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Design and Integration of a Wearable Antenna System for On- and Off-Body Communication Based on 3D-MID Technology

Authors:
Lukas Berkelmann
Timo Martinelli
Aline Friedrich
Dirk Manteuffel

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Lukas Berkelmann[1], Timo Martinelli[1], Aline Friedrich[1], Dirk Manteuffel[1]
[1]Institute of Microwave and Wireless Systems, Leibniz Universitaet Hannover,
Hannover, Germany, berkelmann@hft.uni-hannover.de

***Abstract*—This contribution discusses the application of 3D Molded Interconnect Devices Technology (MID) for a wearable antenna system shaped to fit on the human body. The proposed system consists of two antennas, both operating in the 2.4 GHz band used for Wireless Body Area Networks (WBAN) according to IEEE standard 802.15.6. One antenna is designed to excite a strong Norton surface wave component for on-body communication, while a second antenna is intended to generate a space wave to support an off-body radio link. As both antennas operate at the same frequency, the system is designed to provide a mutual coupling of less than -25 dB. The final design is integrated into a generic 3D housing to be worn on a humans wrist.**

***Index Terms*— wireless body area networks (WBAN), molded interconnect devices (MID), on-body propagation, wearable antennas.**

I. Introduction

The design of wireless wearable devices e.g. for lifestyle, diagnostics, therapeutics, and injury prevention involves many different purposes and potentials. Body worn devices need to be adapted to the body of the user as good as possible to assure a comfortable fit. This is closely connected with the demand for small and highly integrated RF systems. Especially, for the antenna design this often leads to challenging demands. As a consequence thereof, the fabrication method becomes more and more important. The term Moulded Interconnect Devices or Mechatronic Integrated Devices (MIDs) summarizes different fabrication methods that allow for a realization of 3D shaped circuit carriers. More precisely, it describes 3D plastic parts that are metallized selectively. This does not only enable the realization of radiating and shielding elements but also circuit pattern. The technology is already used in a wide range of applications [1]. Due to the challenging requirements on RF systems in wearable devices, MID fabrication could be one possible solution to meet these requirements.

This contribution is structured as follows. In section II different MID fabrication methods are discussed in the context of wearable devices. Based thereon, section III discusses the principles of an antenna design that allows for separate on- and off-body communication. The antenna system is developed to operate in the 2.4 GHz-band for Wireless Body Area Networks (WBAN) according to IEEE standard 802.15.6. It is evaluated on the basis of electromagnetic simulations. Subsequent to these investigations, section IV discusses an example design which is optimized to be manufactured with 3D MID fabrication methods. Finally, in section V a conclusion is drawn.

II. 3D Fabrication of Wearable Antennas

3D MID fabrication in the context of wearable devices is a method to efficiently integrate antennas and the processing circuitry in a housing shaped to fit on the 3D surface of the human body. MIDs are 3D shaped plastic parts that are manufactured e.g. in an single-shot or two-component (2K) injection moulding process or as insert molding part. These parts can be the housing or a frame of an electronic device e.g. a wearable sensor node. The plastic material that can be used in these processes are common thermoplastic or thermoset materials. For wearable devices skin compatibility needs to be ensured.

The surface of the plastic parts can be selectively metallized using different procedures that depend on the basis material used. Using 2K injection molding the surfaces to be metallized are directly integrated in the injection mold. For single-shot injection molded parts the metallization can be applied by the Laser Direct Structuring (LDS) process or with different printing technologies, e.g. Aerosol Jet printing. A third method to metallize MIDs is hot embossing where a special copper foil is pressed on the plastic surface. This method additionally allows for a realization of flexible circuit carriers on foils that may be also interesting for wearable devices. Especially, for wearable systems that are worn for a long time, mechanical robustness is important. For such applications an injection moulded carrier is more suitable.

One MID method frequently used for antenna fabrication of laptops, tablets and cell phones is the aforementioned LDS process. The injection molded plastic carrier consists of a special plastic that is doped with a mixed metal oxide. This LDS additive can be activated by a laser. The activated surfaces allows for a deposition of copper ions in an electroless plating process. To reduce oxidation of the copper layer different surface finishes are available. These are e.g. a layer of nickel-phosphorous and immersion gold or immersion silver. As mentioned before in regard to wearable devices the material of the plastic part is especially important. There are various LDS materials available that are based on typical thermoplastic or thermoset materials with the main difference of having

(a) Tangential half-wave dipole (b) Normal half-wave dipole

Fig. 1. Antennas for off-body (a) and on-body (b) communication

the LDS mixed metal oxide added. The antenna development discussed following is designed for a fabrication with LDS process.

III. Antenna System for On- and Off-Body Communication

Wireless systems for Body Area Networks need to follow several special requirements. Most on-body channels are relying on multipath propagation, including direct space wave components as well as components of space waves that were reflected by the environment [2]. In shadowed regions (with no line-of-sight path) surface waves play an important role, especially in a less reflective environment, viz. outside of buildings. Conventional antennas are usually not designed to optimize on- or off-body communications. Published designs intending this separation typically use a second frequency band (e.g. [3], [4]) in order to reduce mutual coupling or achieve a low profile on-body antenna. In this contribution a system of two decoupled antennas operating at the same center frequency is designed.

As discussed in [5] and depicted in Fig. 1 a normal polarized antenna with respect to the surface of the body excites a stronger Norton surface wave while a tangentially polarized antenna primarily excites a space wave radiated off the body. Consequently, a possible solution to efficiently excite waves for on- as well as off-body communications is to route two antenna elements in 3D dimensions (normal and tangential). This indicates that 3D MID fabrication technology could be an appropriate solution to develop and realize such antenna systems.

A. Antenna Design

Following the results obtained a slotted patch antenna is used to excite a space wave for off-body communication. For the on-body antenna an inverted-F antenna (IFA) is designed, which represents a reasonable trade-off between a strong normal polarization and a low geometrical height. The substrate material used in the following is Vectra 840i LDS a Liquid Crystal Polymer (LCP) suitable for the LDS process. This material has a relative permittivity of $\epsilon_r = 3.55$ and a loss tangent of $\tan\delta = 0.003$ both measured at 2.7 GHz. Both antennas are designed to operate at the WBAN frequency band from 2.36 GHz to 2.4 GHz. The geometry and the associated parameters of the design are shown in Fig. 2 and Table I.

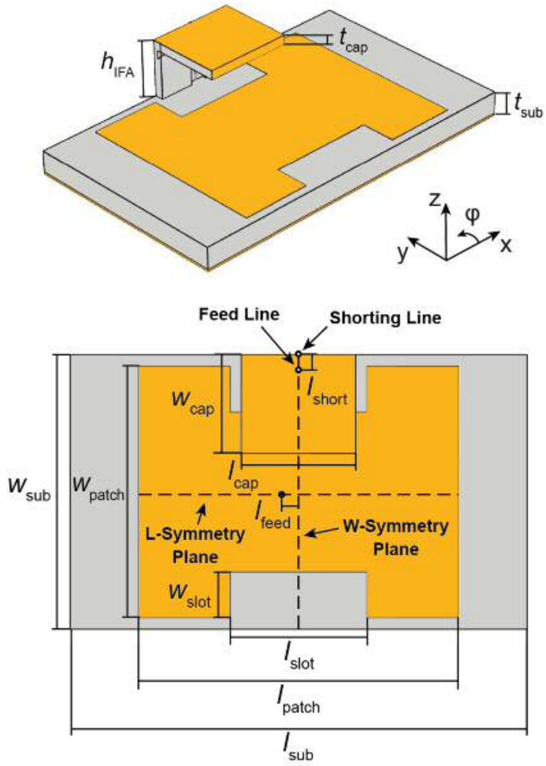
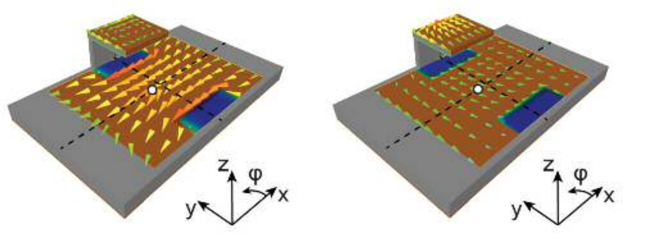


Fig. 2. Antenna System for on- and off-body communication

TABLE I
Related Geometric Parameters

Parameter	Value in mm	Parameter	Value in mm
l_{sub}	40	l_{feed}	3.5
w_{sub}	24	h_{IFA}	6.5
t_{sub}	2.5	t_{cap}	1
l_{patch}	28	l_{cap}	10
w_{patch}	22	w_{cap}	8.6
l_{slot}	12	l_{short}	0.5
w_{slot}	4		

Investigations concerning an optimal positioning of both antennas are made focusing on a compact solution while maintaining low mutual coupling of both antennas. An optimum was found by positioning the IFA at the W-symmetry plane (see Fig. 2(b)). Therefore, the on-body IFA-antenna is applied on a L-shaped substrate which is placed in the middle of the resonating edge of the patch antenna. Feed and shorting line are located on opposite sides of the vertical L-shaped part (see Fig. 2(b)) to take advantage of the 3D-MID LDS fabrication possibilities. By adding slots along the resonant edges of the patch, the structures size is decreased. Besides reducing the patch's resonant length this also allows for a positioning of the on-body IFA inside one of these slots. Fig. 3 depicts the surface currents of the optimized setup on both antennas. In Fig. 3(a) the off-body patch is excited while Fig. 3(b) shows



(a) (b)

Fig. 3. Current paths on metallized structure with exclusive excitation of the off-body patch (a) and the on-body IFA (b) at center frequency $f_c = 2.38\,\text{GHz}$

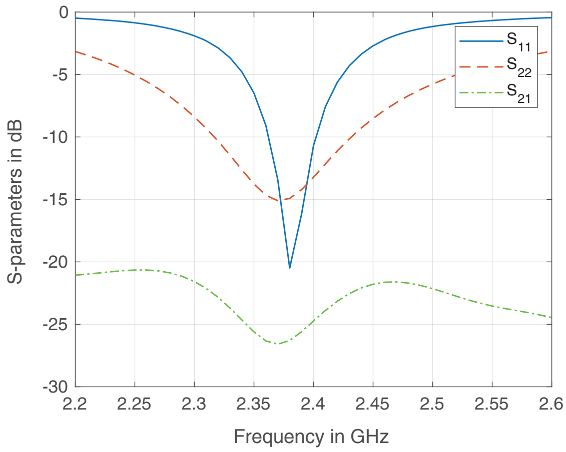


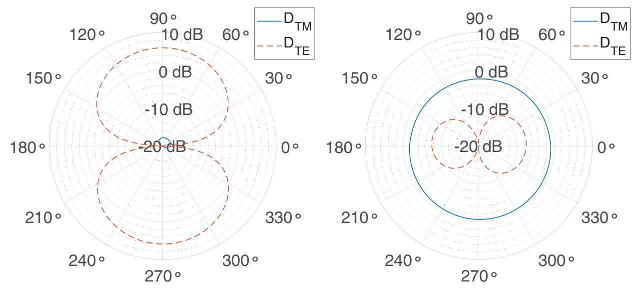
Fig. 4. S-Parameters (port 1: off-body patch, port 2: on-body IFA)

the surface currents for an excitation of the on-body IFA. Obviously both antennas in the proposed configuration reveal orthogonal current paths. As depicted in Fig. 3(b) the port of the patch is positioned on the L-symmetry plane with respect to the excited current distribution on the patch. The resulting impedance ratios ensure a low mutual coupling. Accordingly, the placement of the IFA centered at the patch's resonant edge and the orthogonal orientation of both structures offers an excellent decoupling as well as a small overall size.

B. Simulation Results

All simulations described in the following are done using EMPIRE XPU 7.54. Fig. 4 depicts the simulated S-parameters of the antenna system. The antenna is located 0.75 mm above the tissue to prevent leakage currents into the tissue that is represented by a half space of muscle tissue equivalent dielectric material [6]. As can be seen, the return loss in the operation frequency band is below -10 dB while an excellent isolation between both antennas better than 25 dB is achieved.

To verify the excitation of the on-body TM-Mode and the off-body TE-Mode, on-body-directivities as defined in [7] are calculated. In contrast to the conventional free space antenna directivity the on-body directivity provides adequate parameters for the characterization of on- and off-body radiation. They are determined from the current distribution on the antenna in the presence of the tissue as described



(a) Off-body patch (b) On-body IFA

Fig. 5. On-body directivities in xy-plane

above. The antennas far field is modeled using the analytic solution of Bannister [8] by converting the antennas currents into a distribution of small dipole elements. By separating the antennas far field into its corresponding TE/TM-components and normalizing them to the far fields of equivalent Hertzian dipoles (TM-component: normal dipole, surface wave excitation / TE-Component: horizontal dipole, space wave excitation) the on-body directivity D_{TE} / D_{TM} to evaluate the antennas performance in terms of on-body communication can be defined. The entire method is described in detail in [7]. The resulting on-body directivities of both antennas are depicted in Fig. 5. As shown, the patch antenna has a pure TE-characteristic optimally suited for off-body communication. Moreover, the IFA antenna provides a strong omnidirectional TM-characteristic, thus is well suited for exciting on-body Norton surface waves. Even though the IFA also has a TE-component caused by the horizontal current path on the capacitive top load, the TM-component is dominant.

IV. 3D Example Design

The possibilities of the LDS MID technology are used to optimize the former discussed concept for a potential wristband application. The base area of the structure is bent to ensure a comfortable fit on a human wrist as shown in Fig 6. Additionally, the capacitive loading of the IFA is placed below a curved cover. The cover is 0.5 mm thick and consists of Vectra 840i LDS like used for the antennas substrate. A connection between the metallized part of the housing and the remaining structure could be realized by a contact spring on top of the vertical part of the substrate. The maximum height in the middle of the entire structure is 8.6 mm. Simulations of the adapted 3D structure showed almost equal performance in terms of decoupling and on-body directivity compared to the system discussed in the last section. Fig. 7 depicts a simulated distribution of the E-field of the proposed antenna system placed at the wrist of ITIS voxel model Duke [9]. As can be seen waves excited by the patch antenna propagate away from the body, while the IFA antenna excites surface waves, which follow the body contour.

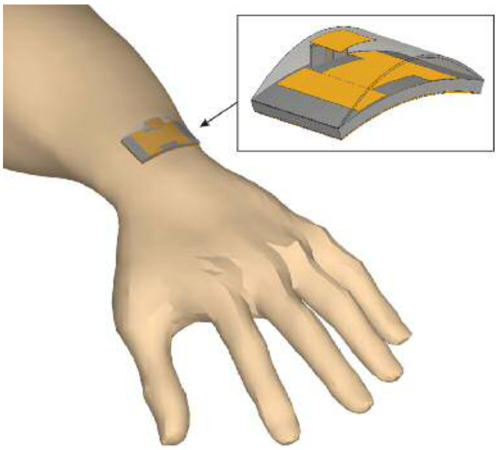
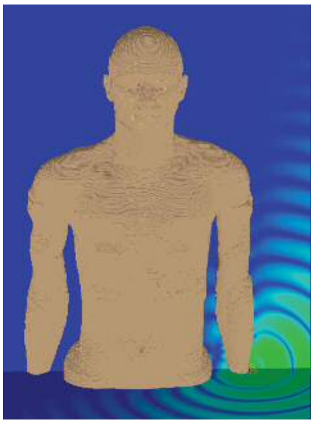
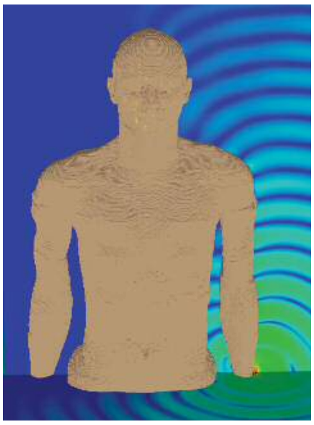


Fig. 6. 3D Example Design on human wrist



(a) Off-body patch



(b) On-body IFA

Fig. 7. Simulation of the electric field distribution of the designed off-body patch (left) and on-body IFA (right)

V. Conclusion

The proposed antenna system shows good qualities for on- and off-body communications. 3D design capabilities gained by 3D MID fabrication method are utilized to achieve the targeted excitation of wave components for on- and off-body communication as well as a volume-efficient integration and fitting to the human body. By an optimized placement of both antennas, an excellent isolation of better than $S_{21} < 25\,\mathrm{dB}$ is achieved, while maintaining a compact solution. The evaluation of the on-body directivity is utilized as a metric for the characteristic of the radiated power flow along the body curvature. Accordingly, the proposed system enables a separate excitation of a strong Norton surface wave or a strong space wave, at the same center frequency. Thereby, the antenna system can be used for separate on- and off-body communication as well as for a body centric MIMO-system. The final design is integrated into a generic 3D housing to be worn at the wrist showing comparable results to those obtained for the non-conformal model discussed in section III. The general design concept can additionally be adapted to other wearable applications.

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