

Precision Laser Metallization of Textile Surfaces for Advanced Smart Fabric Applications

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Abstract

The integration of intelligent sensor systems into textiles opens up new possibilities across various industries, from healthcare and sports to protective clothing and entertainment. Smart textiles, equipped with conductive tracks and embedded sensors, enable continuous monitoring of physiological parameters and interaction with the environment. A key method for manufacturing such textiles is laser-based metallization, which allows precise and selective deposition of conductive traces onto a variety of synthetic fabrics. Copper is one of the preferred materials for metallization due to its excellent conductivity. Through selective laser metallization, these traces can be flexibly embedded into the textile structure without compromising its mechanical properties. This technology enables the creation of thin, durable conductive layers, which can be combined with various sensors. The resulting textiles can be designed to be flexible, lightweight, and wearable, making them ideal for applications in health monitoring, sports science, and industrial protective clothing. Despite the vast potential of laser-based metallization, several challenges remain, including ensuring the durability and washability of metallized surfaces, long-term power supply for integrated sensors, and data security. This publication explores the current advancements and challenges in selective laser metallization of synthetic textiles (Figure 1).

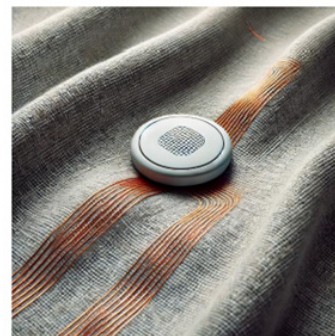


Figure 1: Design study of a smart textile with selective copper conductive tracks and an integrated sensor.

Keywords: Smart textile; Laser-based selective activation; Electrical conductance; Sensor integration

Introduction

Smart textiles have emerged as a key innovation in modern material science, enabling fabrics to perform beyond their traditional mechanical and aesthetic roles. By embedding electronic components such as sensors and conductive pathways directly into textile surfaces, these materials are capable of sensing, processing, and transmitting data, making them invaluable for applications ranging from health monitoring to environmental sensing [1]. A crucial technology facilitating the development of smart textiles is the selective metallization

of textile surfaces, which involves the precise deposition of conductive materials, like copper, onto the fabric to form electrical circuits.

Copper is an ideal material for these applications due to its high electrical conductivity, flexibility, and relative cost-effectiveness [2]. Recent advancements in laser-based metallization techniques have allowed for highly localized, non-contact deposition of copper traces on synthetic fabrics. This method offers superior precision compared to traditional methods such as screen printing or chemical vapor deposition, which often suffer from issues of resolution and material compatibility [3].

The integration of sensors with these metallized tracks opens the door to numerous smart textile applications. For example, sensors embedded in wearable fabrics can continuously monitor vital signs, providing real-time feedback in medical and fitness settings [4]. In addition, the use of flexible, wearable sensors in industrial and military applications enables continuous environmental monitoring and safety assurance [5].

Since 2020, research in this field has significantly advanced. For instance, studies have focused on improving the washability and durability of smart textiles through enhanced metallization techniques [6]. There is also a growing emphasis on sustainable manufacturing, including the use of eco-friendly conductive inks and materials for smart textile production [7]. Additionally, the integration of energy harvesting technologies into textile structures has made strides, enabling smart textiles to power themselves from environmental sources such as body heat or movement [8]. Innovations in sensor miniaturization and multi-functionality have also expanded the capabilities of these textiles, making them more versatile for applications like biosensing and environmental monitoring [9]. Finally, machine learning integration has been explored to enable smart textiles to process sensor data autonomously, enhancing real-time decision-making capabilities [10].

Despite these advancements, several challenges remain in the field of smart textile design. Ensuring the long-term durability

and washability of the metallized textiles, maintaining sensor performance under mechanical strain, and developing reliable energy harvesting or storage solutions are areas requiring further research [11]. This paper explores the current state of laser-based metallization on textiles, with a particular focus on selective copper deposition and its potential applications in integrated sensor systems.

The Laser-Based Selective Activation (LSA) is proposed as a new process for creating partial metallic structures. The process has been investigated for various injection molded polymers and has shown good mechanical adhesion as well as electrical resistance [12,13].

The aim of this work is to prove the application of the LSA process chain for synthetic textiles. To achieve these goals the individual steps: laser activation, palladium nucleation and electroless copper plating have been investigated for the new material.

Process chain for Laser-Based Selective Activation (LSA)

The process chain used in this work is based on a patent for fabricating conductive traces on polymer surfaces, which has been demonstrated in several previous work. The aim is to transfer the LSA process to textile fabrics. The now adapted process chain consists of three steps as shown in Figure 2: a) laser activation, b) infection bath, and c) selective metallization. A major goal of the investigation was the formation of homogeneous electrically conductive tracks d) based on the patent. Therefore, each of the steps has to be modified for textile substrates.

For laser activation (Figure 2a) of the surfaces, an experimental setup with a femtosecond laser was used to activate the fabrics. The system emits a laser beam with a wavelength of 1030nm and the pulse duration was kept constant at 300fs. The laser beam was deflected by a dynamic galvo scanner. An f-theta objective with a focal length of 100mm was used. This resulted in a focal diameter df of 20 μ m and a maximum scan field of 40mm \times 40mm. A direct motion system was used to enlarge the resulting optical scan field.

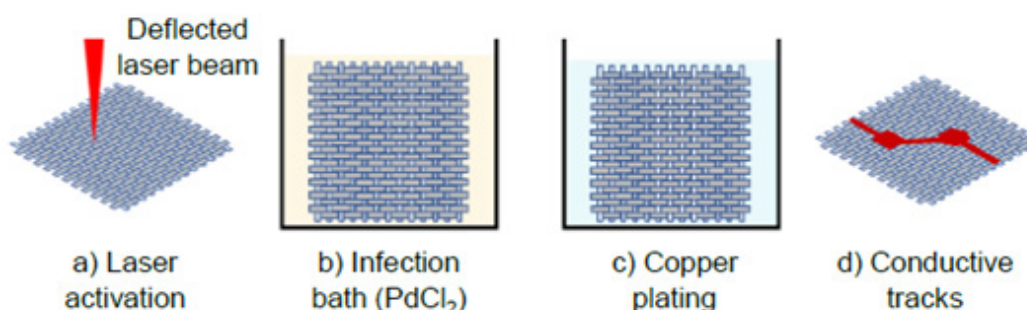


Figure 2: Illustration of the technological process sequence of the new activation method “Laser-based Selective Activation - LSA” [13].

To investigate the metallization parameters, a matrix of 5 \times 5 fields was generated on each sample under atmospheric conditions and at room temperature, as shown in Figure 3. Each field covers an

area of 8mm \times 8mm. The scan path (y-direction) was unidirectional, and the number of passes was set to one. The pulse repetition rate RR was set to 25kHz for all experiments.

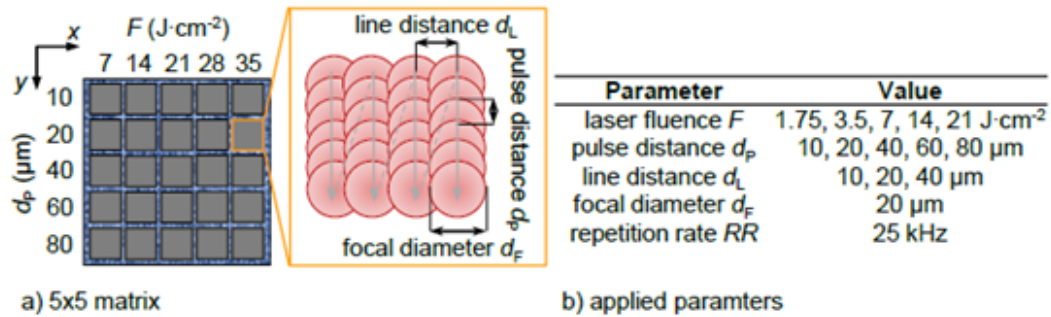


Figure 3: Visualization of the laser and scan parameters for
 a) The matrix (a red dot corresponds to a laser spot; the grey arrows illustrate the scan path) and
 b) The applied parameters.

Materials

As substrate material synthetic woven polyester (PES) were selected. The textile came as woven fabric. The substrate provided by Thorey Gera Textilveredelung GmbH, who also took care of premanufacturing steps of the initial substrate like washing. The specimens were stored under normal atmospheric conditions in a laboratory environment. Before laser processing they were separated with a CO₂-laser system into several parts for clamping them. During the experiments washed and unwashed fabrics are compared.

Result and Discussion

Figure 4 shows the effect with (a) and c)) and without (b) and d)) the pre-washing after the LSA process chain. The process of development for fabrics started with the laser and chemistry

parameters for injection molded plastics. These “non optimized” results are displayed in Figure 4a&b. It can be seen that an increase in laser fluence leads to a darker coloring of the laser processed areas. In contrast, the interaction is weaker at higher pulse spacing. In addition, some textiles may show colour changes in the germination solutions and copper solutions. Without further optimization, the washed and unwashed fabrics show no copper layer after the process chain. In order to generate a proper copper layer on the substrates the parameters of the infection bath and the copper plating as well as the laser and scanning parameters have to be optimized as shown in Figure 4c&d. The results without the initial washing step exhibit a complete and non-selective copper deposition, which can be verified in further experiments. This leads to the results that a pre-wash step was added for all further experiments in order to achieve reproducible and selective copper layers.

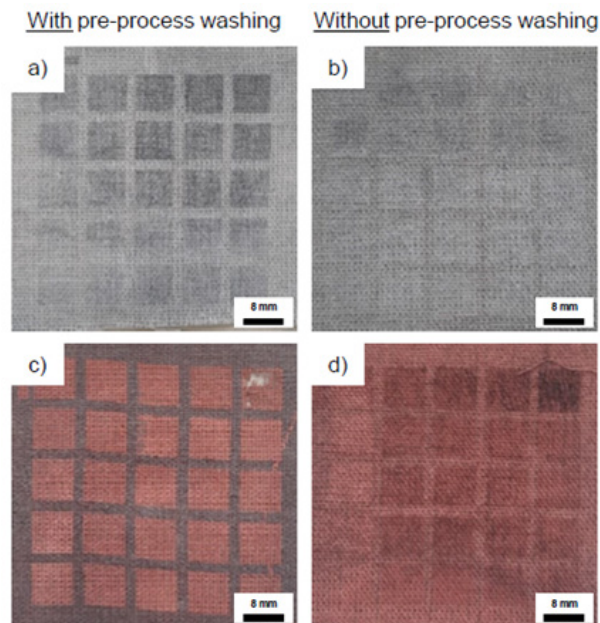


Figure 4: Results after applying the complete LSA process chain for woven textiles.
 a) not optimized parameters of washed woven textiles,
 b) not optimized parameters of unwashed woven textiles,
 c) optimized parameters of washed woven textiles,
 d) optimized parameters of unwashed woven textiles.

Table 1 displays the changes in the process chain that had to be made for textiles. For both baths the exposure time was increased from 5min to 20min. The concentration of palladium and the bath temperature during the infection step were also increased [6].

Table 1: Comparison between starting and optimized parameters for synthetic fabrics.

	Starting Point [6]	Optimized Parameters
Laser process	One overscan	Three overscans
Infection bath	concentration 1g/L temperature 70 °C exposure time 5 min	concentration 2g/L temperature 86 °C exposure time 20 min
Copper plating	Temperature 44 °C exposure time 5 min	temperature 44 °C exposure time 20 min

Figure 5 shows the substrate woven PES as a function of exposure time and line spacing for each matrix. A decreasing exposure time (a)-c)) results in a smaller amount of conductive field and less homogeneous copper layers. For the smallest laser fluence and a pulse distance of 60 and 80 μ m the fields start to form less homogeneous copper layers on the surface, as shown in Figure 5d. This effect continues as the line spacing is further increased. As the energy input per field decreases, the activation of the surface also decreases. This area in the lower left corner can be described as the process boundary for the LSA process.

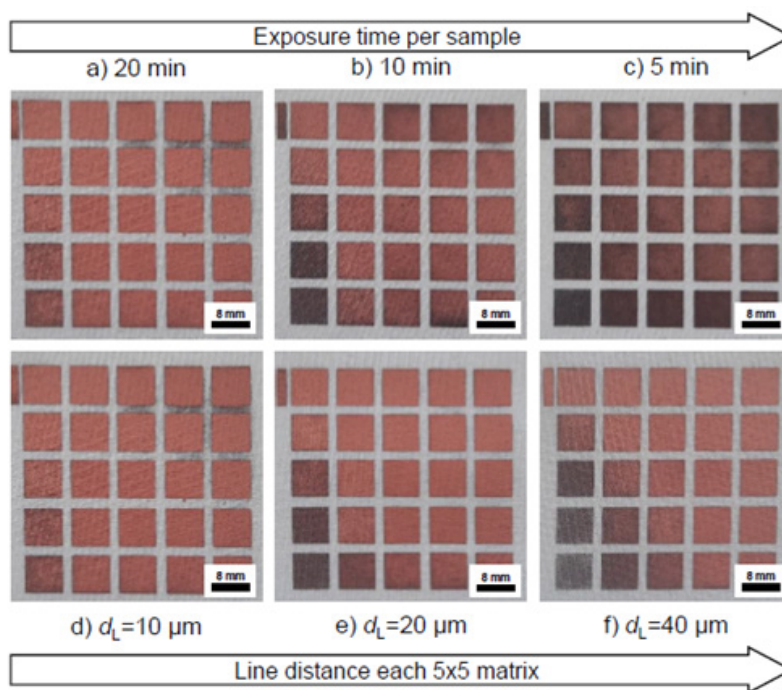


Figure 5: Influence of exposure time and line distance on PES fabric.

a)-c) decreasing exposure time for line distance 10 μ m and PdCl₂ concentration 2g/l,
d)-f) increasing line distance for constant exposure time of both baths 20 min and PdCl₂ concentration 2g/l.

Depending on the density and the air permeability of the fabrics the LSA process can create closed, homogeneous layers (Figure

6b) or metallize individual threads to preserve existing porous structures (Figure 6a).

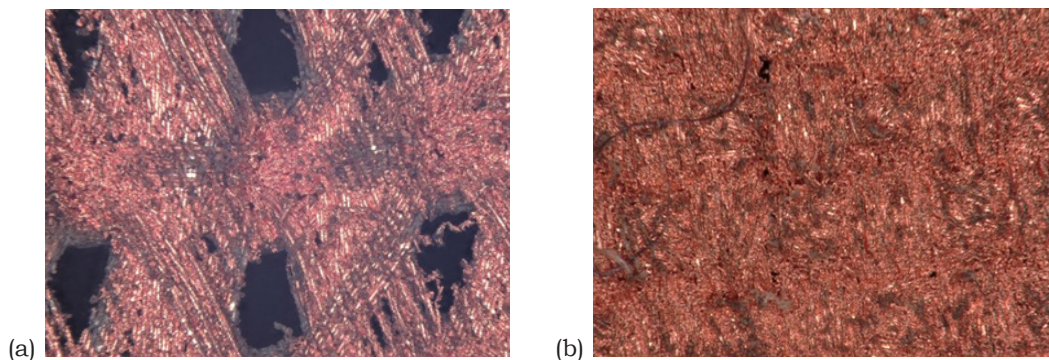


Figure 6: Microscopical images of the same parameters for a) PES knitted and b) PES woven.

A significant industrial parameter for a lot of applications is electrical conductivity. Figure 7 illustrates the electrical conductance for a 5x5 matrix of woven PES. From pulse distances between 10 and 40 μm , the conductance demonstrates a decline with

increasing laser fluences. Conversely, in comparison to the larger pulse distance, the conductance exhibits a reversal in behavior with respect to laser fluence. The majority of the investigated parameter combinations exhibit a conductance value below 200S.

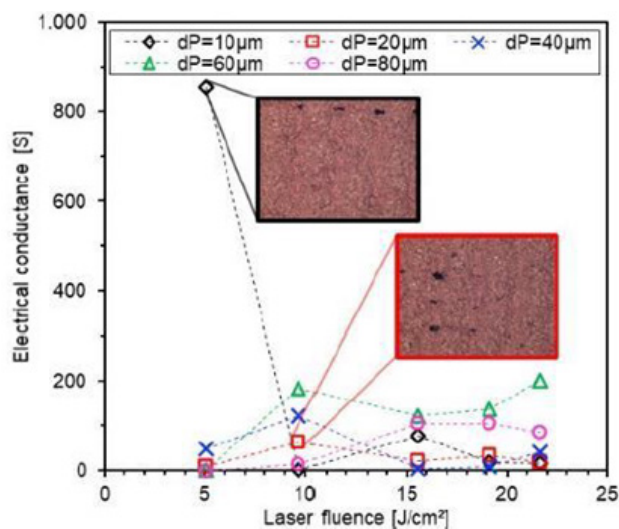


Figure 7: Diagram of the electrical conductance of PESU depending on laser fluence F and puls distance d_p (line distance $d_l = 20\mu\text{m}$), microscopical images magnification $\times 200$.

Following the investigation of parameter combinations to achieve optimum copper plating, an optimum parameter set was defined and applied to generate different geometries for a possible application. For lines, squares, circles and triangle different sizes and spacing between the structures was tested.

Figure 8 illustrates the generated structures and shows that not only very different geometries, but also very small conductive surfaces with small distances between them can be realised.

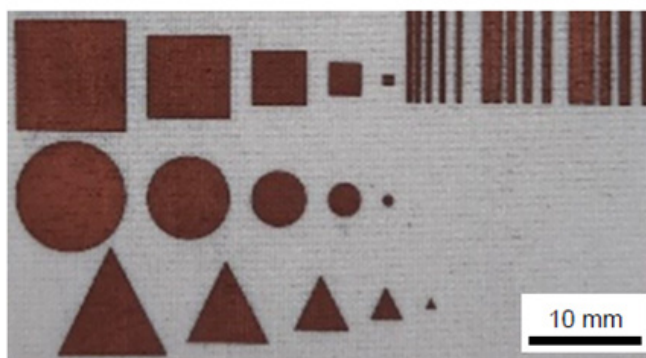


Figure 8: Different geometries applying optimized laser parameters and bath chemistry.

Bonding Technologies for Sensor Integration into Textiles

The integration of sensors into textiles presents a complex technological challenge, as both electrical connectivity and the flexibility and durability of the fabric must be preserved. The bonding technologies, Conductive Adhesives, Low-Temperature Soldering, Reflow Soldering, Printing Techniques and further technologies are used must meet the requirements for mechanical strength as well as thermal and chemical stability in everyday use.

When connecting sensors to textiles, various soldering technologies are used, specifically adapted to the requirements of

flexible textile substrates. Unlike conventional rigid printed circuit boards, integrating sensors into textiles demands techniques that ensure reliable electrical connections while maintaining the fabric's flexibility and mechanical properties. The most common soldering technologies include:

- A. Low-Temperature Soldering
- B. Induction Soldering
- C. Laser Soldering
- D. Ultrasonic Soldering
- E. Conductive Adhesive Soldering

F. Thermocompression Soldering.

Compared to rigid printed circuit boards, textiles present significant challenges in terms of thermal sensitivity, mechanical flexibility, and washability during the bonding process. Many textiles are heat-sensitive, making soldering processes particularly demanding. For this reason, low-temperature soldering methods are commonly preferred. The connections must remain flexible to accommodate the movement of the textile without damaging the electrical connection or the fabric itself. Furthermore, solder

joints must be resilient enough to endure washing cycles and mechanical stress in everyday use. Employing appropriate bonding techniques requires adapted soldering methods that allow for the seamless integration of robust, flexible, and functional sensors into textile materials. It was investigated whether the copper-plated structures in Figure 7 enable a bonding process. The example in Figure 9 illustrates that very good joints can be produced if the correct soldering temperature is selected. These soldered joints (Figure 9c) also show a very good cross-linking behavior to the textile fabric.

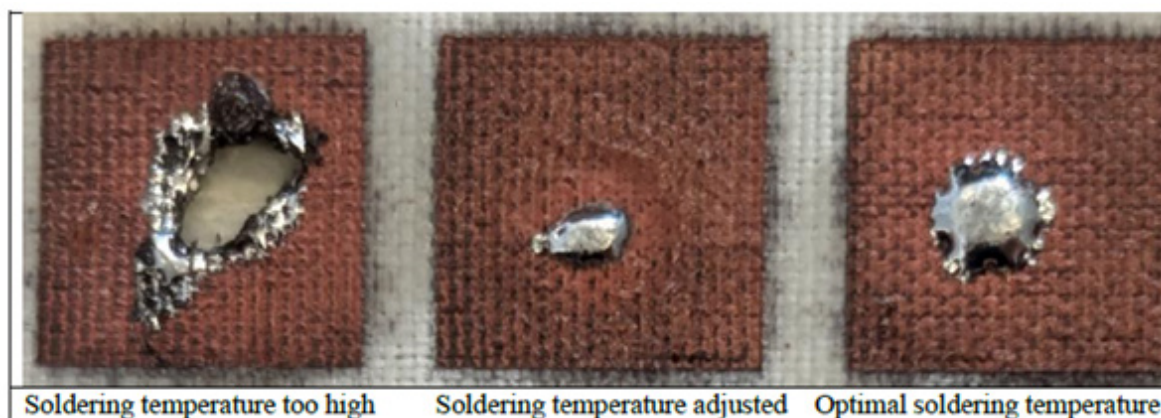


Figure 9: Investigation into Low-Temperature Soldering of PESU fabric.

Summary and outlook

Laser-based selective metallization of textile surfaces offers a promising method for integrating conductive structures and sensors into smart textiles. By precisely and selectively depositing copper tracks onto synthetic textiles, thin, flexible, and simultaneously robust conductive paths can be created, making them suitable for a wide range of applications in healthcare, sports, protective clothing, and more. This process preserves the mechanical properties of the textile, making it ideal for wearable and lightweight solutions.

Despite these advances, challenges remain, such as ensuring the durability and washability of the metallized textiles, as well as developing efficient power supply solutions for integrated sensors. Further research will focus on optimizing process parameters, improving adhesion and conductivity, and integrating microcontrollers and sensors to enhance the functionality and versatility of smart textiles.

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