Efficient Through-Waveguide Wireless Power Transfer for Body Area Networks

Alexander Vorobyov*, Vladimir Kopta*†, John R. Farserotu* and Christian C. Enz†
*Centre Suisse d'Electronique et de Microtechnique (CSEM), Neuchatel, Switzerland
†Ecole Polytechnique Fédérale de Lausanne (EPFL), Neuchâtel, Switzerland

***Abstract*—This paper focuses on a solution for wireless powering of sensor nodes embedded in an artificial "skin", used to provide a sense of touch to persons using prosthetic limbs. The artificial "skin", that consists of an inner dielectric layer with top and bottom soft metallization, acts as a waveguide, providing means to efficiently guide electromagnetic power to sensor nodes. The proposed solution allows removal of wired connections between soft metallization layers and sensor nodes,that are identified as the primary source of failure. Depending on node distances and propagation conditions, measurements indicate that the available power at the receiving node ranges from 46.8 % to 66.1 % of the transmitted power. Lower efficiency, compared to wired powering, is thus traded for higher reliability and reduced production cost.**

I. Introduction

Advances in the fields of micro, nano and biological systems are converging to enable ever more powerful miniaturized sensor devices, opening the door for new solutions made of intelligent materials, such as Smart Gloves or Artificial Skin. These may be viewed as a kind of body sensor network, consisting of one to potentially many sensor devices. Potential applications include health (e.g. prosthetics), safety (e.g. handling of potentially hazardous materials) as well as tactile robots (e.g. factory and service robots). The *WiseSkin* concept for tactile prosthetics [1] targets the restoration of a natural sense of tactility to persons who have lost a limb and are using prosthetics. The "touch information" recorded by sensors on the prosthesis and delivered to the participants stump by the tactile display unit, allows the user to receive tactile feedback about objects and contact surfaces, concept is presented in Fig. 1. *WiseSkin* solves the problem of tactility for active and passive prosthetics via a novel concept in which highly miniaturized, ultra-low power (ULP) sensors are embedded into either glove or a coating of the prosthesis. This glove, or coating, which is normally used to provide a natural appearance, thus serves as an artificial skin that provides both a natural look and "feel".

Delivering power to sensor nodes requires particular attention. In order to allow unobstructed movement of the prosthesis, power lines must be sufficiently flexible and stretchable. One solution is to print a metallic grid on the skin substrate using stretchable biphasic thin metal films [2], and connect sensor nodes to this grid. Wired connections, however, pose a reliability issue, as over the extended period of use these wires could break. A contactless solution would improve the robustness of the *WiseSkin* system, and is therefore preferred.

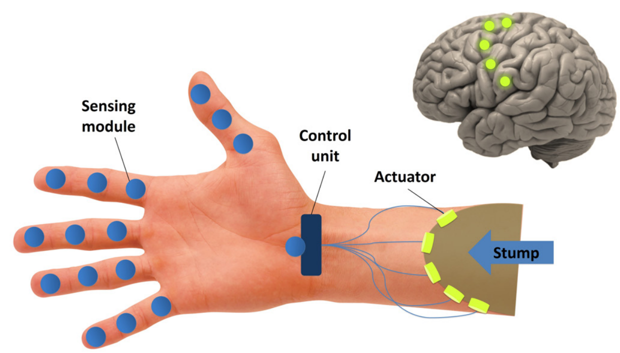


Fig. 1. *WiseSkin* concept - sensor nodes embedded in artificial skin transmit data from sensors to the central processing unit. This data is processed and used to create stimulation patterns using actuators in order to restore the natural sense of touch to the patient.

In addition such approach eases production, reduces cost and allows replacement of nodes.

Wireless power transmission (WPT) takes place in any system where electrical energy is transmitted from a power source to an electrical load, without interconnecting wires. With the development of electronics, short distance wireless power transmission has become popular in consumer and medical electronics [3]. In parallel, it has been shown that reasonable efficiency may be obtained at larger distances. The benefits of WPT extend beyond cost and convenience. Certain conditions, environments, and applications are simply unsuitable for conventional wired sources of electricity. Our research interest lays in mid- and long-distance WPT systems, covering distances from centimeters to meters using guided radio frequency (RF) waves.

The concept of the WPT system is introduced in Section II. Then, in Section III, the antenna design and prototyping is discussed. The measurement setup and characterization results of the realized WPT solution are discussed in Section IV. Conclusions are drawn in Section V.

II. Proposed WPT System Description

Illustration of the wired solution is shown in Fig. 2a. The main source of unreliability is the interface between the stretchable metallic layers and the rigid sensor node. During initial experiments with the artificial skin, these wires would often break, completely disabling the sensor node. Furthermore, these wires are difficult to implement and effectively increase production cost and complexity. Assuming lower energy efficiency of the system can be tolerated, both issues can be solved by WPT.

The proposed WPT system [4] is shown in Fig 2b. The system is wireless in the sense that there is no mechanical connection between the node and the metallic layers. However, the two metallic layers remain present, and together with the flexible middle layer (dielectric such as silicone, textile etc.) form a flexible and stretchable parallel plate waveguide. The power is distributed via the Radio-Fequency (RF) electromagnetic (EM) waves. The principle is similar to that of existing energy harvesters [5], with one important difference. Typically, these harvesters are designed to gather energy from EM waves already present in the air. Since most of the energy is lost in free space, input power levels are low and only modest efficiency can be achieved, unless a dedicated highly directive antenna is used. The proposed system exploits the existing waveguide to confine the transmitted energy and increase the overall efficiency by guiding the wave from the power source to the sensor node. Since relatively high input power levels are available (on the order of 10 dB), the rectifier converting the RF signal into dc power can operate in the high efficiency region, thus improving the overall system efficiency.

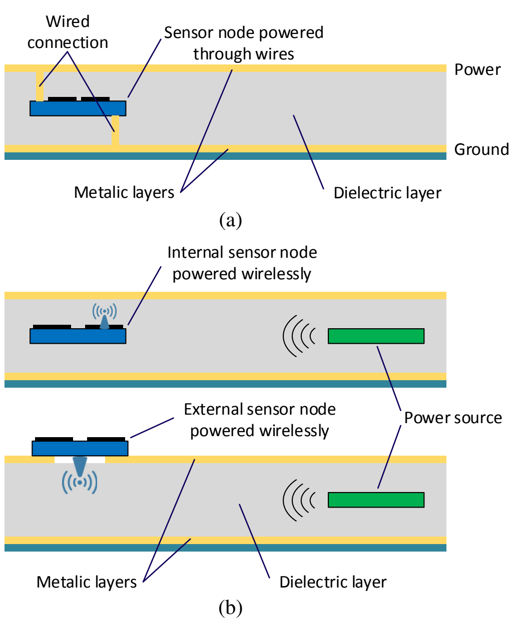


Fig. 2. General concept of a sensor node powered through wires (a) and a sensor node powered via RF energy, harvested from a master or powering node (b). RF energy is distributed via the flexible waveguide.

The general principle can be extended beyond the scope of the *WiseSkin* solution to different applications such as wearable electronics, health care or robotics [6]. Additionally, sensor nodes need not be placed inside the waveguide. They can also be placed on top of the artificial skin, in which case the slot in the metallic layer acts as an antenna.

The proposed flexible waveguide distributes power, enabling a practical means of remote powering and batteryless operation of sensor or actuator nodes. The solution is contactless and wireless, and conformable to different surfaces as required by the application. The proposed solution offers the following benefits:

- Batteryless operation - allows smaller node footprint and a lower cost solution.
- Increased robustness - no mechanical contacts or wires are needed for powering nor communication. Mechanical contacts are difficult to implement and could be the first source of failure. Even if the stretchable metallic layer is broken, the system remains functional and the loss in efficiency can be compensated by increasing the transmitted power.
- Ease of manufacturing and lower cost - removal of the mechanical contacts eases manufacturing, thus also reducing cost and complexity.
- Configurability - assuming detachable layers can be produced, sensor and actuator devices may be placed at different locations within the flexible structure as they are not constrained by wires or fixed connections. Furthermore this allows easier replacement of sensor nodes.

In this work the antenna and the waveguide are optimized for operation in the 2.4 GHz ISM band, although different bands can be used as well. Using higher frequencies leads to smaller antennas and further miniaturization of the sensor nodes. However, the efficiency of rectifiers, needed to convert the input RF signal into power, typically decreases at higher frequencies [5], leading to lower overall system efficiency.

III. Antenna Design

The proposed antenna, shown in Fig. 3, is a compact capacitive loop solution optimized for integration into the PDMS (polydimethylsiloxane) structure with top and bottom metallization. As most miniature antenna solutions, the proposed antenna does not provide high bandwidth. However, the antenna can be fairly easily tuned to the desired frequency, when all parameters are known. For example, by changing the feed location of the antenna, the resonance frequency will

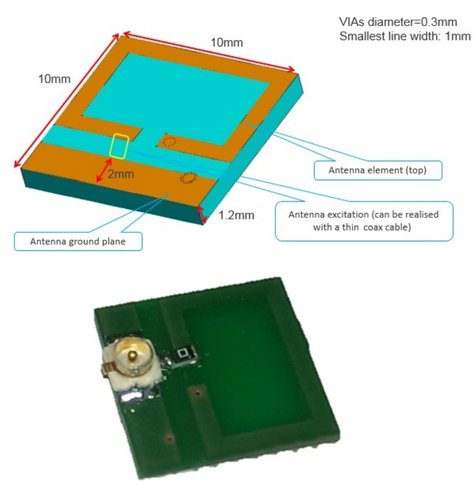


Fig. 3. 3D model of the designed antenna and the manufactured PCB with a μFL connector.

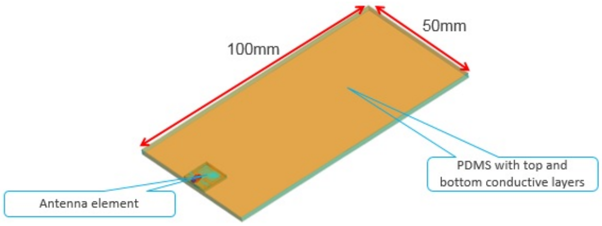


Fig. 4. Model used for antenna optimization.

be smoothly shifted toward higher or lower frequency. Other parameters like the antenna ground plane (GP) and the slot between the GP and the antenna element can shift the antenna resonance frequency as well improve the antenna matching. The antenna is prototype is implemented on a 1.2 mm thick FR4 substrate.

The theoretical model for the antenna design and optimization is shown in Fig. 4 and consists of two elements. First is the PDMS structure represented by a rectangle bloc with metalized top and bottom surfaces. The second is the antenna element placed on one side of the PDMS block, close to the edge and in the middle between the top and bottom metalized layers.

The simulated reflection coefficient is presented in Fig. 5, and shows that the antenna is matched at roughly 2.45 GHz.

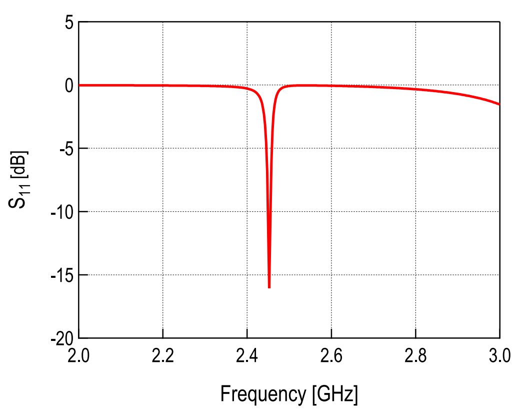


Fig. 5. Simulated antenna S_{11} parameter, antenna is placed between the two metal layers.

IV. Measurement Results

To asses the performance of the proposed power delivery system, several waveguide prototypes were made. A 125 mm thick PDMS was used as the dielectric layer in all samples. To emulate the two metallic layers, conductive tape was placed on both sides of the PDMS, the width of the metallic trace is 16 mm. The used structure is shown in Fig. 6. Three different samples were used in order to measure performance for different antenna distances (waveguide lengths): 60 mm, 120 mm and 275 mm. In addition, a second 275 mm long sample was used, with the top metallic layer cut in the middle (Fig 6). The cut is done in such a way that there is no electrical contact between the left and right part, but that the geometry of the waveguide remains preserved. This should correspond

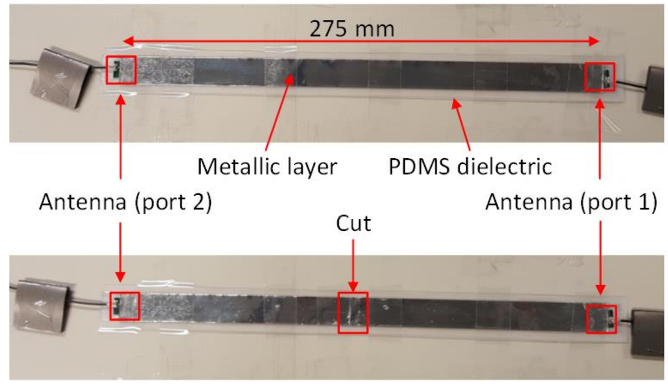


Fig. 6. Examples of the used waveguide samples, 275 mm long waveguide (up) and the same waveguide with a cut in the middle (down).

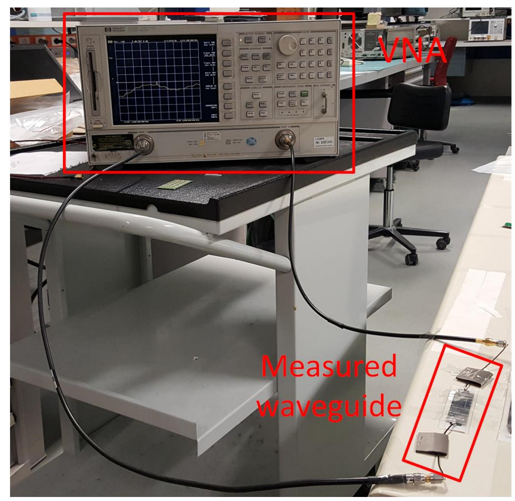


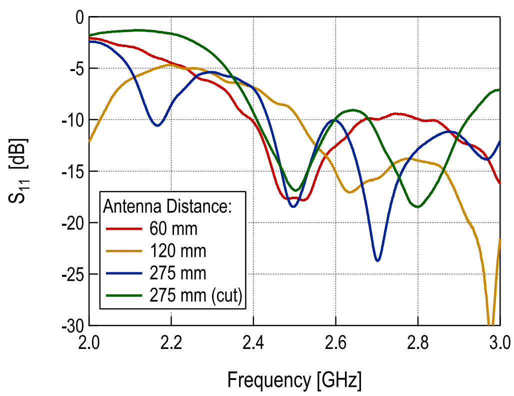
Fig. 7. Test setup with the VNA and the implemented waveguide prototype.

to the case where a fissure appears in the metallic layer of the skin (for example, due to severe stretching). The test setup is rather simple and consists of a two-port Vector Network Analyzer (VNA), connected to the measured sample using a miniature coaxial cable (µFL). Ferrites are placed close to antenna connections to suppress radiation from the cables. The test setup is shown in Fig. 7.

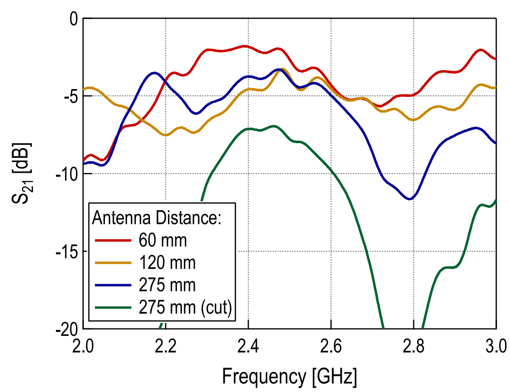
The s-parameters of all the measured samples are shown in Fig. 8. The reflection coefficient (S_{11}) shows good characteristics in all cases and is close to or below -10 dB around 2.45 GHz. For the three cases where the waveguide is not damaged, transmission coefficient indicates relatively small losses, mainly caused by the antenna impedance mismatch. Looking at the small variation of results for the 120 mm and 275 mm samples it is expected that increasing the waveguid length beyond this point does not introduce significant additional losses, and that the concept could be extended to distances of several meters. In this case the test samples are limited by the size of available PDMS sheets.

The transmission coefficient of the sample with a fissure in the metallic layer shows somewhat higher losses, but the energy transfer is still possible. If the metal traces were used to supply dc power to the node, such fissure would completely disconnect the node from the rest of the system. In this case the only consequence is efficiency degradation, however the system remains functional, and increased losses can be compensated by increasing the transmitted power. All the results at 2.45 GHz are summarized in Tab. I, together with the available power at the output, as a percentage of the transmitted power.

To gain insight into the expected overall efficiency of the proposed system (not accounting for the transmitter efficiency), efficiency of rectifiers and rectennas reported in literature is shown in Fig. 9. It should be noted that these were designed for free space, line of sight scenarios, but can nevertheless be used for rough efficiency estimation. For our application the focus is mainly on received power in the range from -5 dBm to 20 dBm. For that range the expected efficiency varies between 60 % and 80 %. This leads to the best case estimated efficiency of 52.9 % for a very short waveguide, and the worst case efficiency of 28 % for a long waveguide with a less efficient rectifier (rectenna). Even if the metallic layer is damaged, the minimum expected efficiency should still remain above 12 %.



(a)



(b)

Fig. 8. S-parameters for different antenna distances: (a) S_{11} and (b) S_{21}.

TABLE I
AVAILABLE OUTPUT POWER

Distance [mm]	S_{21} [dB]	Available power [%]
60	-1.8	66.1
120	-3.2	47.8
275	-3.3	46.8
275 (cut)	-7	20.0

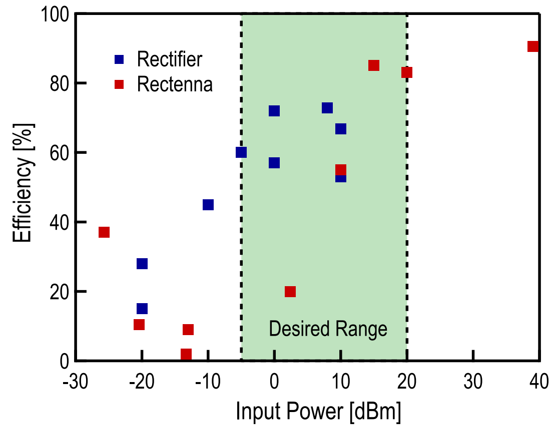


Fig. 9. Reported efficiency of implemented rectifiers and rectennas at 2.4 GHz [5].

V. Conclusion

The proposed solution provides a means of remote powering via guided propagation through a flexible, stretchable waveguide structure. The low loss, waveguide structure enables efficient powering via EM energy, and therefore batteryless operation of sensors and actuators, reliable operation, lower production cost and higher configurability. The solution is contactless and wireless (i.e., there are no contacts or wires required to power the nodes or to connect them). The focus of this work is on a proof of concept used for powering a single node, however the structure may be formed into various shapes and contours, optimized for different application and used to power a plurality of nodes.

Acknowledgment

This work is partly funded by Nanotera national research program under Swiss National Science Foundation (SNF) grant No. 20NA21-143070.

References

[1] J. Farserotu, J. Baborowski, J. D. Decotignie, P. Dallemagne, C. Enz, F. Sebelius, B. Rosen, C. Antfolk, G. Lundborg, A. Bjrkman, T. Knieling, and P. Gulde, "Smart skin for tactile prosthetics," in *2012 6th International Symposium on Medical Information and Communication Technology (ISMICT)*, March 2012, pp. 1–8.

[2] A. Hirsch, H. O. Michaud, A. P. Gerratt, S. de Mulatier, and S. P. Lacour, "Biphasic metal films: Intrinsically stretchable biphasic (solidliquid) thin metal films (adv. mater. 22/2016)," *Advanced Materials*, vol. 28, no. 22, pp. 4506–4506, 2016.

[3] K. Jung, Y. H. Kim, E. J. Choi, H. J. Kim, and Y.-J. Kim, "Wireless power transmission for implantable devices using inductive component of closed-magnetic circuit structure," in *2008 IEEE International Conference on Multisensor Fusion and Integration for Intelligent Systems*, Aug 2008, pp. 272–277.

[4] V. Kopta, J. Farserotu, and O. Vorobyov, "System and method for remote powering at least one sensor or actuator from a rf power source," May 3. 2017, EP Patent App. EP20,150,192,228; US Patent App. 15/336,955.

[5] C. R. Valenta and G. D. Durgin, "Harvesting wireless power: Survey of energy-harvester conversion efficiency in far-field, wireless power transfer systems," *IEEE Microwave Magazine*, vol. 15, no. 4, pp. 108–120, June 2014.

[6] A. Nathan *et al.*, "Flexible electronics: The next ubiquitous platform," *Proceedings of the IEEE*, vol. 100, no. Special Centennial Issue, pp. 1486–1517, May 2012.