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Research Article

Selective Laser Metallization of Natural Fiber Textiles

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ISSN: 2578-0271



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Submission: November 09, 2026
Published: November 18, 2026

Volume 12 - Issue 1

How to cite this article: Robert Schmidt, Andreas Knauft, Andrea Barz, Marcel Bäuml, Andreas Ludwig, Henrik Banse, Jan Langebach and Jens Bliedtner*. Selective Laser Metallization of Natural Fiber Textiles. Trends Textile Eng Fashion Technol. 12(1). TTEFT. 000780. 2026.
DOI: 10.31031/TTEFT.2026.12.000780

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Abstract

Conductive textiles are gaining importance in wearable electronics [1,2], with applications in healthcare, sports, protective clothing, and entertainment [3]. This work investigates the selective metallization of natural fiber-based textiles using ultrashort-pulsed laser. Laser irradiation locally modifies the textile surface, enabling activation through palladium seeding in a $PdCl_2$ solution. Copper is then deposited selectively on the laser-treated areas using an electroless $CuSO_4$-based process, forming selective structures. This approach has mainly been studied on polymers [4] and synthetic textiles [3]. This work extends the process to natural fiber-based cotton textiles. It is investigated how laser parameters, chemical conditions, and textile weave structures of different cotton types influence metallization quality. The aim is to produce copper structures with small feature widths, well-defined geometries, good adhesion, and low electrical resistance for E-Textile applications. The results show that feature sizes of approximately 100µm and sheet resistances as low as 0.01Ω/□ can be achieved, showing the potential for the fabrication of conductive structures on natural fiber-based textiles.

Keywords: E-Textile; Laser-based selective metallization; Electrical conductance; Nature fibre; Textile engineering

Introduction

Electronic textiles are becoming increasingly important in the fields of health monitoring, soft robotics and sports [5,6]. Compared to synthetic fibers, cotton offers several advantages. It is biodegradable and breathable, making it comfortable to wear [1,7].

Several approaches have been developed to make cotton electrically conductive, but each has specific disadvantages [1]. For example, yarns coated with carbon nanotubes (CNTs) show a change of electrical resistance when the fabric is stretched [2]. Thin films deposited by atomic layer deposition, on the other hand, are brittle and fracture under mechanical stress [8]. Studies aimed at flattening the rough textile surface have shown that these layers can delaminate when the fabric is bent. In addition, they make the material stiffer and therefore less comfortable to wear [9].

An alternative is electroless plating. The deposited metal envelops individual fibers and enables high conductivity [1,10]. To improve the adhesion of the metal layer to the natural fiber, this process requires a complex wet-chemical pretreatment [1,11]. For example, complex polymer brushes [1] or chemical adhesion promoters and catalyst inks can be applied in multiple steps [10].

However, these and other methods require multiple immersion and drying cycles for pre-activation [11]. To improve the adhesion of the metal layer through physical means, pretreatment with CO_2 lasers has already been investigated [5,12]. Roughening the fibers with laser radiation increases the abrasion resistance of the copper [5]. However, the interaction between the substrate and the laser radiation causes thermal damage to the fibers, thereby

reducing the mechanical properties of the fabric [12]. This thermal problem can be solved using ultrashort-pulse laser systems [13]. The femtosecond pulses activate the material with almost no heat input, allowing the fiber surface to be modified without damaging the underlying cotton fabric [13]. As has already been demonstrated on plastics and synthetic fabrics, ultrashort-pulse (USP) laser processing can be specifically used for laser-based selective activation (LSA) to selectively deposit metallic conductive tracks [3]. In this study, this approach is applied to cotton textiles. The goal is to selectively activate the cotton fibers using USP laser radiation in order to subsequently create electrically conductive structures via non-current metallization. The study examines laser and scanning parameters, as well as the dwell time in the chemical baths and the intervals between the individual process steps. In addition, the influence of various textile weaves on the metallization results and the resulting electrical surface resistance will be analyzed. Finally, the process's applicability will be tested through soldering tests and by building an initial demonstrator prototype.

Experimental Section

Process chain

The process chain for LSA is shown in Figure 1. For selective metallization of natural fiber textiles, the textile surface is activated using an USP laser system (Figure 1a). Subsequently, the laser-activated surface is seeded with palladium in a $PdCl_2$-containing bath (Figure 1b). Finally, copper is selectively deposited onto the laser-treated areas by an electroless copper deposition process (Figure 1c) based on a $CuSO_4$-containing solution, resulting in the formation of selective conductive structures (Figure 1d) [14]. Each of the steps can be modified for selective metallization of the natural fiber textile substrates.

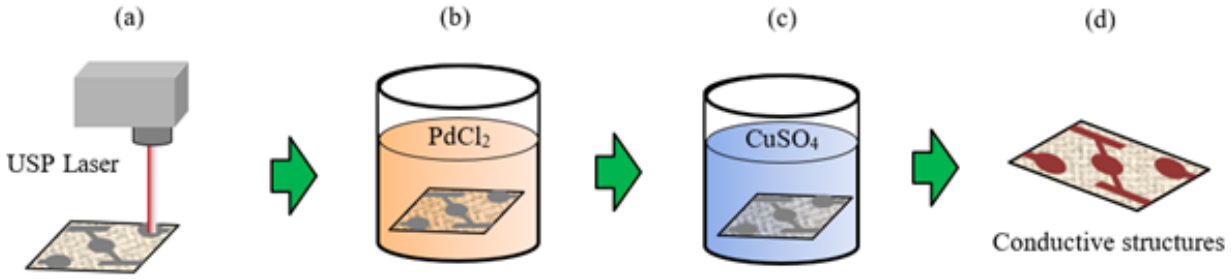


Figure 1: Schematic illustration of the selective metallization process of textile substrates: (a) laser activation using an ultrashort pulse laser, (b) immersion in a $PdCl_2$ solution, (c) selective metallization in a $CuSO_4$ solution, (d) resulting in conductive metallized structures on the textile substrate [14].

The resulting metallization quality is influenced by the material, the surface topography, the selected laser parameters and the chemical process parameters. The relevant chemical parameters include, in particular, the concentrations of $PdCl_2$ and $CuSO_4$, as well as the temperatures and immersion times in the process baths. In addition, the dwell times between the individual process steps also affect the resulting metallization quality.

Laser parameters

An ultrashort-pulse laser (TruMicro 6020, TRUMPF) with a wavelength of λ=1030nm and a pulse duration of 500fs was used for the experiments. The laser beam was focused using an F-theta lens with a focal length of f=167mm leading to a focal spot diameter of d_f=25µm.

A galvanometric scanning system (intelliSCAN se14, SCANLAB) was used to move the laser beam over the textile surface with a maximum scan field of 120mm×120mm. The experiments were conducted on 8x8mm² square areas in a 5x5 matrix on the samples. The laser fluence F_L and pulse spacing d_p were varied as laser parameters (Figure 2). The laser fluence F_l was calculated by the pulse energy E_p and the circular area A of the gaussian laser spot, which is defined by the focal diameter d_F (Equation 1).

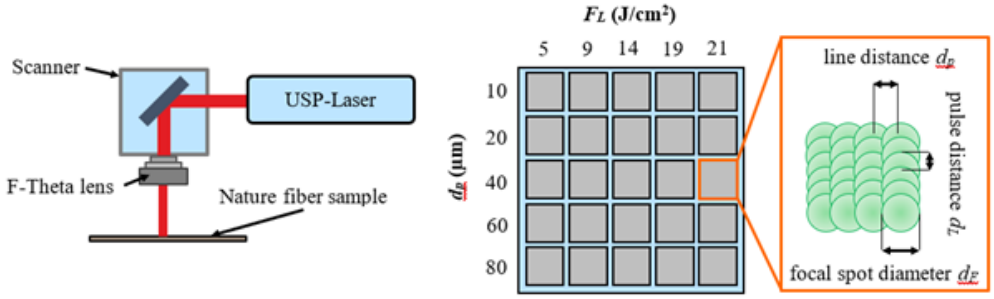


Figure 2: Schematic illustration of (a) the laser and scanning setup and (b) the applied laser parameter matrix (5×5) on the textile surface, with changing laser fluence F_L and pulse distance d_p [14].

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$$F_L = \frac{2E_p}{A} \quad (1)$$

Equation 2 was used to calculate the pulse spacing d_p based on the scanning speed v_{scan} during laser processing and the repetition rate RR [14].

$$d_p = \frac{v_{scan}}{RR} \quad (2)$$

For the experiments in this work, the repetition rate was kept constant at RR=25kHz and the hatch spacing was fixed at d_L = 20µm. Each area was scanned three times [14].

Materials

Different cotton-based natural fiber textiles were used as substrate materials. The textiles in the experiments were provided by the company Thorey Gera Textilveredelung GmbH. The samples were stored under atmospheric conditions and mechanically cut to the required dimensions. In addition, textiles with different weave structures were investigated to evaluate the influence of the textile construction on the metallization process. Three weave structures (Figure 3) were investigated: (a) plain weave, (b) twill weave, and (c) satin weave [15].

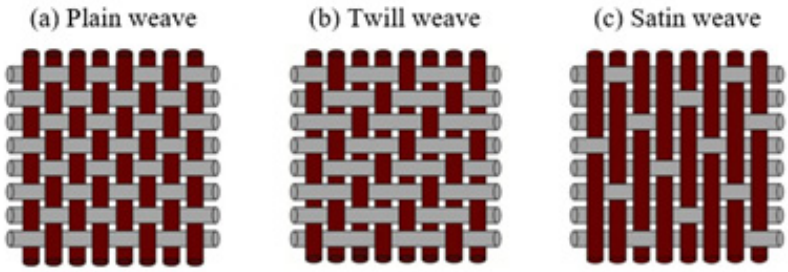


Figure 3: Schematic comparison of the weave structures of the investigated cotton fabrics: (a) plain weave, (b) twill weave and (c) satin weave [15].

The three weave structures are different in the number of interlacing points between the warp and weft yarns. The plain weave has the highest number of interlacing points, resulting in a comparatively dense and stable fabric structure. In the twill weave, the interlacing points are less frequent, forming the characteristic diagonal pattern. This structure gives the fabric a softer drape. The satin weave has the lowest number of interlacing points, resulting in longer yarn floats on the fabric surface and consequently a particularly smooth surface structure [16,17]. In addition to investigating the influence of various process parameters throughout the process chain, the effect of different weave structures on the results of selective metallization is also examined.

Results and Discussion

Influence of laser parameters

Figure 4 shows the influence of the varied laser parameters on the metallization results of a twill-weave cotton sample using a 5x5 parameter matrix.

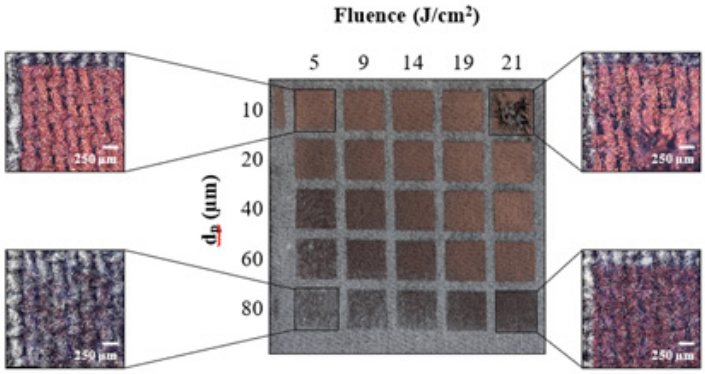


Figure 4: Metallized matrix on twill weave cotton and microscopic images of the metallized structures ($PdCl_2$: 2g/L, 5 min, 80 °C; $CuSO_4$: 10g/L, 10 min, 44 °C).

The images show that process windows exist within the investigated parameter range in which homogeneous and selective metallization can be achieved. Both the laser fluence and the pulse spacing have an influence on the quality of the resulting metallization.

High laser fluence values in combination with a small pulse distance leads to thermal damage to the substrate and can cause damages on the textile cotton structure. A critical substrate damage was observed particularly at a laser fluence of F_L=21J/cm² and a

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pulse spacing of d_p=10µm. This parameter combination was therefore excluded from subsequent investigations to avoid potential contamination of the $PdCl_2$ and $CuSO_4$ process baths by damaged textile fibers.

At low laser fluence with a large pulse spacing, the energy input is too low to ensure effective surface activation and homogeneous metallization. This is visible at F_L=5J/cm² and d_p=80µm where almost no metallization can be observed. Therefore, the laser parameters must be adjusted to minimize substrate damage while maintaining a high degree of metallization and selectivity.

Influence of immersion time

In addition to the laser parameters, the chemical process parameters also can influence the resulting metallization quality. These include, among others, the immersion times in the $PdCl_2$ and $CuSO_4$ solutions. To investigate this influence, the laser parameters shown in Figure 2 were used. Based on these conditions, the immersion times in the two process baths were varied in 5 min increments, while all other process parameters were kept constant. The metallization results for different immersion times in the $PdCl_2$ bath (5-20 min) and the $CuSO_4$ bath (5-10 min) are shown in Figure 5.

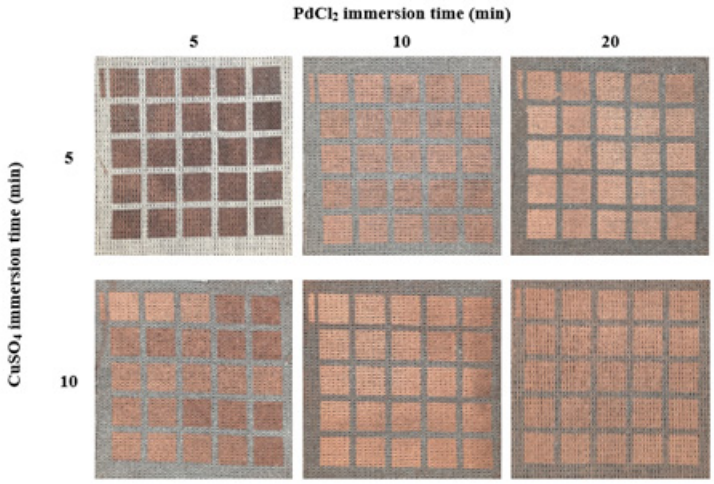


Figure 5: Metallization results on cotton textiles for a matrix of laser fluence (F_L=5-21J/cm²) and pulse spacing (d_p=10-80µm), for different immersion times in the $PdCl_2$ (5-20 min) and $CuSO_4$ (5-10 min) baths. The remaining process parameters were kept constant ($PdCl_2$: 2g/L, 80 °C; $CuSO_4$: 10g/L, 44 °C).

The comparison of the samples shows that an immersion time of only 5 min in each bath is not sufficient to achieve uniform copper deposition. However, this was the only sample that showed no discoloration in the non-laser-activated areas. In addition, the copper coloration of the laser-activated areas was considerably weaker and less homogenous for this parameter combination.

Increasing the immersion time in each bath to 10 min improved the visual quality of the metallization. This improvement was observed both when the immersion time in the $PdCl_2$ bath was increased to 10 min while keeping the $CuSO_4$ immersion time at 5 min, and also when the $CuSO_4$ immersion time was increased to 10 min while keeping the $PdCl_2$ immersion time at 5 min. Further increasing the immersion time in the $PdCl_2$ bath to 20 min also resulted in clearly visible copper deposition.

These results indicate that an immersion time of at least 10 min in one of the two process baths is sufficient to achieve visually uniform metallization. In contrast, reducing the immersion times in both baths to 5 min results in considerably less copper deposition. This shows that both immersion times influence the formation of the copper layer and should therefore be considered together.

Influence of dwell time

Another factor for an effective selective metallization is the storage time between the steps of the described process chain. Figure 6 shows the influence of the storage time between laser activation and palladium seeding (between process steps (Figure 1a) and (Figure 1b)) on the resulting metallization. For this purpose, the samples were stored for different durations ranging from 0 to 6 h under ambient atmosphere and vacuum conditions.

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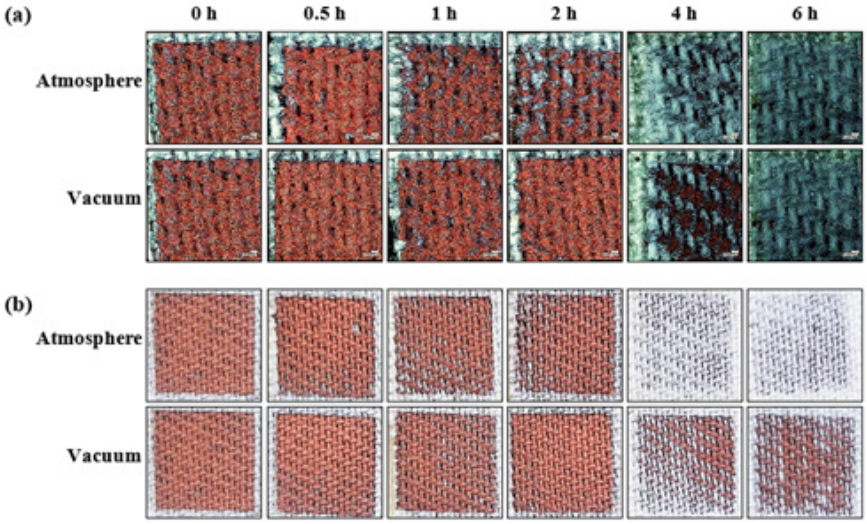


Figure 6: Metallized structures (F_L=19J/cm², d_p=20µm, $PdCl_2$: 2g/L, 1 min, 80 °C, $CuSO_4$: 10g/L, 15 min, 47 °C) on twill weave cotton stored under atmosphere and vacuum after different dwell times between laser activation and palladium seeding for 0h; 0,5h; 1h; 2h; 4h and 6h (a) microscopic images and (b) camera images.

The microscopic images show that the degree of metallization decreases with increasing storage time between laser activation and palladium seeding. This may be caused by changes in the laser-activated surface over time. While clear copper deposition is still observed after storage times of up to 2 hours, a strong decrease is visible after 4 hours.

The first differences between storage under ambient conditions and under vacuum can already be observed after 1 hour. These differences may be caused by the influence of oxygen and moisture, which can affect the laser-activated surface in different ways. After a storage time of 4 hours, the distribution of the metallized areas differs clearly between the two storage conditions. The sample stored under vacuum shows a preferential diagonal direction of copper deposition. This may indicate that areas with stronger laser activation retain their activity for a longer time.

Figure 7 additionally shows microscopic images of the metallized areas for different storage times between palladium seeding and the subsequent metallization in the $CuSO_4$ solution (between process steps (Figure 1b) and (Figure 1c)).

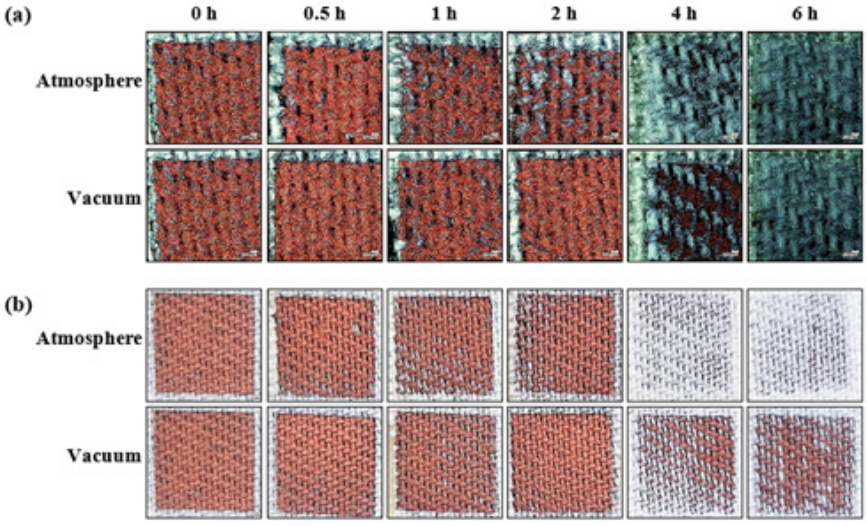


Figure 7: Metallized structures (F_L=19J/cm², d_p=20µm, $PdCl_2$: 2g/L, 1 min, 80 °C, $CuSO_4$: 10g/L, 15 min, 47 °C) on twill weave cotton stored under atmosphere and vacuum after different dwell times between palladium seeding and metallization in the $CuSO_4$ solution for 0, 1, 2, 4, 6 and 8h.

Compared to the storage time between laser activation and palladium seeding, the influence of the storage time between palladium seeding and metallization is smaller. Nevertheless, a slight decrease in the degree of metallization can be observed as the stor-

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age time increases. A high degree of metallization is still achieved after 6 hours. After 8 hours, the copper layer becomes noticeably less homogenous, although metallization remains visible. Almost no differences can be observed between atmosphere and vacuum. Overall, the results show that the storage time between palladium seeding and subsequent metallization has a smaller influence on the metallization results than the storage time between laser activation and palladium seeding.

Minimum structure width

For technical applications of LSA, it is important to determine the minimum achievable width of conductive tracks on the textile substrate. Figure 8 shows Scanning electron microscopy (SEM) images of the metallized surface of a plain-weave cotton activated at F_L=14 J/cm² and d_p=40µm.

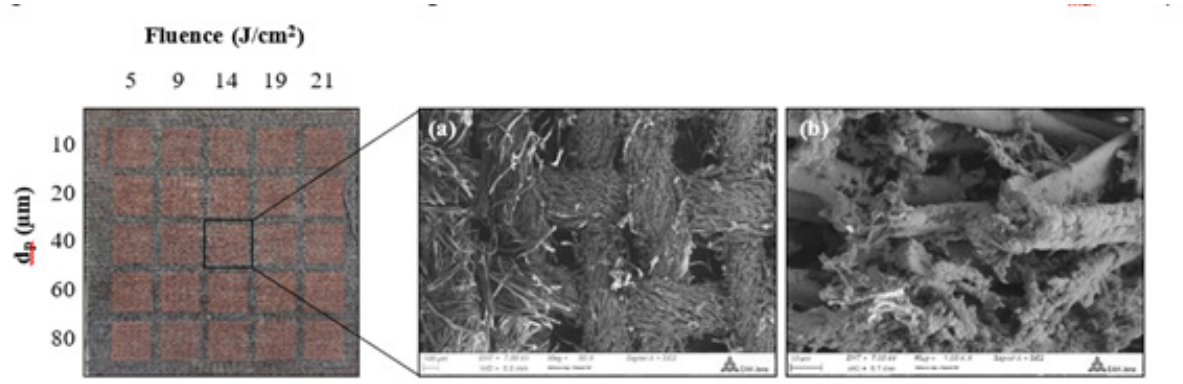


Figure 8: SEM images (Plain weave) for 14J/cm², dp=40µm, $PdCl_2$: 2g/L, 86 °C, 20 min, $CuSO_4$: 10g/L, 44 °C, 20 min (a) of the transition zone between the selectively metallized region and the surface without laser activation and (b) of the selectively metallized region for higher magnification.

Figure 8a shows the transition zone between the metallized area and the untreated textile. The image demonstrates that the process enables selective metallization with comparatively well-defined edges. At the same time, it becomes visible that the textile mesh structure limits the minimum achievable feature resolution.

Furthermore, slight changes and localized damage to individual fibers are visible compared to the untreated textile surface. These features are particularly visible in the higher-magnification SEM image (Figure 8b). Despite these localized changes, the overall weave structure of the textile remains intact at the selected laser parameters. No critical destruction of the textile structure or clearly visible damage to the material in deeper regions is observed.

To investigate the minimum achievable feature resolution more in detail, small line structures were fabricated on a twill-weave cotton substrate. A suitable set of process parameters was selected to investigate different line widths while keeping the spacing between adjacent lines constant. Line widths of 500, 400, 300, 200, 100, and 50µm were fabricated, with a constant distance of 500µm. The resulting structures are shown in Figure 9. In addition, two different $CuSO_4$ concentrations (10g/L and 13g/L) were compared to adjust the copper deposition rate in the activated areas. The resulting structures are shown in Figure 9.

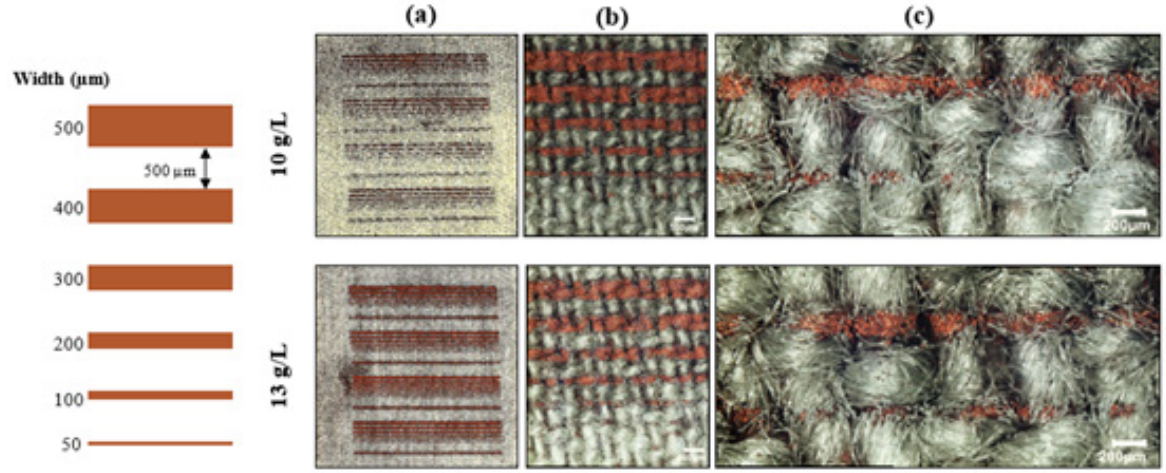


Figure 9: Line patterns on twill weave cotton fabric after LSA (F_L=14J/cm², d_p=40µm, $PdCl_2$: 2g/L, 1 min, 80 °C, $CuSO_4$: 15 min) for 10g/L (top row) and 13g/L (bottom row). (a) Overview of the lines (b) microscope image at medium magnification (500µm -50µm line width) and (c) at high magnification for 100µm and 50µm line width.

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The images show that fine lines can be selectively metallized on the textile surface. Line widths of 100µm can still be produced. However, lines with a width of 50µm cannot be produced reliably. This is likely due to the mesh size and the surface structure of the textile, which limit the achievable feature resolution. For the investigated twill-weave cotton fabric, the minimum feature resolution is therefore around 100µm. These results show that the achievable feature resolution depends not only on the process parameters but also on the structure of the textile.

Influence of the weave structure

In addition to the storage times and the chemical, laser, and scanning parameters, the weave structure of the natural fiber textiles can also influence the metallization results. Figure 10 presents the results obtained for three different cotton fabrics processed under same conditions.

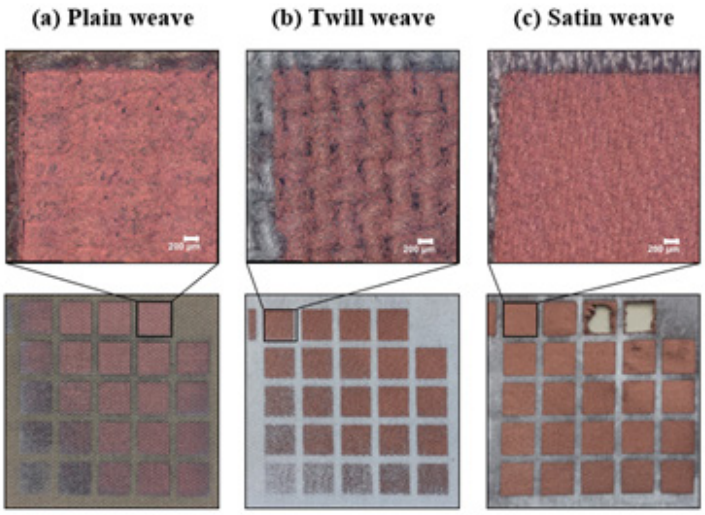


Figure 10: Images of the metallized structures (F_L=5-21J/cm², d_p=10-80µm, $PdCl_2$: 2g/L, 80 °C, 20 min, $CuSO_4$: 10g/L, 47 °C, 20 min) for (a) Cotton plain weave, (b) cotton twill weave and (c) cotton satin weave.

The images show differences in the achievable metallization quality and the corresponding process windows. For the plain weave, the process window within which complete metallization of the processed areas can be achieved is comparatively narrow. However, particularly uniform and continuous metallization is obtained at a laser fluence of 19J/cm² and a pulse spacing of d_p=10µm. This may be attributed to the smaller mesh size compared to the other investigated fabrics.

The metallization results obtained for the twill weave are generally comparable to those of the plain weave. However, due to its larger mesh size, the textile structure remains more clearly visible after metallization. In particular, the individual fabric meshes can still be distinguished within the processed parameter fields.

In contrast, the satin weave shows the widest process window, allowing complete metallization for most of the investigated parameter combinations. Furthermore, good metallization results can already be achieved at lower laser fluences. However, the satin fabric was more sensitive to laser-induced damage under certain processing conditions. This may be related to its weave structure, which has fewer interlacing points and longer yarn floats than plain and twill weaves, what can affect the stability of the cotton textile [17]. As a result, some of the processed areas show signs of substrate damage during laser activation and the subsequent metallization process.

Figure 11 additionally shows the measured electrical sheet resistance for the applied laser parameters and the different weave structures. The sheet resistance was measured based on the Van der Pauw method by contacting the sample at four points along its edges. This four-point measurement reduces the influence of contact and cable resistances on the measured values [18]. Howev-er, it should be noted that the classical Van der Pauw theory assumes a continuous, homogeneous, and isotropic film. Because the three-dimensional topography of the textile substrate can induce local inhomogeneities within the copper layer, these ideal conditions are not fully met, which may introduce systematic measurement uncertainties. Nevertheless, as all samples were characterized under identical conditions, the obtained values allow for a reliable relative comparison of the coatings. Parameter fields for which no sheet resistance could be determined due to insufficient metallization are shaded in grey.

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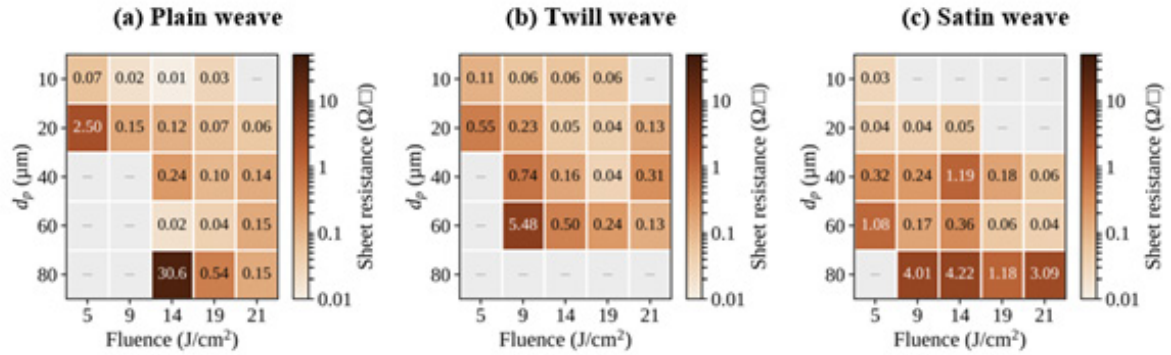


Figure 11: Sheet resistance in dependence of the Fluence and pulse distance ($PdCl_2$: 2g/L, 80 °C, 20 min, $CuSO_4$: 10g/L, 47 °C, 20 min) for (a) Plain weave sample, (b) Twill weave sample and (c) Satin weave sample.

The measured electrical sheet resistance as a function of the laser parameters shows that both the laser fluence F_L and the pulse spacing d_p must be adjusted to the respective textile material to achieve the lowest possible sheet resistance. The optimal parameter combinations differ considerably between the investigated weave structures.

For the plain weave, the lowest sheet resistance is obtained at a pulse spacing of d_p=10µm. The lowest measured value is 0.01 Ω/□ at a laser fluence of F_L=14J/cm². For the twill weave, the lowest measured sheet resistance is 0.04 Ω/□, which is achieved with several different combinations of laser fluence and pulse spacing. The satin weave also shows a low sheet resistance, with a minimum value of 0.03Ω/□. Particularly low values are obtained at low laser fluences and small pulse spacings.

A comparison of the three weave structures shows that the plain and satin weaves achieve lower sheet resistance values than the twill weave under suitable processing conditions. One possible explanation is the difference in mesh size between the fabrics. In particular, the larger mesh size of the used twill weave may result in a less continuous metallized structure after LSA and, consequently, poorer electrical connections within the copper layer. Overall, the results show that the optimal laser parameters depend on the textile material and must be adjusted.

Metallization of differently colored textile areas

In addition to the weave structure and process parameters, the color of the textile may also influence the metallization results. To investigate this effect, a cotton sample with differently colored areas was processed under identical conditions. The results for the applied laser parameter matrix are shown in Figure 12.

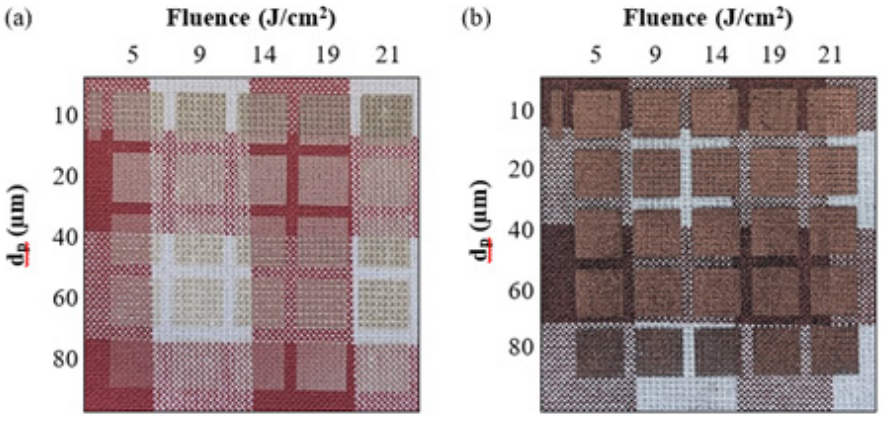


Figure 12: Matrices of (a) laser activated and (b) metallized pads on plain weave cotton with different dyeing (F_L=5-21J/cm², d_p=10-80µm, $PdCl_2$: 2g/L, 5 min, 80 °C; $CuSO_4$: 10g/L, 10 min, 44 °C).

The results show that selective copper deposition is possible for the differently colored textile areas. However, also for this sample the degree of metallization varies between the individual parameter fields. Some differences can also be seen at the transitions between the differently colored regions. One possible reason is that the dyes may affect how palladium attaches to the textile and, as a result, influence the copper deposition. Different dyes may also change how the laser interacts with the textile surface. These results suggest that also the textile color may influence the metallization process.

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Solderability of metallized cotton textile surfaces

To investigate the contractability of the metallized structures, additional soldering tests were carried out using a commercially available soldering iron. A low-melting-point Sn42Bi58 solder was used. The soldering temperature was varied between 150 and 500 °C. It should be noted that these values refer to the temperature set on the soldering iron and not to the actual temperature at the soldering position. Figure 13 shows the resulting solder joints and the reverse sides of a twill weave cotton textile sample at the respective temperatures.

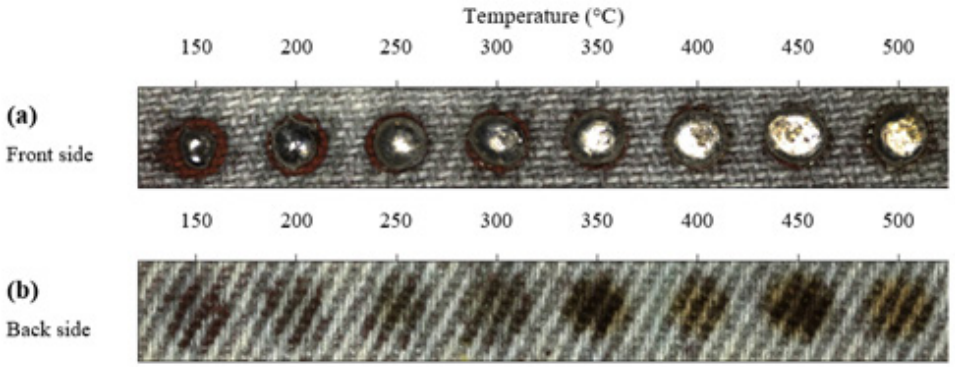


Figure 13: Solderability of laser-activated and metallized cotton textiles (F_L=19J/cm², d_p=20µm, $PdCl_2$: 2g/L, 1 min, 80 °C, CuSO4: 10g/L, 15 min, 44 °C) at different soldering temperatures ranging from 150 to 500 °C, (a) resulting solder joints at the front side and (b) thermal discoloration back side.

The results show that, under the selected laser and process conditions, a soldering temperature of at least 250 °C is required to achieve a uniform solder joint. Dark discoloration is visible on the reverse sides of the cotton samples at all investigated temperatures. This is partly be caused by metallization extending through the textile structure. However, the discoloration becomes considerably more pronounced as the soldering temperature increases, indicating increasing thermal damage to the cotton fibers. At 500 °C, clear signs of burning are already visible, particularly on the front side of the sample. This temperature therefore represents the upper limit of the investigated temperature range for soldering.

Overall, the experiments demonstrate that the laser-structured and metallized cotton surfaces can generally be contacted using conventional soldering techniques. This provides an important basis for electrically connecting metallized textile structures and integrating them into more complex electronic systems.

Functional E-textiles

To demonstrate the practical applicability of the developed selective metallization process, a functional electronic circuit was fabricated directly on a cotton textile substrate. The demonstrator consists of a light-dependent circuit incorporating a photoresistor, resistor, MOSFET, microcontroller, and light-emitting diode (LED), as shown in Figure 14. A voltage converter was additionally mounted on the reverse side of the textile. The fabrication of the demonstrator by LSA enabled the electrical interconnection of the components directly on the textile surface without requiring a separate circuit board. The electronic components were soldered onto the metallized copper tracks using low-melting-point Sn42Bi58 solder at a soldering iron temperature of 350 °C.

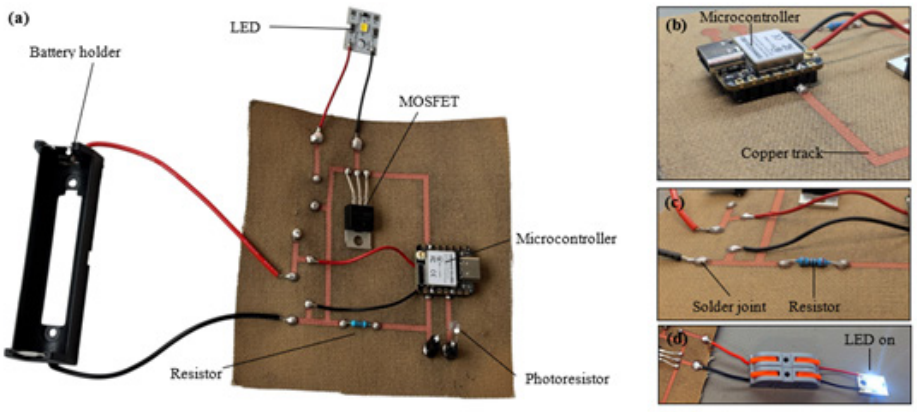


Figure 14: Demonstrator of a light-sensitive circuit on plain weave cotton fabric (a) Finished demonstrator, (b) microcontroller, (c) soldered components and (d) LED demonstrating the electrical functionality.

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The functionality of the demonstrator was successfully verified. The circuit responds to changes in ambient illumination, activating the LED under dark conditions. The metallized conductive tracks and soldered connections provided sufficient electrical stability for the operation of the demonstrator.

These results demonstrate that the developed metallization process can also be applied to the integration of functional electronic circuits on natural fiber textiles. This represents an important step toward the development of natural fiber smart textiles with integrated sensing and electronic functionalities.

However, further investigations are required to evaluate the long-term reliability of the metallized structures and electrical connections under practical operating conditions. In particular, the effects of repeated bending, stretching, washing, and environmental exposure must be examined. Future developments may also include protective coatings for the solder joints, improved component integration, and the implementation of additional sensing functions.

Summary and Outlook

In this study, a selective metallization process for natural fiber-based cotton textiles was investigated using USP laser activation followed by palladium seeding and electroless copper deposition. The influence of laser parameters, chemical processing conditions, intermediate storage times, textile weave structures, and textile coloration on the metallization quality was systematically examined.

The results demonstrate that homogeneous and electrically conductive copper structures can be produced within suitable process windows. Both laser fluence and pulse spacing influence the metallization quality and must be adapted to the respective textile structure. The investigated plain, twill, and satin weaves exhibited different metallization characteristics, with satin weave providing a comparatively wide process window but showing increased sensitivity to laser-induced damage under certain conditions.

The immersion times in the chemical baths and the storage intervals between individual processing steps can influence the metallization results. In particular, longer storage between laser activation and palladium seeding reduced the degree of copper deposition. These findings underline the importance of controlling the entire process chain to achieve reproducible metallization results.

Selective conductive structures with feature widths down to approximately 100µm were successfully fabricated. The achievable resolution was mainly limited by the textile surface topography and weave structure. Low electrical sheet resistance values of 0.01Ω/□, 0.04Ω/□, and 0.03Ω/□ were achieved for plain, twill, and satin weaves, respectively.

Furthermore, the solderability of the metallized textile surfaces was demonstrated using low-melting-point Sn42Bi58 solder. The successful fabrication and operation of a light-sensitive electronic demonstrator confirmed the feasibility of integrating electronic components directly onto selectively metallized cotton textiles without an additional printed circuit board.

Overall, the results demonstrate the potential of USP laser-based selective metallization as a flexible manufacturing approach for electrically functional natural fiber textiles. The combination of localized laser activation, selective copper deposition, and direct electronic component integration provides a promising basis for future smart textile applications.

Further research should focus on improving the long-term stability and practical usability of the metallized textiles. Particular attention should be given to the adhesion of the copper layers, resistance to repeated bending and stretching, washability, and the reliability of soldered electrical connections. In addition, the influence of textile coloration and surface treatments requires further investigation to improve process reproducibility.

Another important objective is the reduction of overall processing time through optimization of laser scanning strategies and chemical treatment steps. The scalability of the process to larger textile areas and simultaneous processing of multiple samples should also be evaluated. These developments will be essential for transferring the demonstrated laboratory process toward practical manufacturing applications in wearable electronics, textile-integrated sensors, and other functional textile systems.

Acknowledgment

This article presents results from the research and development project “UKPiño“ (reference number 03RU2U033I). We would like to thank the Federal Ministry of Research, Technology and Space (BMFTR). The authors are responsible for the content of the publication.

Bundesministerium für Forschung, Technologie und Raumfahrt

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The authors gratefully acknowledge the use of the scanning electron microscope, which was acquired within the NARELA project, funded by EAH Jena and the Thüringer Aufbaubank (TAB) within the FTI-Thüringen FORSCHUNG call (grant no. 2024 FGI 0027).

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