the knit structure. It is also not necessarily a practical means of creating a large area of illumination, as each vertically inserted yarn would have to be fed using a separate yarn feeder, which would limit the number of POF strands that could be inserted into the knitted fabric.

Further opportunities for POF Knitted fabric development

The research into POF integration into knitted fabric is somewhat stagnant, as inlay remains as the primary integration technique for POF for both sensory and illumination purposes in knitted fabric. As highlighted in the previous section, inlaying POF can restrict the design possibilities for the POF garment. Research demonstrating the ability to knit other high modulus yarns indicates that it is hypothetically possible to form POF into a looped structure, Savci et al. (2001) and Hu and He (2011) demonstrated the ability to knit glass and basalt fibres, respectively. Due to the high stiffness and a high coefficient of friction, there are factors to consider, such as tension for the yarn and the fabric, knitting speed and the amount of contact the yarn has with metal surfaces. In addition to the practical considerations needed to form more challenging fibres into the looped knit structure, the relationship between the looped structure and the light emission properties of POF need to be considered when knitting POF.

Furthermore, there are essentially only two modes of knitting technology explored in the existing POF research, handcraft e.g. hand knit, crochet and macramé at one end of the technology scale and computerised knitting at the other. Computerised knitting has many advantages over using handcraft techniques, primarily its speed, control and ability to produce complex knitted structures. However, the machinery itself can be a limiting factor. Inlay capabilities are not all computerised knitting machines, for instance, Stoll knitting machines require the 'Weave-in Device' feature in order to produce inlay. Depending on the machine capabilities, shaping fabric with inlay POF can be difficult. Oscarsson et al (2009) attempted to knit POF into a shaped piece but without success. The shaping method used, which consists of knitting either more or less rows of knit in parts of the fabric to create a shaped piece, caused stress on the POF that resulted in breakages. Oscarsson et al (2009) suggested that individually steered takedown rollers could resolve this problem, which are available on certain machines, e.g. the Multi-Flex Takedown system on Stoll knitting machines.

Handcraft techniques can be considered more accessible since it relies more on the maker's skill, rather than the technical capabilities of the tool. POF has been successfully formed into looped structures through using handcraft techniques, as demonstrated by GloFab, with their Macramé wall hangings (Fehrenbacher, 2006), and in the crochet POF samples by Kruusk (2014). The key advantage of using the handcraft approach is the high level of control it gives the maker, who monitors the material during the making process. The maker can adjust the tension or the speed of their actions to suit the material during the process of making. The handcraft process also means that the fibre makes less contact with metal surfaces when compared to machine knitting. In crochet, the fibre has a limited number of contact points with the tool, since crochet is accomplished with a single hook tool. However, on balance, these techniques create very open POF textiles structures, which is a design limitation. A further limitation is that it can be more time consuming than machine production.

Both approaches have been limited in the range of knit structures explored and each offers the research juxtaposing opportunities. Existing POF knit research has used plain knit or full needle rib for the knit structure, hence it is unclear how POF might behave in alternative knit structures, which can have the potential to influence the behaviour of the fabric, and how effectively POF can be integrated into the looped structure.

Research has not explored the use of hand flat knitting machines in the production of POF knitted fabric, which falls in the middle of the technology scale between handcraft and computerised knitting machine. Hand flat knitting machines produce fabric in a very similar way to computerised knitting machines but lack the computer control element. Hand flat knitting machines are driven by a person rather than by a motor, as such have the potential to provide the degree of control afforded by using handcraft, with a faster speed of production associated with the computerised knitting machines.

Hypotheses

Underpinned by analysis of existing POF research, this project is based on two hypotheses. The first hypothesis is that POF can in integrated into the looped structure while still producing an illuminated fabric. Previous research has emphasised the need to minimise damage and done so by inlaying the fibre to prevent excessive bending. However, some level of damage to the outer cladding of the POF is required for illumination. It is critical damage, that needs to be avoided. Critical damage can be defined as any damage to the fibre that abruptly stops the light from being emitted along the length of the fibre, such as breakages or severe bends. The second hypothesis for is that once a technique for knitting POF had been determined, it should be possible to design a tight-fitting knitted POF garment, using shaped knitted POF fabric panels. This provided that the takedown tension of the fabric can be managed to accommodate the inclusion of POF into the knitted structure.

Methodology

Based on the lack of exploration of knitting POF fabric using a hand flat knitting machine, and the potential advantages of using this type of equipment for material development, a Wealmart industrial hand flat 7 gauge knitting machine was used to produce the knitted samples and the garment.

Acrylic yarn 2/15nm was used as the main knit fabric. It serves as the base for the POF to be integrated into. 0.25mm PMMA polymeric optical fibre was chosen as the minimum bending radius, ‘the radius of the arc formed by the fibre as it is bent’ (Oscarsson et al., 2009) is lower for smaller diameter fibres. This is less of a concern for inlaying POF but a low minimum bending radius is more significant if the fibre is going to be knitted, as it needs to cope with the small bends of the looped knitted structure. In addition, this diameter of POF has been already been successfully integrated into woven fabrics (Tan, 2015).

The research is split into two parts, firstly, the development of the knitted POF structure, and secondly, the design and production of the knitted POF garment. The development of a knit structure for knitted POF explored the impact of different knit structures on the illumination of the POF in the knitted fabric. The factors impacting the knittability of high-modulus yarns identified by Savci et al. (2001), were considered. The optimum tension settings and knitting speed had to be determined to reduce the risk of POF breakages. The experimentation with different knitted POF fabric structures was conducted to find a means of reducing the amount of contact the POF had with metal surfaces such as the needles, and to minimise the number of tight loops the POF is subjected to.

The design of the knitted POF garment used the POF knitting technique developed in the first part in a knitted garment. In order to illustrate how knitted POF can be used in a form fitting garment, that uses shaped pattern pieces, a raglan sleeve jumper design was used. A raglan sleeve jumper consists of front and back pieces with a diagonal seam that runs from the armpit to the neck, which is connected it to the sleeve pieces. To knit a fully-fashioned raglan sleeve jumper, the knitted fabric pieces need to be shaped. The POF was integrated into the bust section of the front pieces, which is where the shaping occurs.

Part 1: Determining a technique for knitting Polymeric Optical Fibres

Establishing a basic POF knitting method

A full needle rib structure was the starting point for experimentation. While POF can be knitted into the structure, as stated by El-Sherif (2005), the loop structure causes too much critical damage, preventing the light from travelling along the length of the fibre (Figure 4).

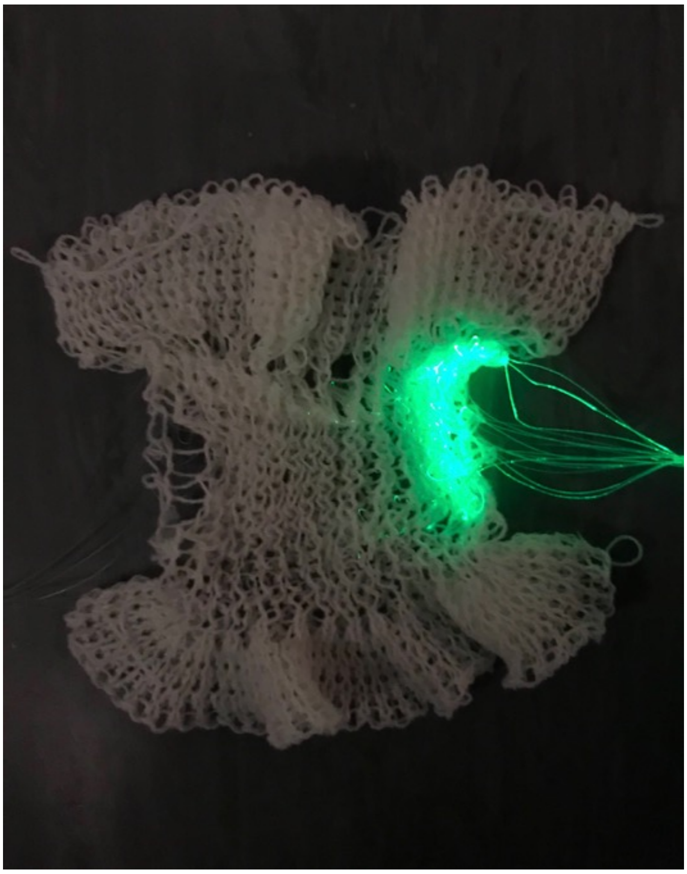

Figure 4. Polymeric Optical Fibre knitted into a full needle rib structure.

In order for the critical damage to be reduced, the number of loops for POF must be reduced, which is the principle behind inlaying POF. However, while the number of needles in the working position could be spaced further apart, this would create a looser knitted fabric. Instead, the approach that was taken was to knit the POF on a single needle bed, while the acrylic yarn is knitted on both needle beds. As a result, the POF can be knitted with frequent floats, but the overall knitted fabric will resemble a single bed plain knit structure. Although ‘six adjacent needles are usually the maximum number for a continuous float’ (Spencer, 2001), it was found that the POF could be integrated successfully into the knitted structure if the floats were 5 to 9 adjacent needles long.

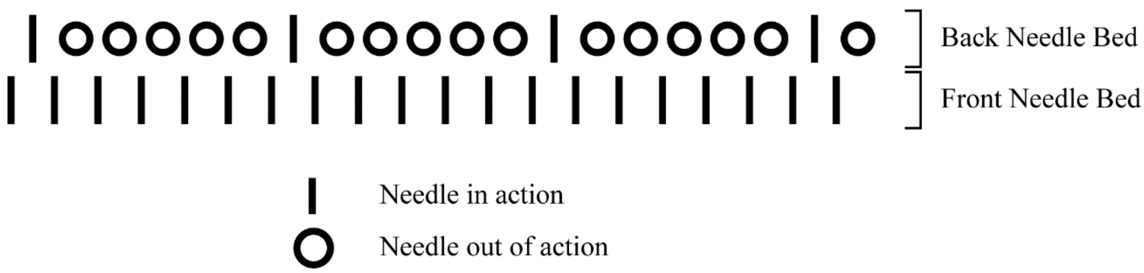

Figure 5. Needle setup for knit POF fabric (5 needle spacing ‘5x1’)

The stitch cam setting for the POF was set to a slightly higher value than for the acrylic yarn, eleven for the acrylic and thirteen for the POF. A higher stitch cam value correlates with the longer loop length. Research by Hu and He (2011) found that stitch cam settings that were too low or too high resulted in higher levels of damage for basalt and glass fibres, while the stitch cam settings did not significantly impact the wool/acrylic yarn. By using two different stitch cam settings, the appearance of the main knitted fabric (acrylic yarn) could be maintained, while the fibres would be knitted at a setting which would be less likely to cause critical damage. The stitch cam value for the POF was only increased by a value of two as to not cause a significant imbalance in the takedown tension for both needle beds, causing problems for loop formation. The POF was knitted on the back bed, while the acrylic yarn was knitted on the front, as early trials found that the POF loops were not securely held by the front bed.

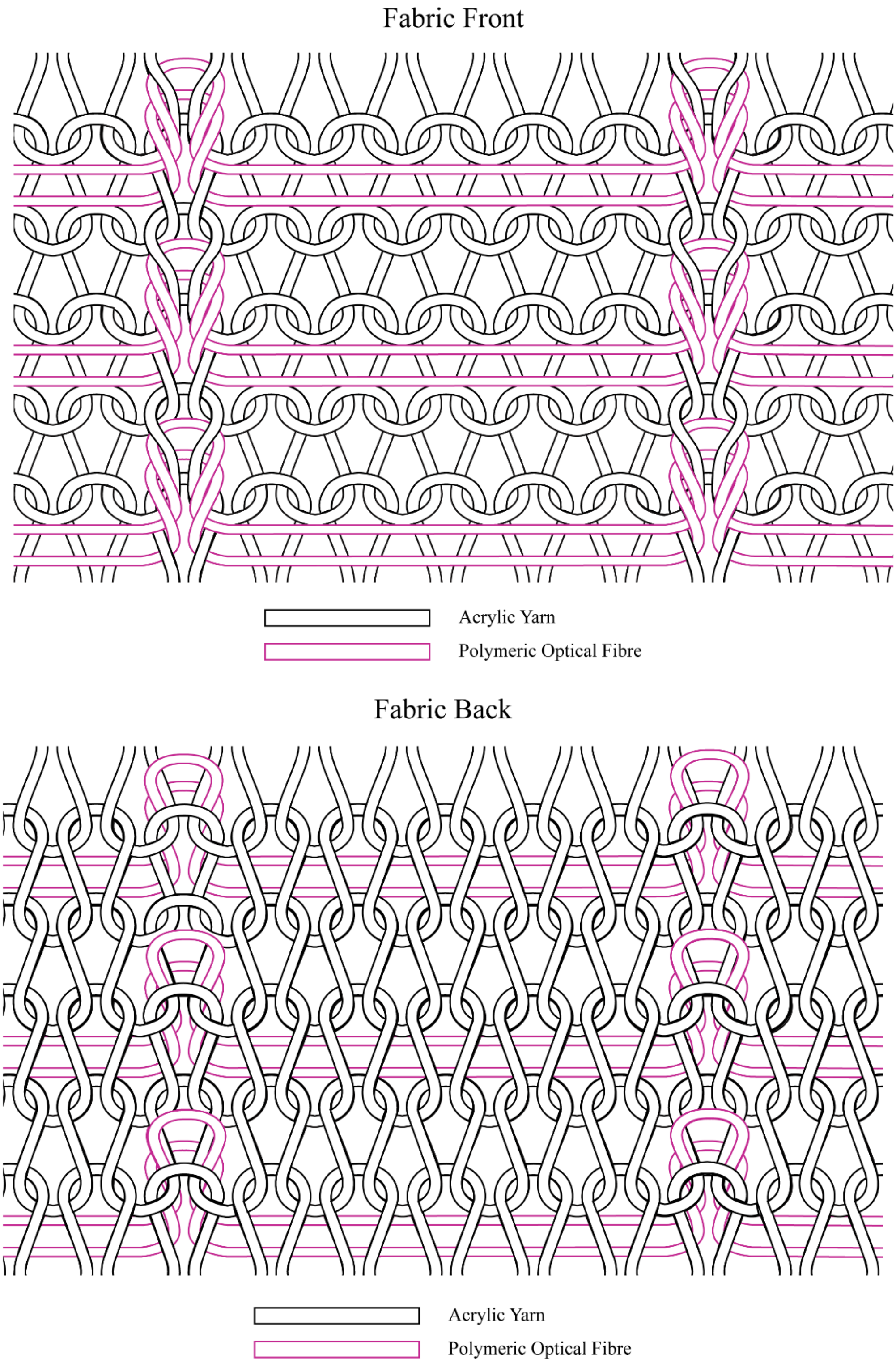

Figure 6. Knit structure diagram (Fabric front and fabric back)

In order to produce a dense area of illuminations, the pattern used was two courses of acrylic yarn on both beds, followed by knitting two courses of POF on the back bed only. This pattern was designed to keep the fibres attached to the main fabric, as opposed to knitting the POF as a separate layer. Two courses of acrylic yarn kept the POF courses spaced close together. The two-course minimum was due to a limitation of the machine, which required the carriage to be returned to the right side of the machine to switch yarn feeders. The acrylic courses could be increased to change the spacing between the POF courses.

Knitting for attachment to the light source

Another aspect of POF that needed to be considered in the design of the knitted fabric structure was the light source attachment. POF needs to extend beyond the width of the fabric, in order for it to be bundled and attached to a light source. In order to produce this, an additional narrow section of knitting (Fig. 7) was added to the edge of the fabric to create sections of loose, floating POF for bundling. The additional section, the 'waste' section, consists of a 3-needle wide section of single-bed back bed knitting placed 20 needles or more away from the edge of the main fabric. After the main fabric was cast on, the waste section would be cast on separately, with the takedown tension for these sections maintained by claw weights.

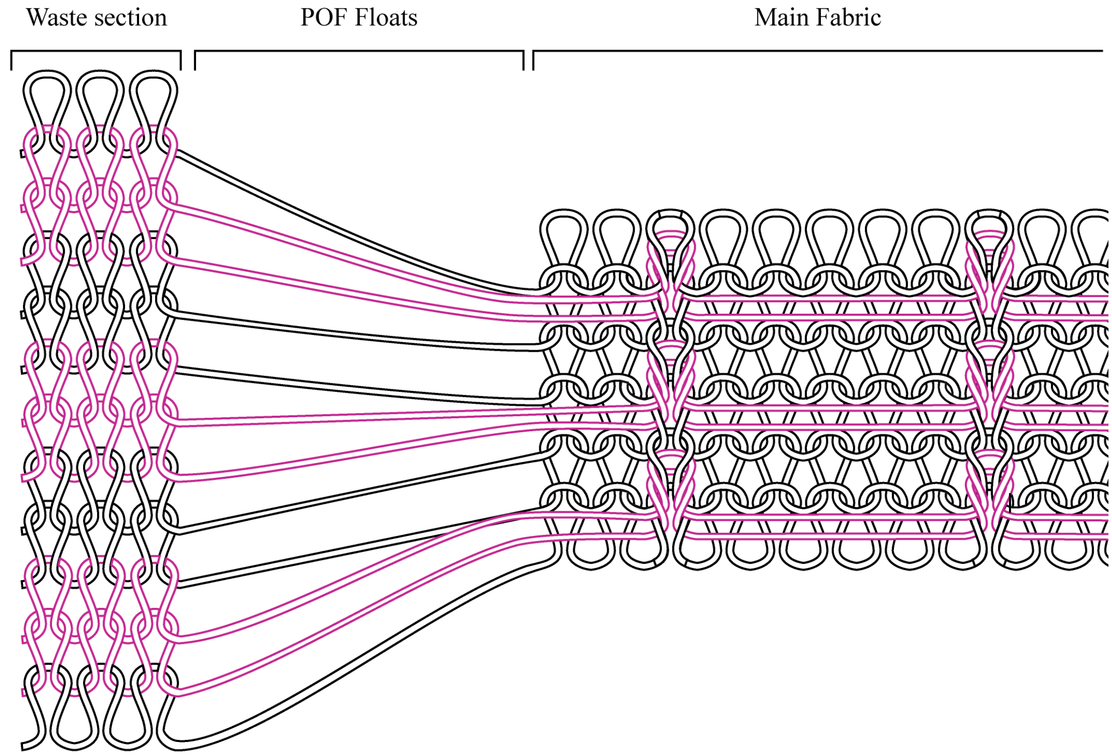

Figure 7. ‘Waste’ section of knitting spaced away from the main POF knit to extend the POF beyond the width of the main fabric

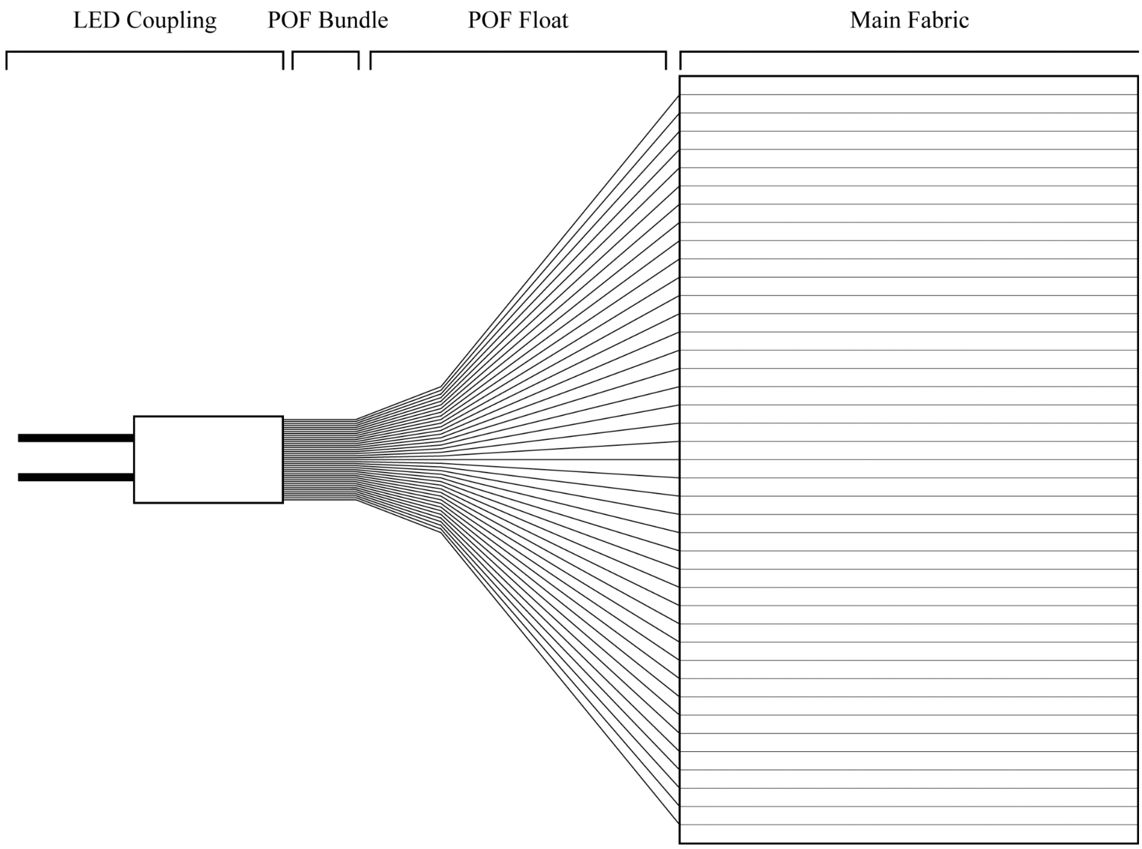

Figure 8. Diagram showing the means for attaching the light source (LED Coupling) to the POF

Knit POF appearance

The knitted POF fabric has a different appearance to inlay POF. Figure 9 an inlay POF sample and a knitted POF sample which both use the same needle setup, illuminated from the same light source. While both integrate POF horizontally in the fabric, the creation of the loops in the knitted POF creates areas of increased light emission along the vertical direction. The appearance of the fabric is that of an overall area of illumination, with vertical stripes of stronger illumination. The travel distance of the light in the knitted sample is shorter than that of the inlay sample, likely due to the increased damage in the fibre. The inlay POF creates even illumination over the fabric, however, it is dimmer than the knitted POF. There is less damage to the POF in the inlay sample, since the light has travelled to the opposite end of the fabric. In contrast, there is no light visible on the opposite end of the knitted POF fabric.

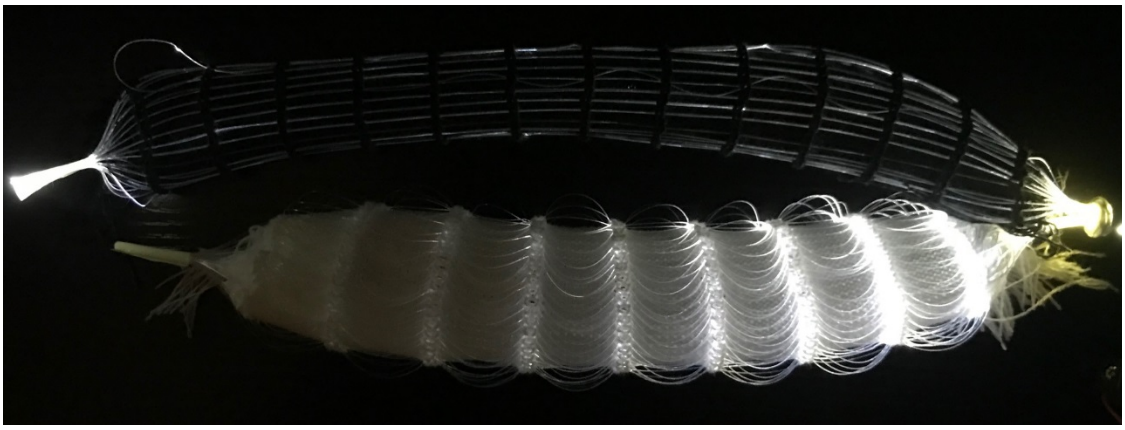

Figure 9. Inlay POF sample and Knitted POF Sample connected to the same light source

Part 2: Constructing a POF knitted garment

Shaping knitted POF pieces

A raglan sleeve knitted jumper was designed to test the shaping capabilities of POF knitted fabric. A simple design was chosen, which used straight diagonal lines for the shaping. The POF knitted section was placed in the shaped area on the front piece of the garment, as a wide horizontal strip across the chest. The '5x1' POF needle setup pattern, with the pattern of two courses of acrylic yarn to two courses of POF was used. The key element that needed to be resolved was the inclusion of the additional waste sections in the shaped knitted piece. Casting on the waste section at the same time as casting on the knitting for the main section would negate some of the benefits of knitting a shaped garment piece i.e. less wasted material. As such, the waste section was cast-on at a later stage in the knitting process and incorporated into the shaping of the garment (Fig.10). The three stitches on the edge of the fabric were transferred to the back needle bed to become the waste section, while the adjacent stitches were transferred in according to the shaping pattern. Once the spacing between the waste section and the main fabric was 20 needles long, the POF could be knitted into the fabric piece. Additional weights were added to the edge of the fabric to maintain sufficient fabric takedown force. The waste section was not transferred in, as it was not necessary to maintain a consistent length of POF floats, only a minimum length. It is more beneficial to have longer POF bundles that can be trimmed down to the required length.

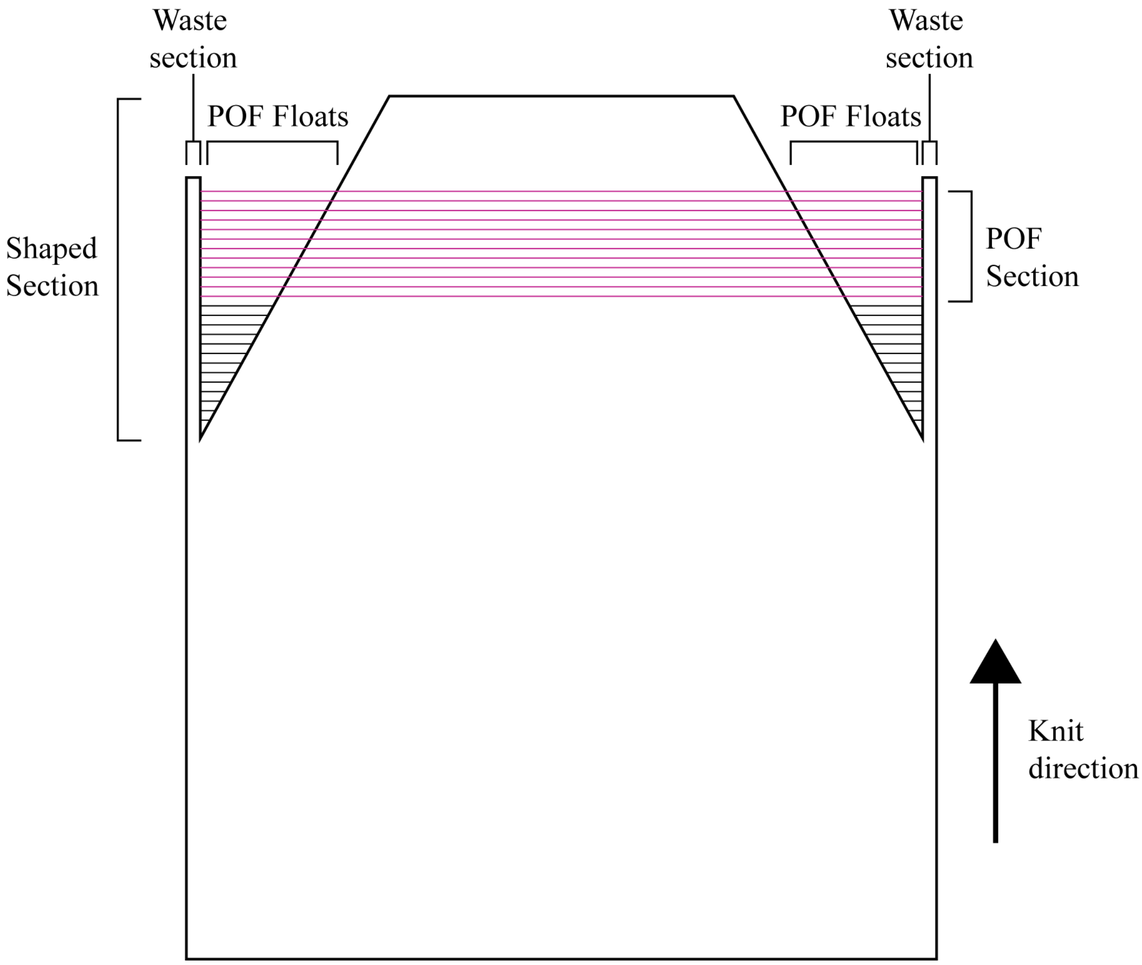

Figure 10. Diagram of garment front piece

Figure 11. Knitted POF raglan jumper front piece (Pre-bundling)

Garment assembly

The other pieces of the garment: the back, sleeves and collar and waistbands, were knitted without POF. The POF bundles were prepared prior to linking, firstly by gluing the fibres into bundles and trimming away the excess yarn. The POF section of the front piece included two bundles on either side. Using two smaller bundles reduced the gathering of the fabric in this section. An LED coupling was attached to each side as the light emission from one LED would only reach the centre of the garment. Once the garment was linked together, the remaining electronics were connected. The LED couplings were attached to the POF bundles and the wires were soldered together to connect the LEDs to a battery placed in the waistband.

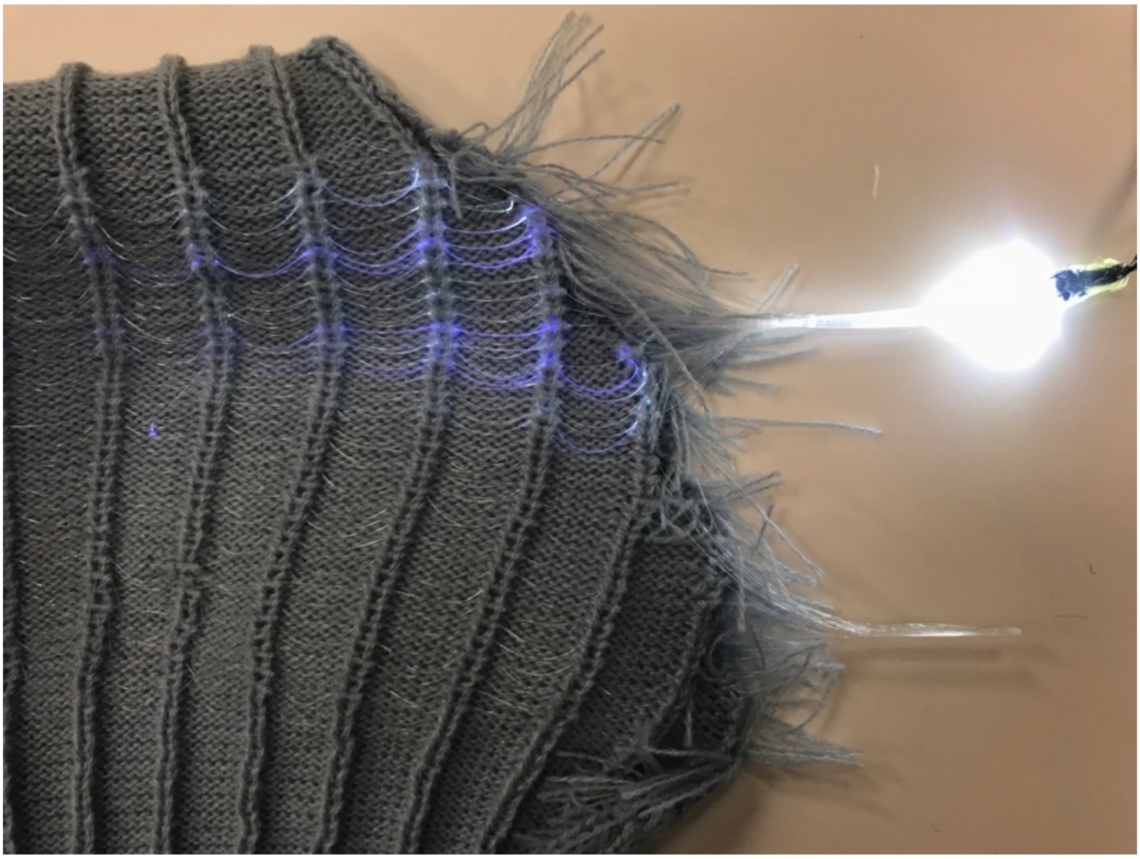

Figure 12. Knitted POF raglan jumper front piece (Post-bundling)

Figure 13. Knitted POF raglan jumper, illuminated in a dim room

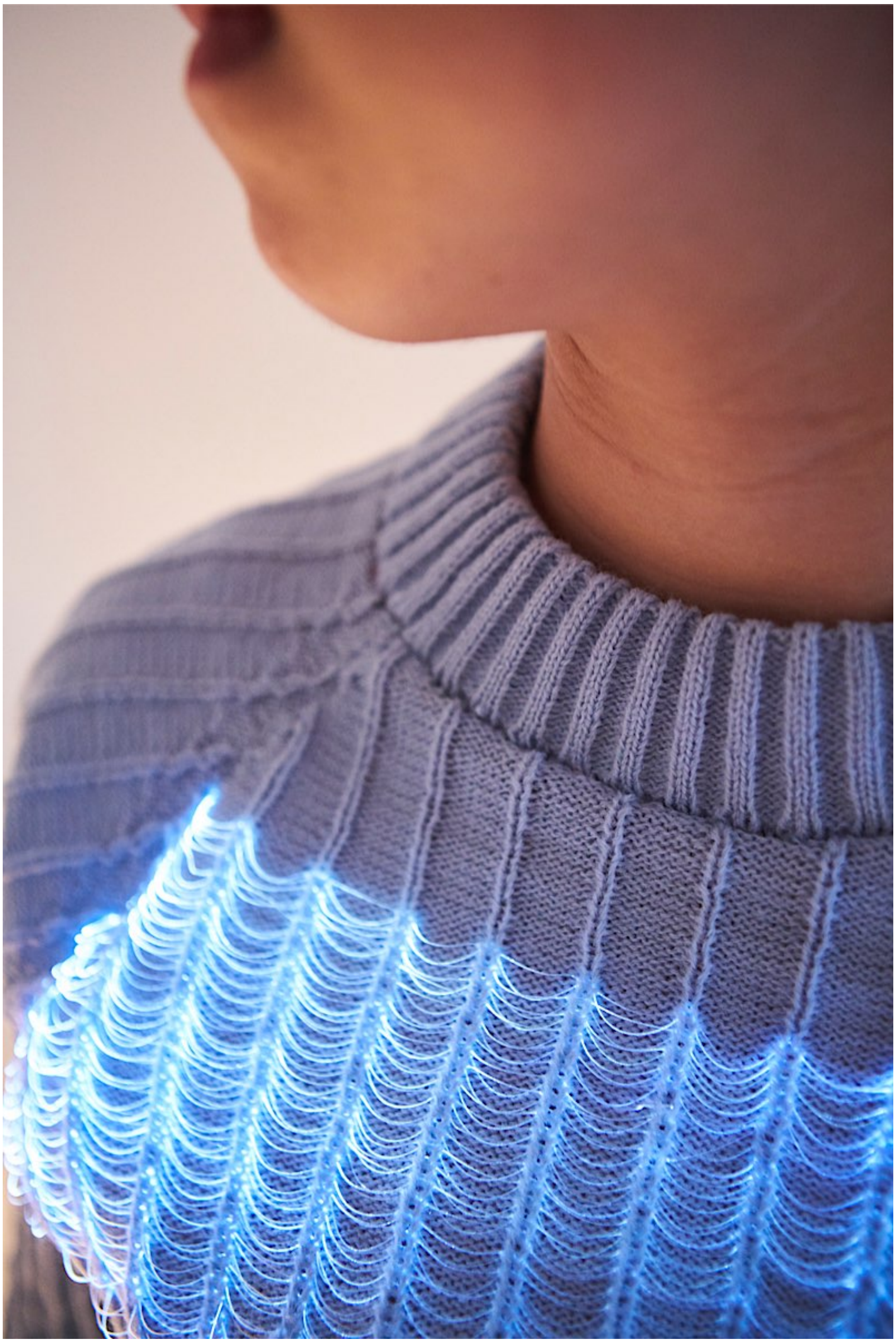

Figure 14. Knitted POF raglan jumper, illuminated in a dim room (Detailed angled view)

Evaluation

Design Benefits

The knitted POF jumper demonstrates the design possibilities for POF when used within a knit structure. For textiles design, knitting POF creates an illuminated fabric that is more textural when compared to inlayed POF. There is opportunity to further explore the manipulation of the knit structure and its impact on the illumination pattern.

For fashion design, the ability to create shaped POF garment pieces reduces the restrictions on the garment design. The knitting technique can be used in conjunction with fabric shaping to create shaped fabric pieces, which in turn, can be used to create more form fitting garments. The extensibility provided by the knitted structure also lends itself to this purpose. The knitted POF has can stretch vertically and has a small amount of stretch in the horizontal direction. The POF prevents the knitted fabric from contracting horizontally to the same extent as areas without POF. The weight of the fabric when paired with this diameter of POF means that the POF has not affected the shape of the garment greatly, when compared to the author's previous work, although the effect is still visible, as seen in Figure 11.

A practical advantage for POF garment design is that POF can be selectively integrated into the garment pattern pieces during the knitting process. In contrast, if this same design were to be created in woven fabric, the front pattern piece would either must be split into sections and later assembled into a single front piece, or a woven POF fabric would have to be woven with a section of POF. This would likely produce more fabric wastage since the pattern piece could only be placed on specific areas of the fabric. Using linking to join the garment pieces also suits POF knitted fabric, as it is possible for the fibres to be placed away from the direct path of the needle, preventing additional damage caused in the garment construction process.

Limitations

While the technique developed for knitting POF can produce consistent results, it could not prevent all critical damage to the fibre, as some fibres in the fabric did snap. The key factor is the tensioning of the fibre. The ideal tension on the fibre is slack, to allow the needles to pull the fibres without straining the fibre and to prevent the fibre floating out of the reach of the needle, stopping loop formation. However, it is difficult to maintain the tension as the fibre is wound on a reel, rather than a cone, which unwinds less easily as the amount of fibre on the reel decreases. The slippery nature of POF makes it difficult to wind onto a cone. Providing too much slack to the fibre can also cause the fibre to tangle around part of the machine. Due to the difficulty maintaining the appropriate tension, the knitting speed must be low to allow the fibre time to unwind and reduce tension. Nevertheless, the fabric's appearance was not drastically affected by the breakages, as the dropped stitches did not ladder down the fabric, due to the combination of the POF's rigidity. The use of LEDs on both ends of the fibres also compensated for illumination problems associated with the fibre breakage.

As with woven POF garments, the conventional construction methods had to be altered to accommodate this challenging material. The addition of the waste section for the POF meant that the garment may not be considered completely fully-fashioned, as there is no longer a secured knitted selvedge on the front piece. However, it would have been difficult to secure the frayed edges, as an overlocking machine may have cut the POF bundles. The frayed edges are caused by a limitation of the machine, since the carriage must be returned to the end of the needle bed to switch between yarn feeders, thereby forcing the main yarn to be knitted into the waste section. Using a knitting machine without such a limitation would mean that a secured selvedge could be created.

Conclusion

The knitted POF raglan jumper illustrates the ability to knit polymeric optical fibres and the ability to incorporate illuminating optical fibres into a form-fitting garment. Though it was necessary to take into account certain considerations for knitting a challenging fibre such as POF, it was still possible to push the design possibilities of the knitted POF. In this work, a new textiles structure for textiles-based illumination was created, which addresses the problems of fibre slippage and poor drape qualities associated with inlayed POF. By knitting the POF into a shaped fabric piece, it tackles the design restrictions seen in woven POF garments, allowing form-fitting garments to be creates more easily, through the combination of a more stretchable fabric, and shaped garment pieces.

While a basic technique for knitting and assembling a knitted POF garment has been devised, there is scope for further research. The knitting technique can be further refined to reduce critical damage to the optical fibre and improve the appearance of the shaped pattern pieces. There is scope to further explore POF knitting from a design perspective. The knit structure can be further manipulated to create new textile designs, and to improve the physical properties of the fabric, such as the hand feel, extensibility and draping qualities. Future work can look to determine the relationship between the looped POF structure and the light travel distance, to establish the parameters for illuminated POF fabric.

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