Flexible Antenna Design with Characteristic Modes

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***Abstract*—A dual-band flexible antenna on a 3-D printed support is proposed for wrist worn applications. The antenna is aimed to work at 860 MHz and 2.4 GHz. A spatial diversity technique is used to overcome the blocking of the radiation by the arm. Characteristic Mode Analysis is used as a first step of the design process, analyzing different structures.**

***Index Terms*—Flexible antennas, characteristic modes, diversity, on-body applications.**

I. Introduction

Wearable antennas have attracted a lot of interest during the last decade, as novel flexible biocompatible materials ideal for body-centric applications have emerged. Additive manufacturing techniques have made it possible to reduce the cost of fabrication of the antennas and wearable devices, thus becoming a very attractive technology for fabrication [1].

In this paper, a dual-band flexible antenna over a 3-D printed support is proposed for wrist worn applications. The antenna is aimed to work at 0.86 and 2.4 GHz. Characteristic Modes Analysis (CMA) is used as a first step for the design, as it provides very interesting physical insight into the potential radiation characteristics of the structure.

The paper starts with the CMA of a metallic ring modelling a bracelet and the analysis of some variants of this structure. Then the proposed antenna is presented, evaluating its performance in the presence of the human body. Simulated results are presented, showing a good performance in the bands of interest.

II. Characteristic Modes of a Circular Bracelet

A. Brief Review of Characteristic Modes

The Theory of Characteristic Modes (TCM), defined by Garbacz, Harrington and Mautz [3]-[5], is a powerful tool for the design of antennas following a systematic approach. Many applications have benefited from the use of characteristic modes in recent years, mostly based on the analysis of conducting bodies.

CMA is based on the solution of the following weighted eigenvalue equation [4]:

$$X(J_n) = \lambda_n R(J_n) \tag{1}$$

where λ_n are the eigenvalues, J_n are the eigencurrents, and R and X are, respectively, the real and imaginary parts of the impedance operator. Eigenvalues λ_n range from +∞ to -∞ and their sign determines if the mode contributes to store magnetic energy ($\lambda_n > 0$) or electric energy ($\lambda_n < 0$). The mode is at resonance when its associated eigenvalue is zero ($\lambda_n = 0$).

Associated to the eigenvalue, the characteristic angle (α_n) can be defined as:

$$\alpha_n = 180° - \tan^{-1}(\lambda_n) \tag{2}$$

The characteristic angle ranges between 90º and 270º, and it represents the phase angle between the characteristic current J_n and its associated characteristic field E_n.

B. Characteristic Modes Analysis

In this section, the CMA a metallic ring modelling a bracelet is firstly considered. Since the objective is to obtain a dual-band antenna, two modes will be taken into account for the excitation.

Fig. 1 shows the circular metallic ring to be analyzed (structure A). However, considering that the human arm will block part of the radiation of the antenna, it is necessary to consider spatial diversity and design two identical antennas located at the two opposite sides of the bracelet. Therefore, structure C in Fig. 1 would represent the proposed antenna, which is half of the metallic ring. Structure B in Fig. 1, which presents two slits in the Y-axis, can be considered as an intermediate step between structures A and C, being interesting for the CMA.

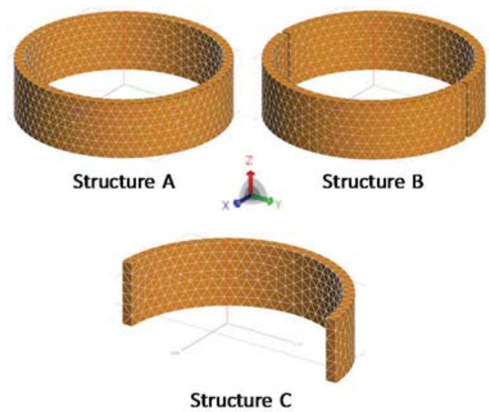


Fig. 1. Geometries considered for the CMA in wrist worn applications.

Fig. 2 shows a comparative of the characteristic angle (α_n) computed with FEKO for the structures shown in Fig. 1. Due to its radiating characteristics and ease of excitation with a voltage gap at the X-axis, two modes (mode J_1 and mode J_7) are considered. The current distribution and the radiation pattern associated to these modes is shown in Fig. 3 and Fig. 4, respectively. As observed, mode J_1 is the fundamental mode, while mode J_7 is a higher order mode. Both modes will be excited in structure C if a voltage gap is inserted in the X-axis, leading to a dual-band antenna.

In the characteristic angle shown in Fig. 2, it can be observed that for mode J_1, the slits in structure B are not affecting the resonance of the mode, but for structure C a lower resonant frequency is obtained. In structure B, a narrowband mode resonating at lower frequencies (mode J_2) also appears, which corresponds to a mode whose current flows in opposite direction in the two parts of the ring (this is called a transmission line mode [6]). Furthermore, with mode J_7, the mode is shifted up to higher frequencies for structure C. In this case, mode J_7 in intermediate structure B is also affected by the presence of the slits.

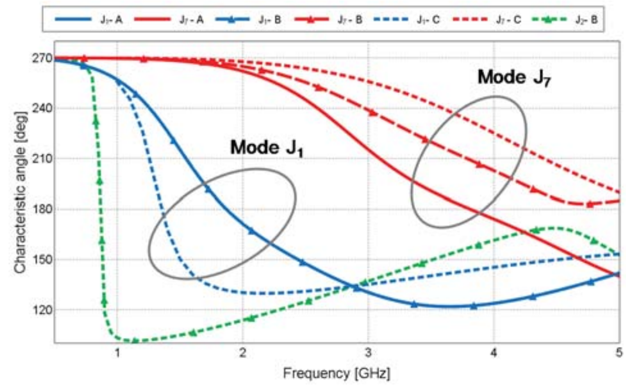


Fig. 2. Characteristic angle associated to modes J_1 and J_7 of the geometries considered in Fig. 1. Mode J_2 is also shown for the structure B.

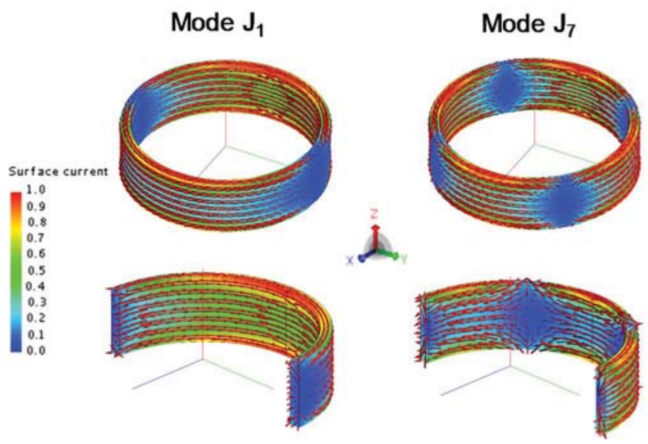


Fig. 3. Current distribution associated to modes J_1 and J_7 for structures A and C.

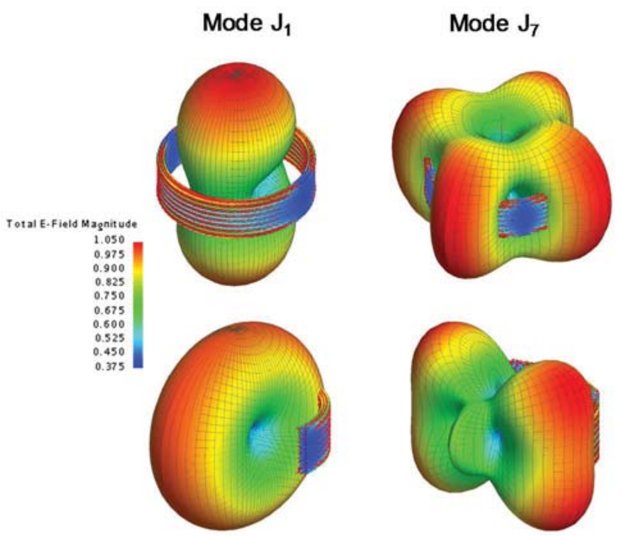


Fig. 4. Modal radiation pattern overlapped with current distribution for the modes J_1 and J_7 for structures A and C.

Therefore, structure C will be considered initially for the design of the bracelet antenna, and modes J_1 and J_7 will be excited for dual-band operation by means of a voltage gap located at the X-axis. As the target operation frequencies are 0.86 and 2.4 GHz, reactive loading with slots will be considered in order to shift down the resonant frequency of both modes. As a result, a meander dipole antenna has been created.

III. Flexible Dual-Band Antenna for Wrist Worn Applications

In the following sections, the geometry of the proposed dual-band antenna aimed to operate at 0.86 and 2.4 GHz and the model of the human arm will be described.

A. Geometry of the Antenna

In order to create a dual-band antenna to operate at 0.86 and 2.4 GHz, a meander dipole has been designed and optimized for bending over a circular surface modeling the human wrist.

In order to confer flexibility to the antenna, a very thin substrate of 51 μm thickness and relative electric permittivity of ε_r=2.9 is used. The geometry of the antenna over a planar surface is shown in Fig. 5, along with its dimensions in mm. As observed, two identical meander antennas have been used in the bracelet for diversity purposes. As the radiated field might be blocked by the presence of the human arm, two antennas located at the two sides of the bracelet should be considered for spatial diversity. Fig. 6(a) shows the arrangement of the antennas in a circular bracelet of 30 mm radius.

Moreover, a bracelet of thickness 1.5 mm has been designed with ABS (Acrylonitrile Butadiene Styrene) with ε_r=2.8, serving a rigid support for the flexible antenna. Fig. 6(b) shows the complete design of the bracelet, with the ABS support and the dual-band flexible antennas.

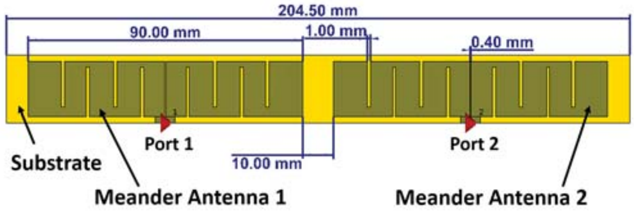
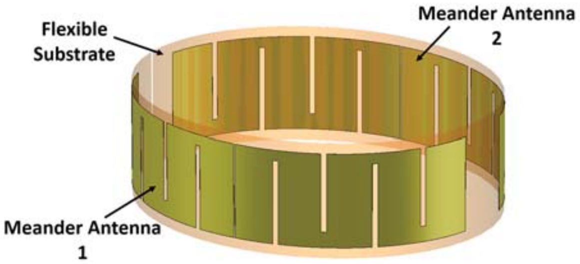
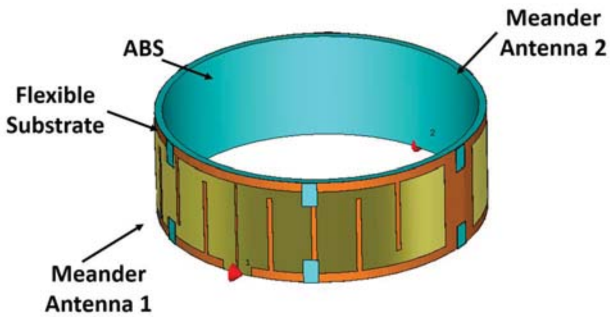


Fig. 5. Geometry of the meander antennas on the flexible substrate in a planar arrangement.



(a)



(b)

Fig. 6. (a) Detail of the geometry of the folded meander antennas; (b) Meander antennas including ABS support for holding the flexible antennas.

B. *Effect of the Human Body*

For the design and optimization of the antennas, the effect of the human body has been taken into account. A 3-layer model of the arm has been considered for the design, as shown in Fig. 7. In this model, the following electromagnetic properties of the human arm tissues at 2.4 GHz have been considered for the simulation [2]: Skin (1mm thickness, ε_r=38 and conductivity=1.4), fat (2mm thickness, ε_r=5.2 and conductivity=0.1) and muscle (29 mm thickness, ε_r=52.7 and conductivity=1.7).

A length of 48 mm has been considered for the arm in the simulation and an air gap between the ABS support and the skin has also been contemplated in the study.

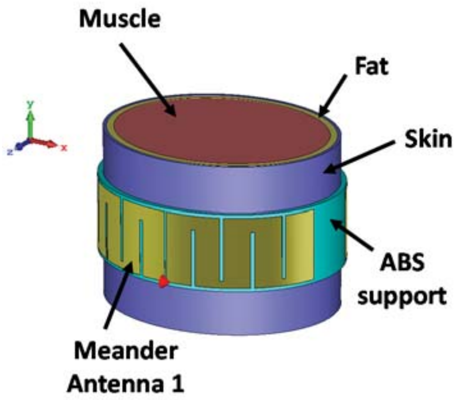


Fig. 7. Three-layer human wrist model with the wrist wearing the antenna on bracelet.

IV. Results

Fig. 8 shows the return loss of the proposed bracelet antenna with ABS support with an air gap of 3 mm between the bracelet and the arm skin. As observed, good matching is obtained for the two bands of interest (0.86 and 2.4 GHz).

Nevertheless, it is observed that the return loss is very sensitive to the gap between the antenna and the arm, as shown in Fig. 9. As it can be seen, operating band shifts down in frequency as the air gap between the bracelet and the arm decreases.

Fig. 10 shows the simulated radiation patterns in XZ-plane for the two bands of interest and the two ports, for an air gap of 3 mm. As observed, good coverage is obtained with the two antennas at the two bands.

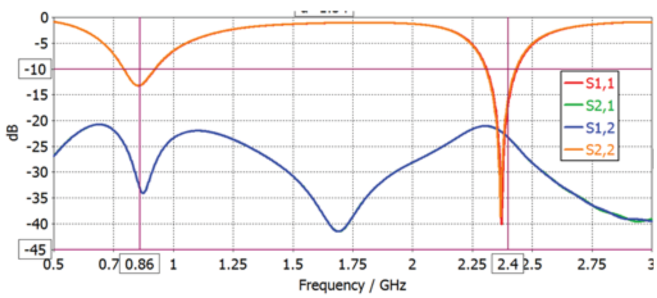


Fig. 8. Simulated S-parameters for the proposed bracelet antenna considering the human wrist with an air gap between the skin and ABS support of 3 mm.

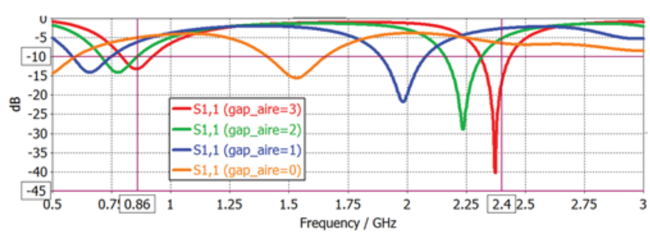


Fig. 9. Simulated reflection coefficient for the proposed bracelet antenna considering the human wrist with different values for the air gap (*gap_aire*) between the skin and ABS support.

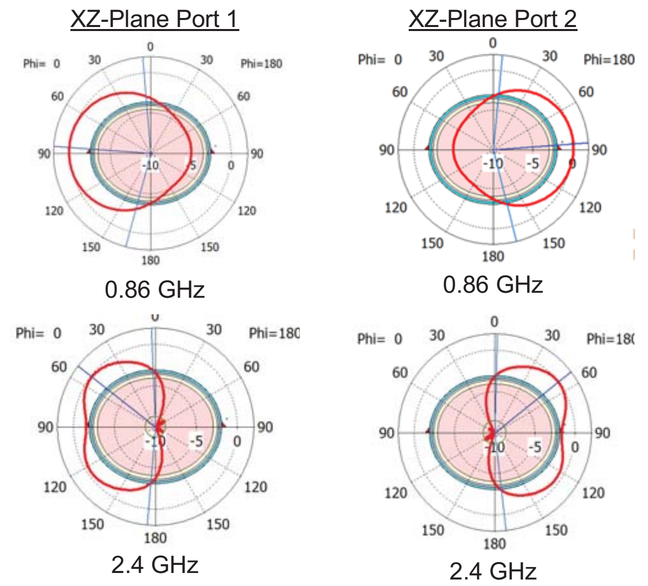


Fig. 10. Simulated radiation patterns in the XZ-plane for the proposed bracelet antenna considering the human wrist with an air gap between the skin and ABS support of 3 mm.

V. Conclusions

A dual-band flexible antenna on a 3D printed support aimed to work at 0.86 and 2.4 GHz has been proposed for wrist worn applications. Spatial diversity technique is used to overcome the blocking of the antenna radiation by the arm. Simulated results have been presented, showing good performance for a certain separation of the antenna from the arm. Measurement results in the presence of the human body as well as the impact of different materials on the performance of the antenna will be presented at the conference.

Acknowledgment

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