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A Novel Approach for Micro-Antenna Fabrication on ZrO_2 Substrate Assisted by Laser Printing for Smart Implants

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Abstract: The use of Yttria-stabilized tetragonal zirconia polycrystals (Y-TZP) in medicine has rapidly expanded over the past decade, driven by its advantageous properties, showing potential to overcome titanium alloy in implant fabrication. The release of metal ions and the aesthetic problems of titanium alloy implants are the main reasons for this trend. In addition to meeting expectations regarding its properties, an implant must possess intrinsic capacities such as auto-diagnostic and auto-treatment. Thus, based on the concept of smart implants, this work proposes a hybrid approach for printing a part of the communication system of a zirconia implant by resorting to laser technology, aiming to endow the implant with intrinsic capacities. Therefore, the antenna was designed and then printed on the zirconia surface. The laser was applied as a versatile tool, whether for preparing the surface of the material in a subtractive way, by creating the micro-cavity, or for printing the silver-based antenna in an additive way through laser technology. The silver powder was used as the conductor material of the antenna. The results revealed that the antenna is capable of communicating from inside the body with the outside world without needing to have an exterior antenna attached to the skin.

Keywords: Nd:YAG laser; smart implants; communication system; antenna; zirconia implants

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1. Introduction

Orthopedic implants are medical devices that are implanted surgically in the human body to replace missing joints and bones or restore the function of a damaged structure [1]. The market for orthopedic implants is one of the biggest in the medical field, and it is expected to expand significantly in the future, mainly due to the continuously growing elderly population. By taking hip replacement surgery as an example, more than 600,000 people need hip replacement surgery every year, and it is estimated that this number will exceed 1 million by 2030 [2,3]. Until present, titanium alloys have been considered the gold standard choice for implant manufacturing, mainly due to their mechanical performance and excellent biocompatibility [4–6]. Despite this, the long-term use of titanium-based implants will result in the emergence of metal grinding particles, which would cause inflammation around the surrounding tissue, in addition to releasing metallic ions into the body. These inevitable phenomena can eventually lead to the failure of and require reoperation, which causes physical pain and financial burden to the patients [4,7]. In this regard, zirconia (3Y-TZP) is a biomaterial that has been increasingly studied as a potential substitute for metal in biomedical implants, as shown in several studies [8–11], such as the dental field [12–16], hip implants and knee prosthesis [17,18]. The remarkable properties reported for 3Y-TZP in the literature include high flexural strength (up to 900–1200 MPa) [15], high fracture toughness (7–10 MPa $m^{1/2}$) [14], wear resistance, optical and biological properties, biocompatibility and antibacterial properties [19–21]. Despite the efforts, the trend toward zirconia implants is still fraught with challenges, mainly due to its brittleness and sensitivity to surface defects. For this reason, good quality control during the manufacturing process is essential for the satisfactory long-term performance of zirconia implants, which raises the need for works focused on evaluating the optimal design for the next generation of zirconia implants.

The ability to monitor the implant's performance along with its use in real time and establish communication with the user could offer advantages in detecting failures, transmitting qualitative data to start treatments and detecting eventual problems in advance. These achievements are only possible with the fabrication of implants endowed with smart implants, which are implantable devices (including sensors, actuators and antenna) that can provide therapeutic benefits and also diagnostic capabilities [22]. They offer a significant role in the patients' lives, covering various sensing and actuation applications in healthcare according to their external stimuli such as stress, light, temperature or magnetic fields [23–26]. In the literature, there are some works reporting biomedical implants with smart devices coupled in their structure; however, in most cases, their size and adaptation along the implant structure can affect their properties negatively [22,27–29].

Therefore, a manufacturing system capable of building, in one process, an orthopaedical implant equipped with smart devices to make possible the analysis of issues in real-time in the implant and make decisions to perform smart actions is still a challenge to be overcome. In order to be accommodated in the implant, the communication module's antenna should be very small and require very low power, making its design a key requirement for an efficient antenna for the communication system [30,31]. An exemplification of a hip implant endowed with smart components is illustrated in Figure 1.

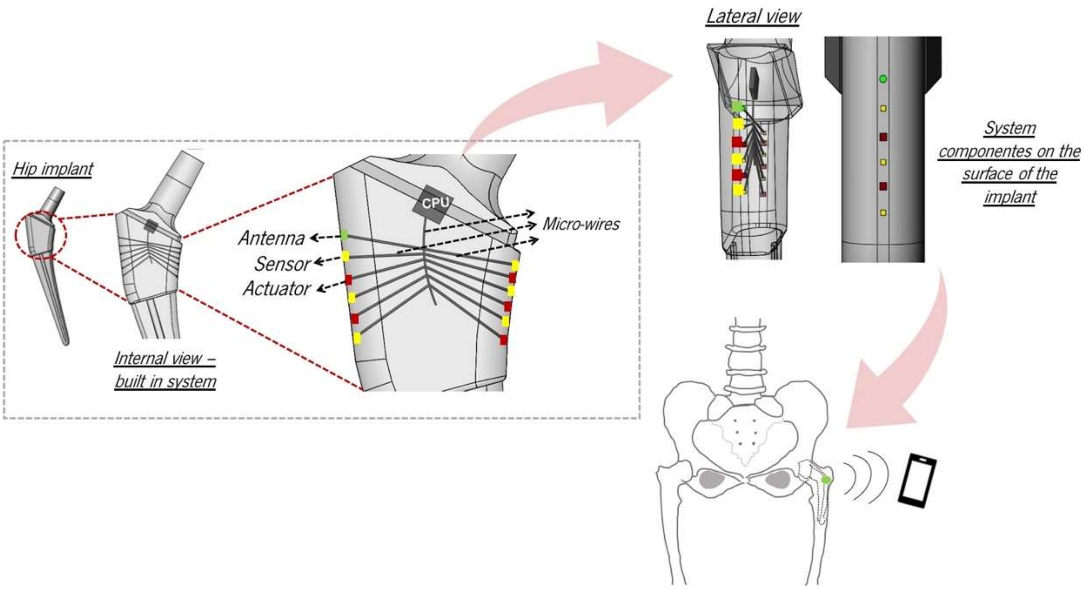

Figure 1. Schematic illustration of a hip implant with smart components printed on its surface in different views, highlighting the antenna. Modified from [32].

The conventional methods used to fabricate antennas in an insulator substrate may entail time-consuming and additional fabrication steps [31,33]. However, resorting to additive manufacturing technology, it is possible to print implants with smart components, namely sensors, actuators and antennas, in a single step. In prior work, the authors printed micro-wires in zirconia substrate, which showed satisfactory results regarding communication ability [32]. Thereby, this study built the next step toward the functionalization of zirconia-based implants, which ultimately deals with the printing of a silver-based communication antenna to compose the communication system. It provides the manufacturing steps and determines the capability of the printed antenna to be used in an implant for communication purposes. In the present study, we first showed the strategy to machine this surface with a laser, creating the cavity where the conductive material of the antenna will then be consolidated. After printing, the antenna will be tested to verify its efficiency in transmitting and receiving signals in an environment that mimics the biological environment.

2. Experimental Details

2.1. Materials

Disk specimens of commercial Yttria-stabilized zirconia (3Y-TZP) were used as the substrate for antenna printing, while commercial silver powder (≥99% pure) from Metalor Technologies, North Attleboro, MA, USA, with an average grain size of 230 nm, was employed as the conductive path. The irregular spherical shape of Ag particles is observed in micrographs of Figure 2a,b, with sizes of about 70–300 nm. Among the conductor's materials, silver presents the greatest electrical conductivity of all metals, with a resistivity of 1.6×10^{-8} ohm.m. According to the literature, at minimal and reasonable concentrations of silver, there are no side effects on the human body [34], and its use in the biomedical field was approved by the US Food and Drug Administration in the 1920s to be used as an antibacterial agent. Therefore, joining its great electrical property with its good acceptance in the biomedical field, this material seems to be a promising choice to compose the communication system of implants as a conductive path for where the electrical current flow.

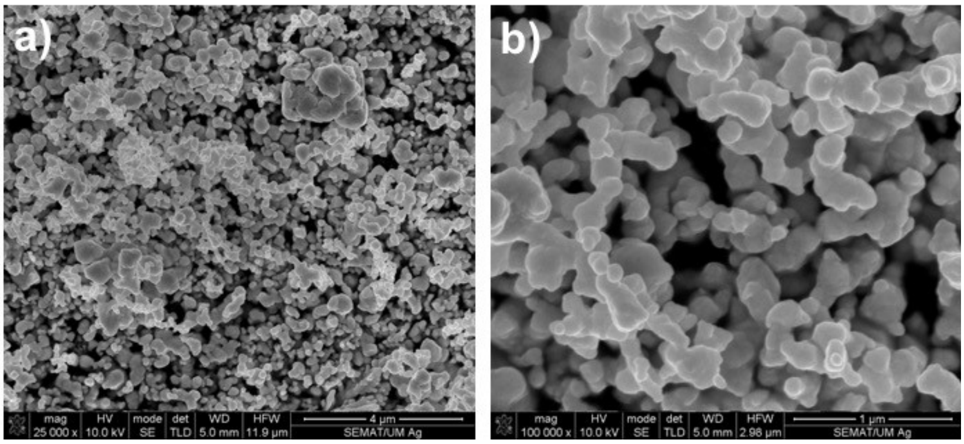

Figure 2. SEM micrographs of silver powder: (**a**) 25,000× and (**b**) 100,000× of amplification.

2.2. Methods

(a) Zirconia substrates preparation

In this study, 3 mol% yttria-stabilized zirconia powder (from Tosoh Corporation, Tokyo, Japan) with an average size of 60 µm was used to produce zirconia substrates. Zirconia disks were produced by cold press and sinter technique by using a cylindrical stainless steel mold of 18 mm in diameter, where zirconia powder was compacted by a pressure of 200 MPa for 30 s. Hereinafter, zirconia disks were sintered using a high-temperature furnace (Zirkonofen 700, Zirkonzahn, Gais, Italy) with a sintering temperature of 1500 °C, a heating and cooling rate of 8 °C/min and 2 h of holding time. Zirconia samples 14.4 mm in diameter and 2 mm thick were obtained after sintering.

(b) Antenna production

The antenna printing was performed in three steps:

i. Micro-cavity creation through laser machining;
ii. Silver powder deposition into the cavity;
iii. Laser sintering of the silver powder.

The schematic representation of laser machining is illustrated in Figure 3.

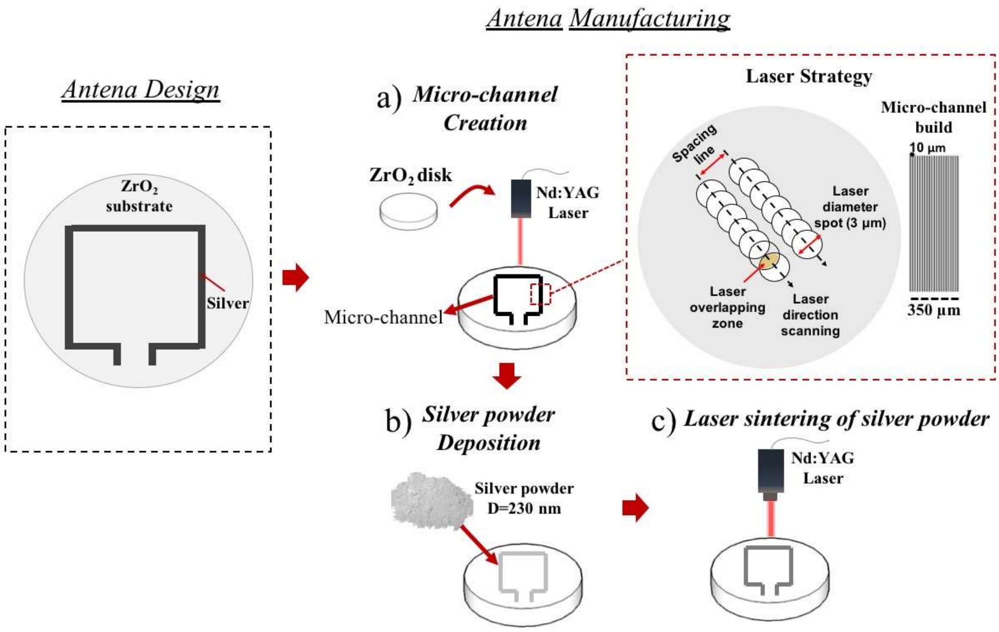

Figure 3. Schematic illustration of the antenna design and manufacturing (**a**–**c**), highlighting the laser strategy used to create the micro-cavity.

i. Micro-cavity creation through laser machining

In this step, a pulsed Nd:YAG laser (OEM Plus, Italy) with 1064 nm of wavelength, a spot size of 3 µm, 6 W of power and a focal length of 160 mm with a gaussian beam mode was applied to create the micro-cavity on zirconia surface (as a subtractive process). In order to create the micro-cavity, a sequence of lines was performed with a distance of 10 µm between them, forming a cavity with a width of approximately 350 µm, as illustrated in Figure 3a. The cavity was created using a laser fluence of 0.72 J/mm^2 and a scanning speed of 50 mm/s, and the laser machining parameters were chosen based on the optimal conditions studied in previously published works by the authors [32,35].

ii. Silver powder deposition into the cavity

After the micro-cavity creation on the zirconia surface, the silver powder was placed and compacted into the cavity with the help of a spatula, and then a pressure of 8 MPa was applied in a hydraulic press to ensure the total accommodation of the powder, as shown in Figure 3b. During the preparation, the excess silver powder was removed from the surface by using a P800 grit SiC paper. After these processes, the micro-cavities were completely filled with silver powder.

iii. Laser sintering of the silver powder

For the silver powder consolidation, an Nd:YAG laser (Sisma, Piovene Rocchette, Italy, 1064 nm of wavelength) with 0.3 mm of spot size and 40 W of power with a gaussian beam mode was used as an additive process for sintering the silver path. Laser energy of 4 Joules was used for sintering silver powder, and this condition was chosen based on previous works [32,35], considering the best condition to melt the powder with fewer defects for the ceramic substrate. In the sintering process, a dual-axis automatic worktable was used to adjust the sample position.

(c) Antenna test configuration

Characterization and testing of the fabricated antenna began by interfacing it with standard measurement equipment. For that, a U.FL cable was cut in half, and its ground and signal lines were separated, as shown in Figure 4a. Each of these terminations was then connected to the antenna resorting to silver conductive paint, resulting in the device of Figure 4b.

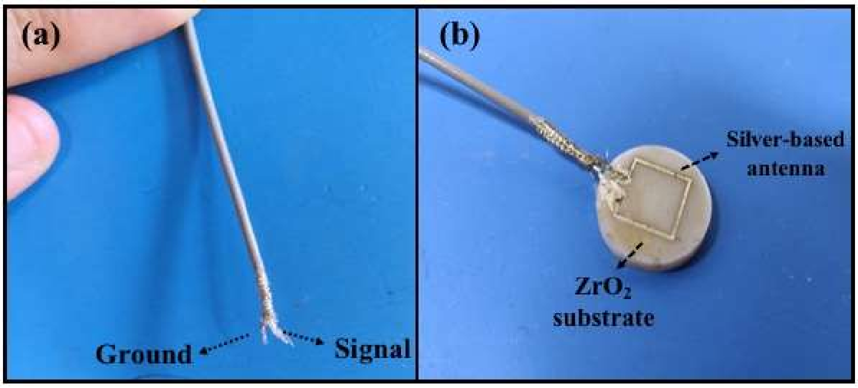

Figure 4. Photographs of the U.FL cable with signal and ground terminations separated (**a**) and of the fabricated antenna ready for testing (**b**).

The antenna was connected to a Vector Network Analyzer (model Keysight E5071C ENA) to measure its properties and determine its suitability for use inside the human body as a communication antenna. This is an important step to test the antenna performance when it is involved in a biological environment since these surroundings have a profound effect on the radiation characteristics of an antenna. Therefore, the antenna under testing was placed between two 1 cm-thick beef steaks to approximate the test's conditions to the antenna's operating conditions once it is implanted [36–38].

The measurement setup is presented in Figure 5. A Q-par Angus WBH2-18S horn antenna was used as a transmitter, and it was placed 25 cm away from the fabricated antenna. A polymeric foam was used to hold the structure of the DUT test, and it is invisible to electromagnetic waves in the frequency range used (it behaves as air).

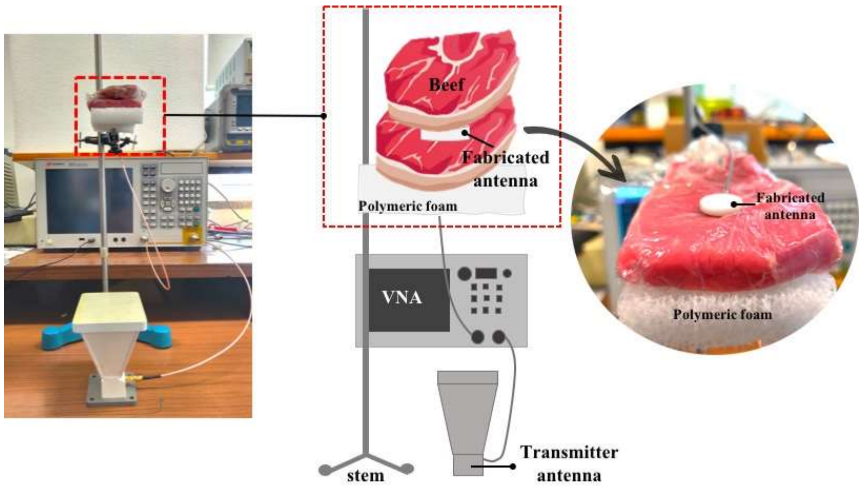

Figure 5. Schematic illustration of the antenna testing setup. The transmitter antenna is distanced 25 cm from the fabricated antenna, which is placed between two 1 cm-thick beef steaks to approximate the test conditions for human body implantation.

3. Results and Discussion

3.1. Antenna Manufacturing

Figure 6 presents the SEM images of the micro-cavity created by laser (subtractive process) on the zirconia surface. The micro-cavity was produced in accordance with the defined antenna design.

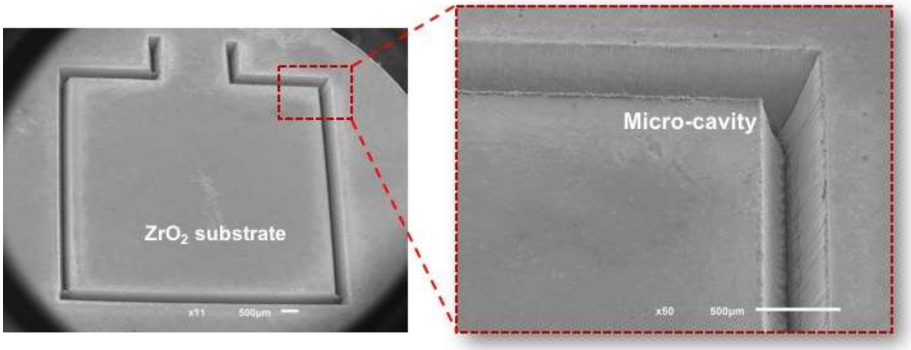

Figure 6. Micro-cavity of the antenna created by laser on zirconia surface.

After the micro-cavity was created on the surface, the silver powder was placed into the cavity and consolidated by a laser sintering approach (additive process). Figure 7 shows a part of the antenna path before and after laser sintering.

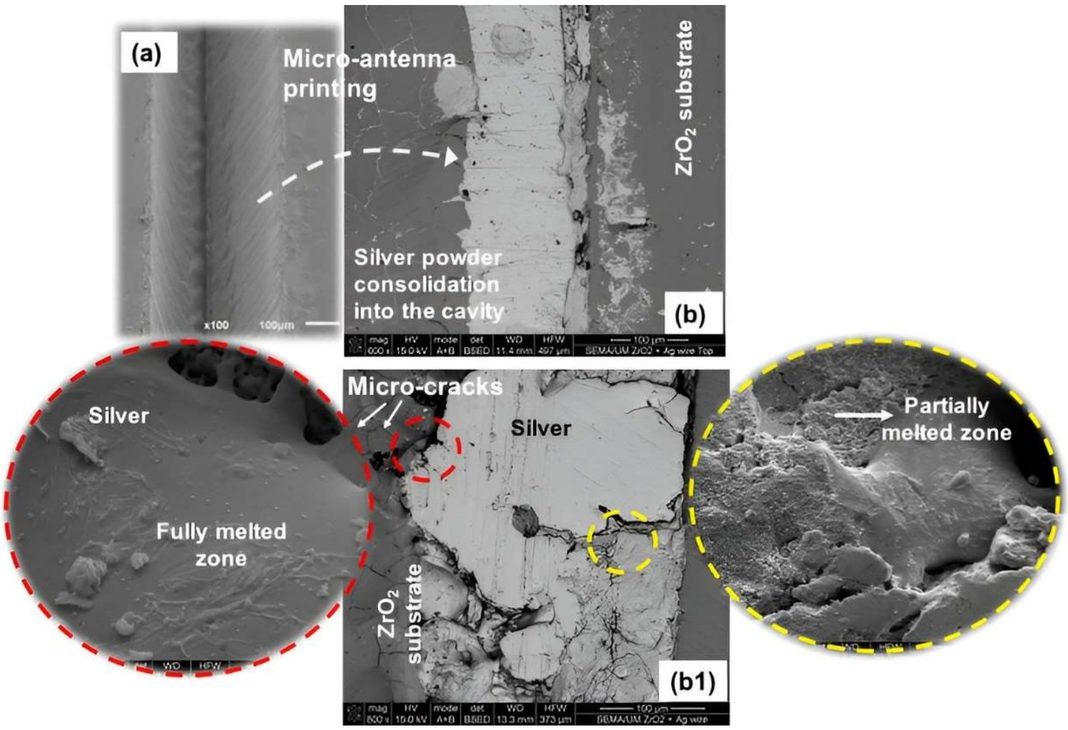

Figure 7. SEM micrographs of (**a**) Micro-cavity before the silver-based antenna printing, obtained after laser machining; (**b**,**b1**) Micro-antenna printed into the cavity through laser sintering process, 800×.

The images from Figure 7 show that the silver powder grains were melted in the sintering condition used. The great advantage of laser sintering is the possibility to sinter specific zones by concentrating the laser energy. However, because of the quick heating and cooling during the laser sintering process, the materials normally receive high residual stress. In some cases, cracks may even be initiated in the surrounding area. The distribution and magnitude of the residual stress are influenced by the laser machining strategy, material properties and environmental conditions. This aspect is evidenced by Figure 7b, in which some micro-cracks are present in the zirconia substrate after the laser sintering process of the antenna. Although the laser beam focused only on the silver path, the heat from laser irradiation promoted thermal stress on the ceramic substrate. Even in previous studies [32,35], the authors verified a decrease in flexural strength of zirconia samples after laser printing of the components. This decline is a consequence of the laser process, which easily forms a tiny accumulation of defects or cracks. However, in this study, even with a decrease in resistance, the values are still within the permissible limits by the standard ISO 13356:2015 (≥500 MPa) for zirconia specimens [32,39].

3.2. Antenna Performance

The return and transmission losses of the antenna are displayed in Figure 8 respectively. Through their analysis, it is possible to conclude that the antenna, when placed inside biological tissue, operates best at 2.4 GHz, as its S_{11} parameter is the lowest at that frequency and the S_{21} parameter is the highest. Operation at 2.4 GHz, i.e., the ISM band, is an attractive feature of the antenna, as common communication protocols, e.g., Wi-fi and Bluetooth, also utilize this band, thus making it easier to establish a communication link with the implanted device.

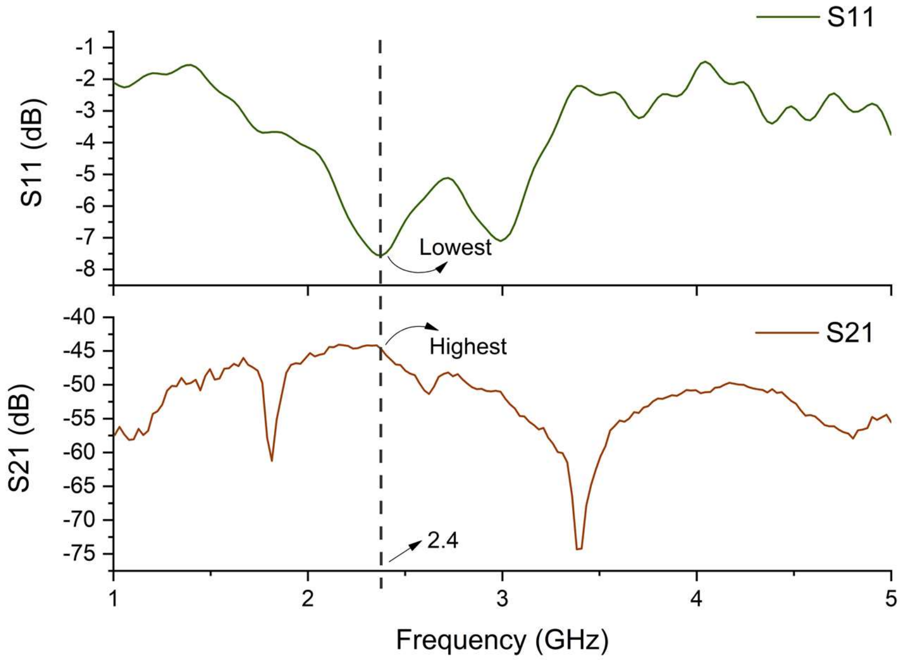

Figure 8. S_{11} (**top**) and S_{21} (**bottom**) parameters measured through the VNA for a frequency range of 1 to 5 GHz, which demonstrates that the antenna is better suited to operate at 2.4 GHz.

Further analysis of the experimental results, namely the S_{21} parameter, indicates that the fabricated antenna is capable of receiving −45 dB of power from the transmission antenna at 2.4 GHz when they are 25 cm apart.

In order to determine the suitability of the antenna for communication in the presented scenario, the Specific Absorption Rate (SAR) of the antenna must be considered. The SAR is a measurement of how much energy from the electromagnetic wave propagating through the tissue is absorbed by said tissue. In order to guarantee the safety of the patient, the SAR must be below a predefined limit, in this case, 2 W/kg, as values higher than this can lead to significant heating of the tissues. Since communication modules that can be used outside the body have sensitivities of −90 dBm, −125 dBm and even as low as −150 dBm [10], the transmitter inside the body can be transmitted with an extremely low power level, for example, −10 dBm, thus guaranteeing a low SAR. With such an output power, −55 dBm would still reach the receiver (in the previously described scenario of Figure 5), a value well above the mentioned sensitivities.

Thus, we can state that given that communication modules can easily achieve sensitivities of −120 dBm, and assuming the implanted antenna will transmit data with a very conservative power of −10 dBm, the S21 could be as low as −110 dB for −120 dBm of power (the detection limit) to reach the communication module. As it is −45 dB, we have 65 dB of margin, which means we receive signals with power more than six orders of magnitude higher than the minimum that the receivers can detect. Furthermore, the test performed on the antenna allowed mimicking the real scenario with the use of biological tissue. Thus, considering the setup in which the antenna was tested and the high margin of power achieved, it is clear that the developed antenna is suitable for wireless communications from inside the body.

4. Conclusions

A promising approach to producing a silver-based antenna on a ceramic substrate was presented in this work. As a versatile tool, the laser technique was utilized to produce the micro-cavity in zirconia substrate (as a subtractive process) and also to sinter the silver antenna into this cavity (as an additive process). A micro-cavity with the desired antenna design was created by laser on the zirconia surface, and then the silver powder was successfully sintered into this cavity, forming a conductor path. In addition to being a fast and inexpensive manufacturing technique, this approach can also be applied to other and more complex designs. According to the results, the fabricated antenna can receive −45 dB at 2.4 GHz from a horn antenna placed 25 cm away from it while safeguarding the safety of the patient. The antenna fabricated through the proposed method can be used safely in an implant to bidirectionally communicate data with the outside world without the need to have the exterior antenna attached to the skin, thus allowing for truly tether-less applications.

Author Contributions: C.M.: investigation and writing; H.D.: investigation and writing; Ó.C.: technical guidance; P.M.: investigation and reviewing; R.N.: investigation and reviewing; F.S.: investigation and reviewing. All authors have read and agreed to the published version of the manuscript.

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