POF-yarn weaves: controlling the light out-coupling of wearable phototherapy devices

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Abstract: Neonatal jaundice (hyperbilirubinaemia) is common in neonates and, often, intensive blue-light phototherapy is required to prevent long-term effects. A photonic textile can overcome three major incubator-related concerns: Insulation of the neonate, human contact, and usage restraints. This paper describes the development of a homogeneous luminous textile from polymer optical fibres to use as a wearable, long-term phototherapy device. The bend out-coupling of light from the POFs was related to the weave production, e.g. weave pattern and yarn densities. Comfort, determined by friction against a skin model and breathability, was investigated additionally. Our textile is the first example of phototherapeutic clothing that is produced sans post-processing allowing for faster commercial production.

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1. Introduction

Many new-borns initially show symptoms of neonatal jaundice [1]. Especially premature
infants are at risk with 80% developing hyperbilirubinemia. Neonatal jaundice (with its name-
giving yellow discoloration of the skin, mucous membranes, and sclera) is caused by elevated
total bilirubin values [1, 2]. Blood transfusion becomes necessary for high total serum
bilirubin (TSB) values within the high-risk-zone (depending on postnatal age) to avoid brain
damage [3, 4]. The most common treatment option, however, is phototherapy, usually
performed with blue wavelengths-light (430-490 nm) enabling the conversion of the
naturally-occurring z,z-isomer of bilirubin (Fig. 1 showing the unconjugated molecule) to
photoisomers which are less lipophilic and can then be excreted [4–7]. The conversion is
dependent on the intensity of the used light (Fig. 1).

![Fig. 1. Decline of serum bilirubin content depending on the average spectral irradiance shown
with an exponential fit added to guide the eye, adapted from [4]; inset showing the
unconjugated bilirubin molecule with the intramolecular hydrogen bonds between the oxygen
(red) and hydrogen (white) atoms with dashed lines.](image)

Phototherapy is usually performed in incubators. These require the baby to lie undressed,
with eye protection, for extended periods of time underneath the lamp. Not only does this
remove the warming clothing layer and resulting air gap microclimate but it also prevents
body contact from its mother. Different products that worked towards a more flexible
treatment option including optical fibres have been released in the recent years. Natus
Medical Incorporated has developed blankets of 500 and 250 cm² treatment area respectively
[8]. Both can supply 30-50 μW/cm²/nm of spectral irradiance for treatment. The bilisoft
phototherapy system (GE Healthcare, Little Chalfont, United Kingdom) also uses a fibreoptic
solution and is produced in two sizes (450 and 750 cm²) targeted at neonates at different
weights (below and above 1500 g) that adhere to phototherapy guidelines (35 and 50
μW/cm²/nm respectively) [9]. Similarly, the Lightex textile and the O-blanket use optical
fibres but are not commercially available yet [10, 11]. However, all of these require additional
covers of skin-friendly fabric to protect the neonate’s skin. Additionally, these structures are
still mostly rigid with low water vapour diffusion, leading to decreased sensorial and thermal
physiological comfort of the patient.

Polymer optical fibres (POFs) have recently been used for many solutions in the
healthcare and medical sector [12]. Weaving of POFs, also for the treatment of neonatal jaundice, has been investigated before. However, within those research projects, not all
parameters in textile production were examined or focused e.g. on only one weave structure
or single-point measurements [13–17]. The authors then rather evaluated isolated fibres or
smaller textile patches. Cochrane et al. produced a homogeneously-lighting weave of 100 cm². However, the used, complicated weave pattern makes loom preparation difficult. Additionally, the factors influencing the light intensity were not completely described [17]. Many of these approaches also include mechanical or chemical treatment of the fibre for light out-coupling which adds complexity and cost to the production process [18–20]. Patents on the weaving of POFs, regardless of application, also include pre- and post-processing steps such as hot pressing, lamination, fiber deformation, notches, scratches, coatings or diffusers [21–26]. Alternatively, set-ups are proposed in which the textile haptic is lost: with encapsulation or covers of the light-emitting surfaces [27, 28].

Our previous work with in-house developed, ductile polymer optical fibres included the development of flexible, textile sensors by means of embroidery: These were applied for the sensing of vital parameters and health monitoring [29, 30]. Specifically, the oxygen saturation with polymer optical fibres in reflection mode was measured [29]. In a LED-powered set-up, the heart rate was also measured in reflection mode from the forehead [30]. There, we have also demonstrated the washability of these bi-component fibres. This reusability therefore could be also applied to a lighting fabric. Washing renders it a promising candidate for commercialization by increasing the life cycle.

The same technology, embroidery, has already been explored before in our research team for creating a homogeneous lighting fabric [31–34]. In these earlier works, however, conventional, rigid POFs based on PMMA have been used. These fibres present a worse haptic when compared to our in-house developed ones.

In this paper, these yarn-thin POFs were used in weaving to obtain homogeneous emission of light towards the neonate’s skin by means of bend-out-coupling. The out-coupling is based on the concept of total reflection of light within the fibre, up to a critical angle [12]. Hence, the bending radius within the weave structure influences the light loss. Here, we investigated the influence of warp yarn thickness, weave pattern, and weft yarn density and used these results to produce a homogeneously-lighting fabric. Homogeneity was defined as constant intensity across the produced fabric. For the treatment of neonatal jaundice, the novelty of this research is the possibility of removing the incubator, making the treatment more flexible. With this textile, treatment could be continued during nursing. Due to the ductility and low diameter of our in-house produced POFs, the objective of this research was hence to develop a flexible luminous fabric neither requiring post-processing nor an additional textile cover on top of the light source. We paid special attention to comfort in terms of friction and breathability, as well as easy-care and hygiene.

2. Materials and methods

2.1. Weave production

The weaves were produced with a semi-automatic loom (Patronic B60, ARM AG, Biglen, Switzerland) using in-house produced polymer optical fibres as weft yarn and a modified polyester (Trevira CS) as warp yarn. The POFs were produced by melt-spinning, a continuous, high-speed production method [30]. The weft fibres had a diameter of 161 ± 4 μm while the warp thread diameter was 261 ± 42 μm. Both were evaluated by microscope (Keyence VHX-1000 Multiscan microscope (Osaka, Japan)) after embedding in epoxy. The warp beam was produced by hand as we varied the number of warp threads per heddle eye. Hence, textiles with warp thread densities of 12, 24, and 36 ends/cm were produced while the reed was kept unchanged. The weaving pattern denominations were chosen to conform to reed set-up. The five different used weaving patterns were: plain weave, plain weave alternating with Trevira CS, Satin 2/2(2), Satin 3/3(3), and Satin 6/6(6). With the varying warp thread counts, all weave patterns were hence produced for 12, 24, 36 ends/cm.

Table 1 shows the schematics as well as microscope images of the produced weaves. The images show – to some extent – also the changing weft fibre density. The warp thread and weft fibre densities (ends/cm and picks/cm) are listed in Table 2. With decreasing number of
interlacing points, e.g. from plain weave to satin 6/6(6), the weft yarns can be pushed together more tightly. Similarly, with a higher number of warp threads, the weft yarn density decreases. Table 2 also lists further parameter of the weaves which are discussed in the investigation of thickness. All densities were normed to 1 cm$^2$ of weave as to include the Trevira CS content into both weft and warp direction. The weaves with alternating Trevira CS as weft fibre (weaves ID02, ID07, and ID12) were produced for a more textile feel. Even though they are comparable in weft fibre density, they should show different haptics. Finally, the table also lists several variations on weave ID10: These were produced with different POF densities (per cm$^2$) as to confirm the effect of light re-in-coupling from POF to POF. They are obtained by pushing the POF tighter together with the reed during weave production.

2.2. General characterization

This subchapter deals with considerations and requirements of the produced textiles: While thickness and drapability influence mostly the textile haptic, other parameters can strongly influence whether the textile can be used in a medical environment. Such, the coefficient of friction is highly important for usage at sensitive skin. Additionally, breathability is important for a comfortable skin climate at the fabric interface.

The weaves were hence initially characterized by thickness which was measured in norm climate (20 °C, 65% relative humidity (RH)) after conditioning for 24 h. The measurement followed EN ISO 5084 (1996) for textiles with a Frank Typ 16302.010 (Karl Frank GmbH, Weinheim, Germany). For this, a load of 1 kPa was applied to the textile patches for 30 seconds before measurement.

Additionally, the coefficient of static friction was investigated: the weaves should exhibit coefficients of static friction comparable to commercial textiles. Since the fibres are smooth, discomfort due to the fibre topography (such as the amount of short fibre ends) is ruled out. Important textile factors influencing the friction and abrasion resistance of a textile are yarn twist, diameter, ply, crimp fabric thickness, thread density, and type of weave. In this investigation, the influencing factors are limited to the type of weave as well as thickness [35]. For comparing all weaves, all weaves were tested under the same load (10 N). This value was determined by the grammage of the thickest weaves and corresponds to typically-used abrasion resistance measurements. This value also provides stable values from the textile friction analyser. The skin-fabric interface was simulated with a mechanical skin model, Lorica soft® (Lorica Sud, Milan, Italy) [36, 37]. The samples were tested for 1000 cycles after run-in. The mean static coefficient of friction was calculated by averaging 50 cycles and three repetitions per weave type. The stroke length was 20 mm with an oscillation frequency of 1.25 Hz. Weave 01, 02, and 03 were prepared with double-stick tape only at the rims due to their thinness. All tests were performed in standard climate conditions (20 ± 1 °C, 65 ± 2%RH) with the textiles conditioned for 24 h before the test as well. For evaluation across all weaves; the mean value was taken across all 1000 cycles. The standard deviation was calculated with taking error propagation into account.
Table 1. Production parameters and schematic of the weaves: Trevira CS is depicted in grey while the POF is marked in blue; fibres are not to size. a Pattern denomination corresponding to the set-up on a 12 ends/cm- reed; b scale bars equal 1 mm; “alt.” denoting weaves with one pattern repetition of Trevira CS-yarn in weft direction after each repetition of pattern of POF-fibres.

| ID | Pattern⁴ | Schematic | Image³ |
|----|----------|-----------|--------|
| 01 | Plain weave | ![Schematic](image1.png) | ![Image](image2.png) |
| 02 | Plain weave alt. | ![Schematic](image3.png) | ![Image](image4.png) |
| 03 | Satin 2/2(2) | ![Schematic](image5.png) | ![Image](image6.png) |
| 04 | Satin 3/3(3) | ![Schematic](image7.png) | ![Image](image8.png) |
| 05 | Satin 6/6(6) | ![Schematic](image9.png) | ![Image](image10.png) |
| 06 | Plain weave | ![Schematic](image11.png) | ![Image](image12.png) |
| 07 | Plain weave alt. | ![Schematic](image13.png) | ![Image](image14.png) |
| 08 | Satin 2/2(2) | ![Schematic](image15.png) | ![Image](image16.png) |
| 09 | Satin 3/3(3) | ![Schematic](image17.png) | ![Image](image18.png) |
| 10 | Satin 6/6(6) | ![Schematic](image19.png) | ![Image](image20.png) |
| 11 | Plain weave | ![Schematic](image21.png) | ![Image](image22.png) |
| 12 | Plain weave alt. | ![Schematic](image23.png) | ![Image](image24.png) |
| 13 | Satin 2/2(2) | ![Schematic](image25.png) | ![Image](image26.png) |
| 14 | Satin 3/3(3) | ![Schematic](image27.png) | ![Image](image28.png) |
| 15 | Satin 6/6(6) | ![Schematic](image29.png) | ![Image](image30.png) |
Table 2. Production parameters of the initial weaves as well as the optimizations of weave ID10 in the bottom 5 rows. There, only the number of optical fibres per weave cm is varied. Required space within 1 cm of the loom is defined by the pattern and the used threads’ or fibers’ diameters, values higher than 1 lead to 2D fabrics due to bundling; Volume is calculated from the radii of both POF fibers and Trevira CS threads and their count per cm².

| ID  | Weave pattern | Warp yarns [ends/cm] | Req.space [cm/cm loom]a | POF density [cm⁻²] | Trevira density [cm⁻²] | %age POF [%/cm²] | Volumeb [cm³] |
|-----|---------------|----------------------|-------------------------|-------------------|------------------------|-----------------|---------------|
| 01  | Plain         | 12                   | 0.51                    | 18                | 12.0                   | 60              | 0.010         |
| 02  | Plain alt.    | 12                   | 0.51                    | 8                 | 20.2                   | 29              | 0.012         |
| 03  | Satin 2/2(2)  | 12                   | 0.41                    | 23                | 12.0                   | 65              | 0.011         |
| 04  | Satin 3/3(3)  | 12                   | 0.38                    | 40                | 12.0                   | 77              | 0.015         |
| 05  | Satin 6/6(6)  | 12                   | 0.35                    | 158               | 12.0                   | 93              | 0.039         |
| 06  | Plain         | 24 = 12*2            | 0.82                    | 19                | 24.0                   | 44              | 0.017         |
| 07  | Plain alt.    | 24 = 12*2            | 0.82                    | 8                 | 32.2                   | 20              | 0.019         |
| 08  | Satin 2/2(2)  | 24 = 12*2            | 0.72                    | 20                | 24.0                   | 46              | 0.017         |
| 09  | Satin 3/3(3)  | 24 = 12*2            | 0.69                    | 21                | 24.0                   | 47              | 0.017         |
| 10  | Satin 6/6(6)  | 24 = 12*2            | 0.66                    | 98                | 24.0                   | 80              | 0.033         |
| 11  | Plain         | 36 = 12*3            | 1.13                    | 14                | 36.0                   | 28              | 0.022         |
| 12  | Plain alt.    | 36 = 12*3            | 1.13                    | 6                 | 42.1                   | 13              | 0.024         |
| 13  | Satin 2/2(2)  | 36 = 12*3            | 1.04                    | 15                | 36.0                   | 30              | 0.022         |
| 14  | Satin 3/3(3)  | 36 = 12*3            | 1.00                    | 24                | 36.0                   | 40              | 0.024         |
| 15  | Satin 6/6(6)  | 36 = 12*3            | 0.97                    | 88                | 36.0                   | 71              | 0.037         |
| 10_1| Satin 6/6(6)  | 24 = 12*2            | 0.66                    | 102               | 24.0                   | 81              | 0.034         |
| 10_2| Satin 6/6(6)  | 24 = 12*2            | 0.66                    | 19                | 24.0                   | 44              | 0.017         |
| 10_3| Satin 6/6(6)  | 24 = 12*2            | 0.66                    | 62                | 24.0                   | 72              | 0.025         |
| 10_4| Satin 6/6(6)  | 24 = 12*2            | 0.66                    | 94                | 24.0                   | 80              | 0.032         |
| 10_5| Satin 6/6(6)  | 24 = 12*2            | 0.66                    | 158               | 24.0                   | 87              | 0.045         |

Water vapour resistance is given as the water vapour pressure differences between the two faces of a material and was measured only for weave ID10_5 following the standard EN ISO 11092:2014 with a 20 x 20 cm measurement area at 35 °C and 40% RH. The air velocity was 1 m/s. Using a porous plate as a thermoregulation model of the skin at 35 °C, the difference in water vapour partial pressure between the air in the channel and at the skin model gives information on the water vapour permeability of the fabric. This information is derived from the heating power needed to maintain a constant temperature. The measurement was repeated thrice for an average value.

Weave ID10 was also tested for fire retardation with a base test targeted at small samples for first investigation. The test is performed under air flow. A propane burner (at 45° angle to the sample) is used for 15 seconds to inflame the lower edge of the tested fabric. The time of burning is then measured until the flame reaches the fabric 150 mm from the lower edge. If the flame extinguishes before reaching this location, the burning duration is noted. The classification differentiates between three classes, 3-5, with 5 being the best. In class 5, the flame does not reach the end of the fabric, while it takes more than 20 seconds for class 4. The samples were washed three times with hospital-type washing detergent at 40 °C to
remove dust and remains of spin fluid from production. They were then stored for a minimum of 24 h at standard conditions before testing. A weave of type ID10 prepared with 100 POF/cm, the density of the optimum textile, was used to show the effect of the POF – the weaker component in this weave – in the fire retardation test in weft direction.

2.3. Optical characterization

The normalized light out-coupling intensity from a blue LED (λ_{peak} = 470 nm with a spectral bandwidth of 25 nm, E92b, Industrial Fibre Optics, Tempe, Arizona, USA) was evaluated along the POFs with an optometer (P9710, Gigahertz-Optik GmbH, Türkenfeld, Germany). The narrow spectrum ensures that neither UV- nor IR-light is emitted during treatment which would otherwise be harmful to the neonate. The out-coupling intensity was noted every centimetre (limited by detector head size). The wavelength range of the LED was then used for calculating the spectral irradiance from the measured power density. For alignment along the textile, a paper mask was prepared to ensure correct placement of the optometer across the prepared weaves. The measurements were repeated to take connector and LED-variability (at a current of 10.6 mA) into account. The used detector covered from 400 to 1000 nm (RW-3705-2, SN21103) with an 11 mm diameter diffusor window.

3. Results and discussion

3.1. General characterization

The thickness of the weaves is shown in Fig. 2 (upper left). Except for two outliers, the thickness increased with increasing number of warp yarns per heddle eye. One of the outliers is eliminated when converting to normalized thickness by dividing with the weft fibre number (POF/mm). Weave ID05 shows a proportionally higher weft fibre number (Fig. 2 (lower left)). The other outlier, weave ID07 is probably caused by an irregularity in the weave since the standard deviation is much higher than for the other weaves. This weave otherwise also fits in with the trend of decreasing percentage of optical fibres (Table 2) with increasing number of threads per heddle eye. It can be noted that the Satin 6/6(6) weaves showed much higher thickness, also differentiating themselves by the much higher weft yarn density (Table 2). For all weaves, the maximum density at complete alignment (one POF next to the other) is 62 POF/cm. Therefore, weaves with higher weft yarn density show a much denser fabric and have to be pushed together and overlap each other. This leads to an increase in thickness.
Fig. 2. (Upper left) Thickness of the weaves: At each section, three bars are plotted for (red) 1 warp yarn per heddle eye, (yellow) 2 warp yarns per heddle eye, and (green) three warp yarns per heddle eye; (lower left) Normalized thickness of the weaves in which the thickness is divided by the number of weft fibres per mm; (upper right) Static coefficient of friction of all weaves with 2 threads per heddle eye (ID06-10) in dry, stable conditions over 1000 friction cycles; (lower right) Coefficient of static friction of the prepared weaves averaged over 1000 cycles. The two lower graphs show the same colour-coding as described in the upper left.

Investigating the static coefficient of friction (COF), the plain weaves and the satin weaves showed distinctly different results. The plain weaves (ID01, 02, 06, 07, 11, and 12) showed much lower coefficients of friction than the satin weaves (Fig. 2(c) and 2(d)). These weaves additionally showed a much longer run-in effect. Due to flexible nature of the POF and the higher pattern width of the satin weaves (and the higher weave factor); we believe that the satin weaves flattened out more during the test. With less intersections of warp and weft yarn, they can consequently behave similarly to flat surfaces. Due to a higher contact area, these then result in higher COFs. Figure 2(c) also shows the non-averaged results of weaves ID06 to ID10. The COF stays stable over the 1000 cycles, as was already demonstrated by the small standard deviations on the bars of averaged results. Except for ID06 and ID07, all coefficients of static friction increase with higher twill order of the weave (from plain weave to satin 6/6(6)). However, this is not an effect of Amonton’s 2nd law of friction since all weaves consist entirely of the investigated fibres but rather their different structure. Interestingly, though the weave factor (describing the interlacing points of weave and weft yarns) increases from 1 to 2, 3 and finally 6, the largest difference is seen between weave factor 1 and the rest [38].

The water vapour resistance gives an indication of the breathability of the material and is derived from the EN ISO 11092:2014 Standard; values below 6 classify as excellent following the Hohenstein scale. For this test, we chose a weave with the highest weft yarn density available. With thinner fabrics of the same type, the value should decrease. The POFs themselves, with the highly-fluorinated cladding, should show hydrophobicity since Ok et al. reported near-superhydrophobicity of their THV-electrospun fibres [39]. The weave ID10_5 (with the highest density of 158 POF/cm) averaged at 5.8 m²*Pa/W, hence a very good value [40]. The values is close to cotton underwear as reported by Scott [41]. It indicates that the
Textiles are able to prevent sweat accumulation, hence preventing heat building up at the body. It shall be noted that the fibres do not take up large amounts of water and are skin-friendly. Mechanical as well as optical properties of the used POF can be referred to in a previous publication [30]. They have proven to be washable as well [30].

Choosing a commercial polyester thread as warp thread has the advantage of rendering a homogeneous weaving outcome as shown in Fig. 3(a). Trevira CS adds to this primary advantage by being inherently flame retardant (following various fire standards) without a chemical finish while being certified for the Oekotex 100 Standard. Trevira CS also does not need special care and withstands abrasion and methods of disinfection [42]. The weaves did then show very good fire retardation as also shown in Fig. 3(d) and 3(e) respectively. It was evaluated as class 5, the highest class. These experiments indicate that the luminous textiles are promising also for alternative applications in public spaces. Besides the application proposed here (healthcare), they could therefore also be very interesting for innovative lighting applications, an application in which fire retardation is a concern. For that purpose, however, larger weaves would have to be produced to verify safety of use in public buildings or similar, as ISO classification requires testing of numerous larger specimen. These preliminary tests were performed only in weft direction since the POFs were aligned in that direction. We assume that the fire retardation of the warp direction should show similar or even better values since the Trevira CS yarn is, as noted in the Materials section, inherently flame retardant.

![Fig. 3. (a) Produced weaves ID01 to –05 all showing good flexibility; the POFs are bundled at one end to enable light in-coupling; (b) and (c) Production of weave ID10_5 with connecting POFs and both sides of the textile on the semi-automatic loom; Images of the polymer optical fibre weaves after washing before (d) and after (e) the fire retardation test in weft direction (3 samples each); (f) Bundling of threads in the loom for 3 threads per heddle eye for the satin 6/6(6) (weave ID15), produced solely from Trevira CS; the scale bar indicates 1 mm.](image-url)
3.2. Optical characterization

The light out-coupling was evaluated initially by connecting LEDs to one side of the fabric. For this, optical fibres were bundled and glued into connectors. These bundles are in the following discussion denoted by “line”. The decrease in light intensity starting from one side of the fabric was hence logged. Due to varying in-coupling efficiency from the LEDs, the light intensity was normed to be able to compare the different weaves. For this, each measurement point of a line was divided by the average value of this line. This also eliminates errors arising from single fibre breaks at the edge of the textile.

For a tight but 1D arrangement of the yarns, some of the weave patterns can be excluded. Weave ID11, e.g., requires 1.13 cm per available 1 cm of loom. It hence has to lead to bundling of yarns, as can be seen in the microscope image (Fig. 3(f)), also making theoretical evaluation of bending curvatures more difficult. Therefore, the weaves primarily discussed here are weaves that contain a tight pattern while not bundling the yarns drastically, as calculated in required space (Table 2).

Examining the results of two warp threads per heddle eye, a tendency becomes apparent: With increasing pattern width, i.e. from plain (samples ID06 and ID07) to satin (samples ID08, ID09 an ID10), the light out-coupling changed from an exponential loss curve to one resembling a linear fit (Fig. 4 (left)).

At the same time, comparing the satin 6/6(6) weaves, the two warp threads per heddle eye (ID10) showed the lowest slope (Fig. 4 (right)). The lower slopes of weaves ID10 and ID15 compared to ID05 could be explained by a higher percentage of re-in-coupling of light to the neighboring POFs since ID05 present a very loose fabric.

For light losses, an exponential loss can be fitted to the experimental data, with the equation given in Table 3. The solver function (Excel Add-on, Microsoft Corporation, Redmond, WA, USA) provides the coefficients to these fits for all of the initially produced weaves. While this fit results in high R²-values for all weaves, the primary objective, a homogeneously lighting fabric, cannot be evaluated by an exponential fit. Therefore, a linear fit was also performed for evaluation of these weaves. The coefficients of the linear fit to the data are also shown in Table 3.

The theoretically-optimum coefficients have to show a high R²-value (>0.9) as to ensure homogeneity across each line. At the same time, the slope and the y-axis intersect value of the fits have to give a positive value at textile width = 19 cm, as given in Table 3 (marked in bold). Another criterion was a low slope (or a high value for I(19)) as to maximize light intensity. Weave ID10 was chosen as the best option due to a low slope and low intersect with the y-axis while showing a large R²-value. Additionally, the k-value in the exponential fit is the lowest of all, speaking for fewer outliers. Weave ID09 showed even slightly better values...
in the linear fit; the higher linearity of ID10 however made the difference in selection. The feasible options for each coefficient of the linear fit are marked in bold-face (Table 3). From this, it is clear that weave ID10 is the only weave complying with all the prerequisites.

Table 3. Coefficients to the exponential as well as linear fit for the light out-coupling of the weaves, illuminated from 1 side. The $R^2$-value is given for all weaves for both fits. Coefficients of the linear fit feasible following calculations are marked bold as well as $R^2$-values above 0.90.

| Weave ID | Coefficients of exponential fit $I(x) = A \cdot e^{kx}$ | Coefficients of linear fit $I(x) = b \cdot x + y_0$ |
|----------|------------------|------------------|
|          | $A$       | $k$       | $R^2$-value | $b$       | $y_0$ | $l(19)$ | $R^2$-value |
| 01        | 7.25     | 0.33     | 0.98        | -0.25     | 3.36  | -1.39   | 0.70         |
| 02        | 14.8     | 0.56     | 0.98        | -0.32     | 4.01  | -2.07   | 0.48         |
| 03        | 2.46     | 0.11     | 0.99        | -0.10     | 2.02  | 0.12    | 0.94         |
| 04        | 2.38     | 0.10     | 0.97        | -0.09     | 1.91  | 0.20    | 0.80         |
| 05        | 2.28     | 0.10     | 1.00        | -0.09     | 1.87  | 0.16    | 0.90         |
| 06        | 6.79     | 0.32     | 0.99        | -0.2      | 2.96  | -0.84   | 0.64         |
| 07        | 10.5     | 0.43     | 0.96        | -0.24     | 3.42  | -1.14   | 0.53         |
| 08        | 2.33     | 0.10     | 0.99        | -0.09     | 1.85  | 0.14    | 0.81         |
| 09        | 1.43     | 0.04     | 1.00        | -0.04     | 1.36  | 0.68    | 0.86         |
| 10        | 1.46     | 0.04     | 1.00        | -0.04     | 1.4   | 0.63    | 0.96         |
| 11        | 1.72     | 0.06     | 0.97        | -0.06     | 1.61  | 0.47    | 0.77         |
| 12        | 2.22     | 0.09     | 0.95        | -0.10     | 2.01  | 0.11    | 0.90         |
| 13        | 2.17     | 0.09     | 0.99        | -0.08     | 1.80  | 0.28    | 0.87         |
| 14        | 2.13     | 0.09     | 1.00        | -0.08     | 1.81  | 0.28    | 0.91         |
| 15        | 1.77     | 0.06     | 1.00        | -0.06     | 1.62  | 0.44    | 0.98         |

To verify that this weave would be the most efficient, the measured data was mirrored (to simulate LED-illumination from the other side as well) and summed. More complicated weaves, with varying weave patterns and warp yarn thickness – and hence bending radii – across the width of the textile, were omitted since these would have made production and loom preparation much more difficult. The theoretical light out-coupling intensity of weaves ID09 and ID10, the weaves fulfilling the requirements as detailed in Table 3, are shown in Fig. 5. They show an average intensity of 2.00 ± 0.15 or 2.00 ± 0.06 respectively. Therefore, we proceeded with the pure weave ID10.

![Fig. 5. Theoretical light out-coupling intensity of weaves ID09 (left) and ID10 (right): (red) measured data in-coupled from the lefthern side of the textiles as well as mirrored for the rightern in-coupling; (blue) the sum of the two. The standard deviation of the total is derived with error propagation of the two single lines. The linear function minimizing $\chi^2$ of experimental data and solving function is plotted with black circles for both weaves. The coefficients can be taken from Table 3.](image-url)
To additionally investigate the effect of weft yarn density, several weaves of pattern ID10 were produced (Table 4, Fig. 3(b) and 3(c) in production). Except for the weft yarn density, the weaves had the same structure and were hence comparable. To evaluate the effective homogeneity across the textile, these weaves were produced with POF bundles for usage of LED connectors at both sides. For analysis, the data was flipped at the middle, also seen from the schematic in Fig. 6(b). With this method, a potential decrease in the middle of the textile can be quantified. It additionally follows the evaluation principle for weaves illuminated only from one end.

Table 4. Confirmation of a re-in-coupling effect: weave production parameters for weaves of type ID10 (as determined as the best fitting (Table 3). Their optical properties are listed as slope and R²-value. These are determined from light out-coupling experiment while illuminated from both sides.

| Weave ID | POF density [cm⁻²] | Coefficients of linear fit \( I(x) = b \cdot x + y_0 \) |
|----------|---------------------|-----------------------------------------------------|
| 10_5     | 158                 | \(-0.060\) \(1.308\) \(0.852\)                     |
| 10_1     | 102                 | \(-0.029\) \(1.143\) \(0.425\)                     |
| 10_4     | 94                  | \(-0.021\) \(1.104\) \(0.682\)                     |
| 10_3     | 62                  | \(-0.024\) \(1.100\) \(0.919\)                     |
| 10_2     | 19                  | \(-0.039\) \(1.195\) \(0.937\)                     |

The value of the slopes, as also depicted for ID10_4 in Fig. 6(a), should be as small as possible. With this, the density of 94 POF/cm was found to be the best at a slope of \(-0.021\) (Fig. 6(a)). Since this density creates a (local) minimum, we hypothesize that the different weft fibre densities influence both the effective bending radius and percentage of re-in-coupled light from one fibre to another. Re-in-coupling of light has been shown in separated experiments of fibre bundles placed next to each other. The local minimum defines the weft fibre density at which bending radius and re-in-coupling effects are balanced.

Fig. 6. (a) Plot of weave type ID10_4 (double warp yarn and satin 6(6/6)) with 94 POF/cm; with a combined linear fit (as shown in Table 4) for both sides of the textile, (b) Schematic of the evaluation procedure when illuminated by LEDs from both sides; orange and blue corresponds to the data sets in (a), (c) Plot of final textile (94 POF/cm) while illuminated from both sides by LEDs, the inset shows the fabric with 1 ferrule illuminated ( = 60 POF), (d) The fabric is wrapped around a Teddy with 120 POF illuminated.
The light out-coupling intensity across the textile (ID10_4) is shown in Fig. 6(c). The light intensity of this demonstrator was, when averaged over the entire width, 1.00 ± 0.04, hence a deviation of only 4%. The figure inset also displays the corresponding weave illuminated from both sides for visual aid. Additionally, a 1.28 cm broad piece of fabric is wrapped around a Teddy (Fig. 6(d)) to demonstrate the high flexibility of the produced weave.

The power density of this weave (ID10_4) averaged 72 ± 10 μW/cm². With a ~1 cm²-resolution, the value hence varied by only 14%. This value was corrected for the full size of the detector head (*1.45, scaling by active detector head area/illuminated area) and takes the detector responsivity for the relative power density scaling (*1/0.72, see Fig. 7 (left)) into account. Converting the power density to spectral irradiance over the emission range of the LED (Δλ = 83 nm), a value of 0.87 μW/cm²/nm from 436 to 519 nm was received at 0 m from the textile surface. Values typically used in intensive phototherapy lie around 30 μW/cm²/nm, depending on weight and age of neonate [4, 43]. Hence, for intensive phototherapy, the power density and/or the spectral irradiance would have to be increased. With a narrower emission spectrum, e.g. by replacing the LED by a laser diode, the value could be increased to ~24 μW/cm²/nm solely due to the smaller wavelength range. Moreover, laser diodes also operate at much higher forward current. An alternative as to maintain a similarly wide emission spectrum, since the photodecomposition of bilirubin is effective over a large wavelength range, would involve the use of other LEDs with higher current (e.g. 1000 mA). With either of these alternatives, the textile phototherapy device could be used in clinical practice with performance similar to commercial devices. On the other hand, since the used LEDs only emit light within the absorption spectrum of bilirubin and the power density only covers relevant wavelengths (as can be seen in Fig. 7 (right)), the fabric as produced here could already be an option for less severe cases.

The developed fabrics can therefore potentially be used to treat neonates with a textile phototherapy device while being held and calmed outside the incubator as well as provided with thermal insulation by resulting air gap microclimate [44]. The textile width of 19 cm is comparable to the commercial solutions presented in the state of the art. The length of our textile is, however, theoretically unlimited, since longer weaves can be produced. Similarly, the width can be easily adapted to the required dimensions, either by using wider looms or joining smaller sections. With the current width, a sleeping bag or pajama could be produced by using two textiles (one from the back and one from the front), to fit around the neonates’ chest and abdomen. For larger neonates, with this modularity and flexibility, further sections could be added for better fit and maximum exposure. Finally, the textile could not only be used by neonates but also other patients with hyperbilirubinaemia (such as the Crigler-Najjar-Syndrome).

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4. Conclusion

We developed a lighting fabric with very high potential to be used in the treatment of neonatal jaundice. It is highly flexible and fulfills the moisture transport requirements to be used as a piece of clothing. The textile showed an extremely homogeneous light intensity with a variation of only 4% over the entire textile. The power density and/or the spectral irradiance can be easily adapted to the requirements of different applications by an adequate choice of LEDs or laser diodes. Most importantly, the here-discussed development does not require any post-processing steps as proposed previously in other optical fiber solutions. Our method is based on an optimal combination of optical and mechanical properties of POFs (that is, high side-emission, bending resiliency, and tensile modulus) and a straightforward textile production technology (weaving). Facile industrialization is therefore anticipated.

This photonic textile could be then used as a wearable phototherapy device, allowing continuous treatment at home, in the presence of the mother or caregiver. It will be a tool for the improvement of the healthcare system of new-born babies while simultaneously contributing to decrease societal and economical burdens to hospitals as well as to the parents.

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Disclosures

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