An Eighth-Mode SIW Antenna for Low-Power Wide-Area Network Applications

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A wearable textile antenna based on the fundamental mode of an eighth-mode substrate-integrated waveguide cavity is presented for Low-Power Wide-Area Network (LPWAN) applications. The antenna operates in the UHF frequency band, at 867 MHz, and exhibits compact size, minimal manufacturing complexity and very low production cost. High isolation from the human body is observed, and a planar size reduction by more than 50% is achieved compared to similar SIW antennas in the literature. The proposed wearable antenna has been designed using CST Microwave Studio, then manufactured and tested, showing very good agreement with predicted performance.

Keywords: wearable antennas; body-antenna coupling; eight-mode substrate integrated waveguide (EMSIW); LoRa

1. Introduction

LoRa (Long Range) is a wireless standard for Low-Power Wide-Area Networks (LPWAN) [1-4], consisting of a spread-spectrum modulation technique which allows the transmission of data at extremely low data-rates (down to few bytes per second), achieving remarkably long ranges. LoRa applications operate in license-free sub-gigahertz radio frequency bands as 433 MHz, 867 MHz (Europe), 915 MHz (Australia and North America), and 923 MHz (Asia). Among the others, wearable electronics is a typical application that can fully exploit the advantages of LoRa technology. Antennas play an important role in a wearable system and their requirements are very different from “conventional” antennas. First, wearable antennas should be easily integrated into a garment, demanding adequate mechanical robustness, and low-cost, ensured by a simple fabrication process. Moreover, these antennas must be comfortable for the wearer, thus compact, lightweight and flexible, and, at the same time, they should operate properly while worn. Therefore, they must show a good robustness to the interaction with human
Recently, substrate integrated waveguides (SIWs) based antennas [5-19] have been implemented in textile materials, in which the vertical vias, shaping the cavity, are implemented through metallized eyelets [5] or embroidered conductive thread [6]. These SIW structures are particularly indicated for wearable applications, thanks to their flexibility [5, 7-8], wideband/multiband operation [7-10], low profile, planar structure, and relatively high isolation with good radiation characteristics [5, 7-9], and have been proposed both with linear [5-11] and circular polarization [13-14]. Furthermore, SIW structures can be easily miniaturized by exploiting the symmetry of the field distributions of their resonant modes [6, 8-11, 13, 15].

According to previous works on the robustness of wearable antennas with respect to the human body [20-24], SIW antennas have proven to provide effective shielding when operating in close range, ensuring a high isolation from the body and from active electronic circuits installed in close proximity to the antenna. Both Planar Inverted-F Antennas (PIFAs) and patch antennas, a popular choice in wearable electronics, are a common and valid solution, but they typically require large ground planes to achieve the same isolation as SIW configurations.

A number of different SIW antennas [5-11, 13, 15], both half-mode, quarter-mode, and eighth-mode, have been already proposed in the recent literature. They operate around 2.4 GHz (within ISM frequency band), or beyond. The feeding is provided by either coaxial cable [6, 8-9, 16] or microstrip lines [5, 7, 10-14, 15, 17]. Although some papers consider the effect of the proximity of the human body [5, 7-9, 15-18] on the antenna performance, their robustness has not been deeply investigated.

In this work, a wearable textile antenna based on eight-mode substrate integrated waveguide (EMSIW) technology for Low-Power Wide-Area Network (LPWAN)
applications is presented, providing a full characterization of the EMSIW topology in the UHF band, which is actually missing in the open literature. In our opinion, the use of SIW technology also at UHF frequencies can allow the designer to exploit their great advantages in terms of robustness and isolation with respect to the human body coupling, performance which could be reached only using a large shielding ground plane in different configurations (such as patch antennas or PIFAs), yet resulting in an extremely uncomfortable antenna.

In [24] the same basic configuration has been designed, but for a significantly different application, namely an RFID tag at 868 MHz. Therefore, the EMSIW of [24] has been experimentally characterized only by the indirect measurement of the reading range, through a commercial RFID reader.

As a consequence, this partial and limited assessment does not provide comprehensive information on the real potential of the considered EMSIW configuration, because the design requirements of an RFID push the designer to choose the feeding point to match the input impedance of the tag to the high reactive load of the integrated CHIP. This design choice is a very particular case, and strongly depends also by the actual microchip chosen by the designer.

In our opinion, the experimental verification based only on the reading range measurement cannot be considered an affordable test to validate the design procedure, and is neither able to provide any useful information on the effective working frequency band and achievable performance using a different kind of feeding, such as, for example, the common 50 Ω coaxial connector. Therefore, the design presented in [24] does not give an accurate characterization which can help the designer to evaluate the EMSIW antenna for applications different from RFID.

To fill this gap, the 50-Ω-coaxial-connector-fed antenna proposed here has been
designed to cover the European LoRa frequency band (863 MHz – 870 MHz). The SMA coaxial feed allows us to directly and experimentally characterize the antenna in terms of frequency response, bandwidth, and robustness of its performance with respect to the presence of the human body, providing a full characterization of the EMSIW topology in the UHF band, which is actually missing in the open literature.

In this paper, an EMSIW configuration has been chosen to minimize the overall antenna size, allowing for an easy integration. Similar design rules as in [24] are adopted to obtain an adequate antenna topology, while optimizing the size of the cavity ground plane to mitigate deterioration in antenna performance due to the coupling with the human body. The resulting antenna size equals $0.3 \lambda_0 \times 0.27 \lambda_0 \times 0.011 \lambda_0$, with $\lambda_0$ the free-space wavelength at 867 MHz, yielding a planar size reduction at least by 50%, and a volume reduction at least by 80% compared to similar SIW antennas in the literature [5-18]. These antennas, shown in Table 1, are all designed for higher frequencies applications (starting from 2.45 GHz, the ISM frequency band).
The comparison performed in Table 1 highlights that the proposed configuration allows a compact design with respect to the other configurations available in the literature. This is the most critical challenge in the design of antennas in the UHF band and is the aim of our work.
Since SIW antennas have not been used in the UHF frequency band around 868 MHz so far, in this comparison we can report only antennas realized in the same technology but at a different frequency. Therefore, the comparison between their dimensions has been normalized in terms of wavelengths.

As shown in Table 1, all the reported antennas, except for [6] and [17], have been designed in substrates with a higher dielectric permittivity compared to our design, therefore their normalized dimension is underestimated. As a consequence, the antennas available in the literature, if properly scaled at 868 GHz, are not able to provide a compact realization if compared with our presented configuration.

In order to compare the presented antenna also in terms of directivity, Gain and radiation efficiency, which strongly depend on the operating frequency, we have scaled our antenna around 2.45 GHz and compared its performance with the antennas of Table 1 having the same dielectric substrate and metallic sheet, and working at the same frequency. From the above comparison, reported in Table 2, the gain of our antenna is a bit lower, but this is consistent with its lowest dimension and effective area.

Table 2. Gain, efficiency and bandwidth of our LoRa SIW antenna scaled at 2.45 GHz and of SIW in Table 1 at 2.45 GHz using the same substrate of our antenna.
The antenna design and all the simulations have been performed using CST Microwave Studio. A prototype of the presented antenna has been fabricated and experimentally tested to assess the antenna performance and its robustness with respect to the human body coupling.

2. Antenna Design

The EMSIW wearable antenna is designed for Low-Power Wide-Area Network applications in the European UHF band (863-870 MHz), with a central frequency of 867 MHz. The dielectric substrate is a 4 mm-thick closed-cell rubber foam ($\varepsilon_r = 1.34$ and $\tan \delta = 0.014$ at 867 MHz), which is commonly employed in firefighter suits. Adhesive copper-coated non-woven PET fabric, characterized by a sheet resistivity of 0.04 $\Omega$/square and a thickness of 0.11 mm, is used to implement the conducting parts of the structure.

A 50 $\Omega$ SMA coaxial connector is employed to feed the antenna. This connector could potentially represent an obstacle when in direct contact with the wearer, causing discomfort. However, the wearable antennas are typically developed for integration into jackets or garments. Therefore, some spacing between antenna and body will always be present, and it is not necessary to characterize the antenna performance for antenna/body separations less than a few millimeters. Possibly, a UFL connector can be used to obtain a thinner structure.

The design rules for the proposed antenna are derived by the formulas for SIW circular cavities [19]. The simulated magnetic field distribution of the fundamental TM$_{010}$ mode inside a circular full-mode SIW cavity with a radius of $R_c = 90$ mm, and resonating at 868 MHz, is reported in Fig. 1(e). Starting from this cylindrical cavity, in the design evolution we exploited the magnetic field symmetry to reduce the cavity size, as
summarized in Fig. 1 (a-d). In the field distribution depicted in Fig. 1(e), the magnetic field lines are symmetric along AOB plane, which can be considered as an equivalent perfect magnetic wall (PMW). Therefore, the full-mode cavity in Fig. 1(a) can be halved, cutting off the half of the cavity below the plane AOB, reducing it to the Half-Mode SIW (HMSIW) resonator shown in Fig. 1(b).

The resonant frequency is approximately the same for both full-mode and half-mode cavities, and the field distributions of these cavities are nearly the same at the fundamental mode, although some modes of the full-mode cavity are not supported by the half-mode one. The resonant frequency of the TM$_{010}$ mode for both cavities is given by

\[(f_{rc})_{010} = \frac{2.404c}{\pi R_c \sqrt{\mu_r \varepsilon_r}}\]

where $R_c$ is the radius of the cavities, $\mu_r$ and $\varepsilon_r$ are relative permeability and permittivity of the filling material, 2.404 represents the corresponding root of the Bessel function, and $c$ stands for the speed of light in free space.
Figure 1. Design evolution: the symmetry of the first resonant mode is exploited to obtain the EMSIW structure.

The simulated electric and magnetic field distributions in the HMSIW cavity corresponding to its TM$_{010}$ mode are shown in Fig. 2. This cavity radiates through the dielectric aperture, therefore in the HMSIW a suitable ground plane and dielectric substrate extension $G_e$ must be kept in correspondence to the magnetic wall cut, as indicated in Fig. 1(b). In addition, these extensions significantly allow improving the on-body antenna performance, increasing its robustness and isolation with respect to the body proximity.
Applying the same design concept to the HMSIW cavity shown in Fig. 1(b), whose magnetic field lines are symmetric along the OC plane, this cavity can be halved in turn, cutting off the half of the cavity at the left of the plane OC, reducing it to the Quarter-Mode SIW (QMSIW) resonator shown in Fig. 1(c).

Finally, in the QMSIW cavity the magnetic field lines are symmetric along the OD plane, allowing to halve the QMSIW cavity by cutting off the half of the cavity at the bottom of the plane OD, obtaining the Eighth-Mode SIW (QMSIW) resonator of Fig. 1(d).

The resulting EMSIW operates as a broadside antenna, radiating away from the wearer (along the z-axis) through the open side walls.

The final layout of the antenna is shown in Fig. 3. The radius of the vias are equal to $R_H = 4$ mm, their spacing is set to $S_H = 21.5$ mm, the extensions $G_e$ have been set to 10 mm, and the lower wedge of the antenna has been cut off ($L_G = 1.5$ mm).

Subsequently, an optimization procedure has been performed using CST Microwave Studio to match the antenna (radiating in free space) to the 50 $\Omega$ coaxial connector within the complete European (863-870 MHz) UHF band. The main points of the design procedure, leading to the configuration of Fig. 3, are the selection of the coaxial feeding
point \((L_X \text{ and } L_Y)\) and the addition of a slot of length \(L_S\), cut out in the top patch. This slot lengthens the current path, further reducing the antenna size. Increasing \(L_S\) reduces the operating frequency, whereas the slot offset \(X_S\) can be used to fine tune the frequency. The slot width \(W_S\) is set to 2.8 mm and the optimized geometrical values are \(L_O = 94.2\) mm, \(L_V = 103.8\) mm, \(L_P = 77\) mm, \(L_S = 29.5\) mm, \(X_S = 24.5\) mm, \(L_X = 9.9\) mm, and \(L_Y = 40.4\) mm. In Fig. 4, the picture of the fabricated antenna prototype is shown.

Figure 3. Layout of the designed SIW antenna. \(R_H = 4\) mm, \(S_H = 21.5\) mm, \(L_O = 94.2\) mm, \(L_V = 103.8\) mm, \(L_P = 77\) mm, \(G_e = 10\) mm, \(L_G = 15\) mm, \(X_S = 24.5\) mm, \(L_S = 29.5\) mm, \(W_S = 2.8\) mm, \(L_X = 9.9\) mm, \(L_Y = 40.4\) mm.

Figure 4. Prototype of the designed SIW antenna. (a) Front view; (b) Back view.
3. Results and Discussion

To investigate the influence of the body-antenna coupling on the device performance, a numerical phantom has been added to the simulation environment, as shown in Fig. 5. The phantom is modeled as a simple single layer mimicking the muscle tissue ($\varepsilon_r = 56.6$ and $\sigma = 1.33 \, \text{S/m at 867 MHz}$), with an overall size of $20 \times 25 \times 10 \, \text{cm}^3$. The corresponding experimental setup in an anechoic environment is shown in Fig. 6. The phantom consists of a $20 \times 25 \times 10 \, \text{cm}^3$ polystyrene box filled up with a solution of deionized water (53%), saccharose (45.6%) and sodium chloride (1.4%) [20], which realizes the above-mentioned muscle-like dielectric parameters.

![Figure 5. a) 3d view and b) side view of the designed antenna on the single-layer phantom model used to perform the numerical simulations.](image)

The performance of the antenna deployed in free space is compared to that of the antenna deployed close to the phantom. The minimum distance of the antenna from the phantom is set to $d = 5 \, \text{mm}$, since the presence of the coaxial connector prevents the antenna to be attached to the phantom. Fig. 7 shows the electric and magnetic energy density distribution in the cavity when the antenna is radiating in free space and at a distance $d = 5 \, \text{mm}$ from the phantom. These images demonstrate that the coupling with
the body phantom only has a marginal influence on the energy density distribution of the fields.

Figure 6. Experimental setup for the measurement of the return loss of the wearable SIW antenna.
Figure 7. Energy density distribution in the antenna substrate for the antenna in free space (a) and at a distance $d = 5$ mm (b) from the liquid phantom.

The simulated and measured frequency response of the designed SIW antenna, both in free space and when it is close to the body phantom ($d = 5$ mm), is reported in Fig. 8. The measured 10 dB return loss bandwidth is equal to 19 MHz both in free space (from 858 to 877 MHz) and for $d = 5$ mm (from 856 to 875 MHz), thus well within the LoRa European bandwidth (from 863 to 870 MHz, depicted in Fig. 8 by a grey band). The measured results are in good agreement with the simulated ones, with an overestimation of the operating bandwidth.
Figure 8. Simulated and measured frequency response of the designed SIW antenna: (a) free space; (b) antenna at a distance $d = 5$ mm from the liquid phantom.

In Fig. 9, the input matching of the antenna is investigated for different distances $d$ between the antenna and the body phantom. The agreement between simulation and measurement is still very good, showing an excellent robustness of the proposed configuration. In fact, the return loss maintains larger than 10 dB in a relatively large frequency band, independently of $d$, thus ensuring a stable antenna performance in the presence of unavoidable random movements of the wearer, maintaining complete coverage of the required band.
Figure 9. Simulated (a) and measured (b) frequency response of the designed SIW antenna for different values of the distance \(d\) between the antenna and the liquid phantom.

Finally, Fig. 10 displays the simulated far field in the E-Plane and H-Plane when the antenna radiates in free space or in proximity of the human body (\(d = 5 \text{ mm}\)). It can be noticed that the back radiation reduces due to the absorption of the body phantom.

The simulated antenna gain is -2.7 dB in free space (with radiation efficiency 30\%) and -1.45 dB for \(d = 5 \text{ mm}\) (with radiation efficiency 26\%). Then, a reduction of the antenna gain is observed when increasing the distance of the antenna from the human body, mainly due to the reduction of the directivity.

More stable radiation characteristics could be achieved by increasing the ground plane extension \(G_e\). However, this is not an optimal trade-off, since it would result in a less comfortable antenna. On the other hand, a further ground plane enlargement seems not necessary, since the performance of the proposed antenna in terms of return loss and efficiency is very good for the LoRa application with a reduced ground plane extension by only 10 mm, as set in our design (see Fig. 3).
Figure 10. Simulated far field plots for the designed SIW antenna at 867 MHz.

In order to estimate the radiation absorbed by the human tissue, the SAR values are computed using CST Microwave Studio for the layout shown in Fig. 5, where the human body has been modelled with a single layer phantom. When the SIW antenna is placed at 5 mm from the human tissue, the calculated maximum SAR value for 500 mW input power at 867 MHz is equal to 0.25 W/kg, averaged over 1 g of tissue. The simulated value of the SAR decreases to 0.198 W/kg, averaged over 1 g of tissue, when the distance...
between the SIW antenna and the phantom is increased to 30 mm, as indicated in the plots shown in Fig.11. Both these values are well below the maximal limit of 1.6 W/kg averaged over 1 g of tissue, and this result is not surprising, considering the simulated on-body radiation patterns shown in Fig.10, and the stable reflection coefficient of Fig.9, which suggest that most of the radiation is directed away from the body, thanks to the use of a ground plane and vias of the SIW structure.

![Figure 10](image.png)

Figure 10. Simulated SAR values for the SIW antenna placed a) at 5 mm from the phantom; b) at 30 mm from the phantom.

4. Conclusion
An eight-mode substrate integrated waveguide (EMSIW) wearable textile antenna has been designed in the UHF frequency band for Low-Power Wide-Area Network (LPWAN) Applications. The proposed antenna is very compact and comfortable for the wearer. It can be realized with a very low-cost procedure, since it requires minimal patterning and embroidery. A planar size reduction of about 50% and a volume reduction
of about 80% with respect the similar state-of-the-art SIW antennas found in the open literature is achieved. Antenna robustness with respect to the coupling with the human body has been successfully tested, making the proposed SIW antenna very promising for LoRa systems and applications.

References


Disclosure statement
No potential conflict of interest was reported by the author(s).