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Wearable Fabry-Pérot Antenna

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***Abstract*—A wearable version of Fabry-Pérot antenna is presented. This is a simple way of designing a medium to high gain antenna with low back radiation. The study of the effect of antenna bending in the performances is presented. Besides, the replacement of a superstrate layer by a metallic FSS is proposed. In this way, there is no need of finding a specific material and thickness for a targeted gain and frequency. Experimental validation confirms the viability of this design.**

***Index Terms*—Textile antenna, Fabry-Pérot antenna, Leaky-wave antennas, Gain enhancement, Wearable.**

I. Introduction

Wearable and textile antennas are nowadays a reality as many applications have emerged that integrate them in our clothes and objects. Most of the examples we can find in the literature are based on the use of patch antennas or dipoles or more sophisticated versions of them. Many examples are also dealing with designs for tags to be integrated as part of RFID systems.

The textile technology is mature enough and studies including effects of washing [1], advanced manufacturing [2] including the very trendy embroidering process [3] and even works measuring specifically SAR for these technology [4] can be found in the recent literature.

In general terms, the applications for wearable technology deal with users moving and for that reason low directivity antennas are typically required. Nevertheless, there is a concern for improving the forward direction as claimed in [5] and [6] as the energy radiated towards the human body, despite being undesired, is especially a waste of power. This means that for many applications it will be of interest to have antennas with a medium directivity. An example of that can be found in [7]. Also a new challenge for this technology is that even high frequencies are being considered recently [8], [9].

We propose in this paper to evaluate the performance of a simple Fabry-Pérot type antenna made for the first time in textile/wearable technology to be considered as a good candidate for medium-gain antenna i.e., an alternative to an array of patches. Two different designs will be proposed and both will be analyzed in terms of bandwidth and gain as a function of the possible bending in the two main planes. Section II presents the initial design and the effect of bending is included in Section III. Section IV proposes the alternative design based on equivalent FSS and again the analysis of the bending effects. Finally, Section V contains the summary of the experimental validation and the main conclusions are summarized in Section VI.

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II. Initial Design

A classical Fabry-Pérot antenna, needs a feed and a superstrate at a distance $\lambda/2$. When thinking about implementing such an antenna in wearable technology, the best antenna to use as a feed is a textile patch antenna. The permittivity of the superstrate determines mainly the directivity and the bandwidth of the antenna. Looking for a commercial textile material (or at least a washable one) with a moderate to high permittivity, rubber was selected as first option to be used as superlayer. Obviously, some other materials like silicone may also be suitable for this application. With these materials in mind, the initial design was as it is proposed in Figure 1.

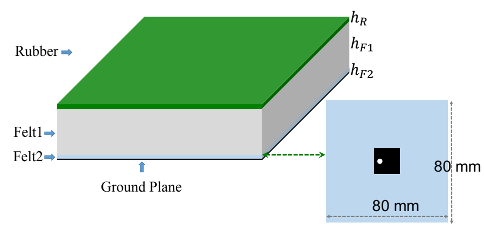


Fig. 1. Proposed antenna design. The thickness of the rubber is h_R =3 mm. The material inside of the cavity is felt with a permittivity close to 1 and a height of h_{F1} =15 mm and the patch antenna is located on top of a felt layer with a approximate thickness of h_{F2} =1.5 mm.

A first step was to electromagnetically characterize the commercial rubber. To this aim we have used a network analyzer and the material characterization kit. The commercial material used in this work has a thickness of h_R =3 mm that will determine the specific frequency of operation within the X band. For that frequency range the material shows a permittivity of ϵ_r=5.85 and loss tangent of tanδ=0.016. With that permittivity and thickness, the frequency where that rubber layer is $\lambda_{\epsilon_r}/4$ is close to 10 GHz and consequently the feeding patch antenna was designed for that frequency. The patch is designed using electrotextile material for the patch itself (with 0.05$\Omega/^2$ surface resistivity) and for the ground plane and felt as substrate (ϵ_r= 1.22, tanδ= 0.016 with 1.5mm heigth).

In a Fabry-Pérot design, the total antenna size depends on the permittivity of the upper dielectric layer and determines the directivity and the bandwidth. Considering that in this case the permittivity of the superlayer is not very high we can expect a medium directivity and at the same time we do not need to use a very big antenna as the leakage rate will high and no strong reflections will occur at the edges. Parametric studies

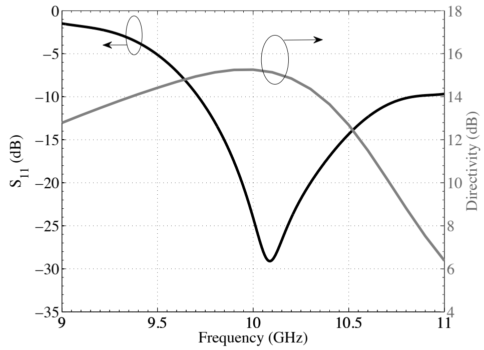


Fig. 2. S_{11} and Directivity of the proposed antenna design.

changing the total antenna size have been carried out and the final selected size was 80 mm side for the total antenna. We show in the following figures the simulation results for this antenna in terms of matching and achieved gain (Fig. 2) and also the antenna radiation pattern (Fig. 3). The bandwidth is around 13% and the maximum directivity of 15dB.

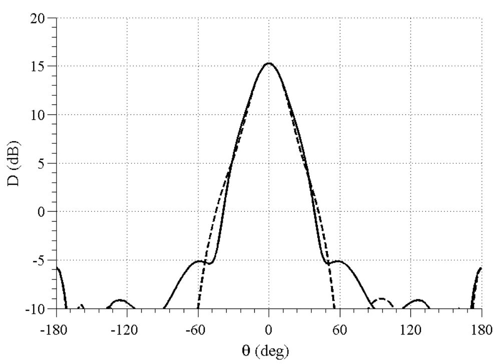


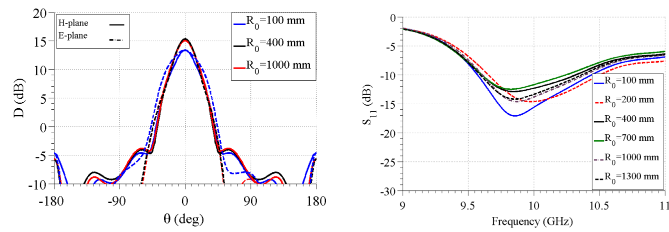
Fig. 3. Radiation pattern in the two main planes for the proposed antenna design.

Another important consideration is the fact that this design requires a $\lambda/2$ space in between the feeding antenna and the dielectric superlayer, but in this case due to the intended application this space must be filled with some material to allow the antenna to be integrated in a garment. The same felt employed for the feeding patch has been used to this aim as it has a very low permittivity (close to 1) that will not excite strong surface waves.

III. Effect of bending

When dealing with textile antennas, it is also necessary to study how they behave when they are conformed in garments. As a preliminary study, in this work we propose to model the effect of this conformity with a cylindrical shape as it was previously done in [10] , [11] or [5].

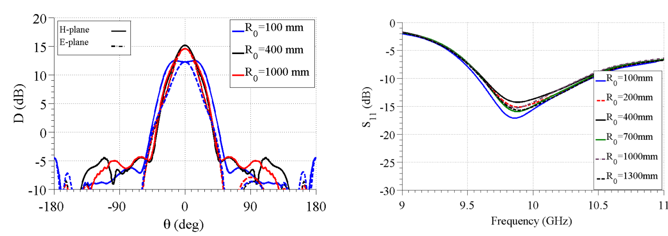
The initial study analyzes how this type of possible bending for each of the two main planes affects the main antenna characteristics. Fig. 4 contains the antenna matching and radiation patterns in the two main planes for different curvature radii when the antenna is bent in the E-plane (for readability of the graphs we have included less simulation results in the radiation pattern graph). Contrarily to what it is expected due to the resonant nature of this antenna, the antenna is quite robust to this type of change. Only extreme variations (not corresponding with the natural curvature of a shoulder or a human back) can really cause a serious degradation on the antenna performance. Even more, the matching is barely affected. Only the radiation pattern losses 2dB for a radius of 100mm.



(a) Radiation pattern at 10GHz. (b) S_{11}.

Fig. 4. Effect of bending the antenna with rubber superlayer in E-plane

Similar simulation results but bending the antenna in H-plane are presented in Fig. 5. The conclusions are identical to the ones for E-plane, as far as the curvature is not extreme, the antenna has a quite good performance. When the radius is too small there is a meaningful loss of directivity but the antenna matching is still good. No big differences between the bending in the different planes for this case are encountered, so no special sensitivity is observed in one plane compared to the other.



(a) Radiation pattern at 10GHz. (b) S_{11}.

Fig. 5. Effect of bending the antenna with rubber superlayer in H-plane

IV. Antenna with FSS superlayer

The proposed design is very limited in terms of reproducibility at any frequency or even being accomplished with different requirements in terms of directivity (less or more) by the availability of textile dielectric superlayers with specific permittivity or thicknesses. Having in mind that there are not many textile materials with dense permittivities and also that not an arbitrary thickness can be obtained in general (and a thickness of $\lambda/(4\sqrt(\epsilon_r))$ is the basis of operation), the proposed design seems to be quite limited in nature.

However, in [12] equivalences between Fabry-Pérot antennas made with dielectric superlayers and canonical equivalent metallic FSS replacing the superlayer have been demonstrated. Even more, if the equivalent FSS is designed as the inductive version, it has been proven that a slightly higher directivity and more symmetric patterns can be achieved with respect to the equivalent dielectric version.

This means that for any desired or required permittivity for the superlayer (i.e., for any required directivity), we can always get the same performances by synthesizing an equivalent metallic FSS. This FSS can obviously be manufactured in textile technology by using metallic fabric or embroidering to implement the metal strips.

Following, a summary where the equivalence process is detailed is presented, and a comparison of the performance of this design with the previous dielectric one is shown.

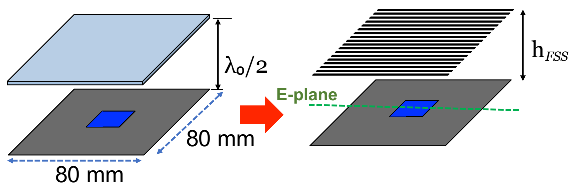


Fig. 6. Equivalence between dielectric superlayer and inductive FSS.

The equations to calculate the equivalent inductive FSS (height h_{FSS} and inductive impedance χ_i) according to Fig. 6 are ([12])

$$\chi_i = \eta_0 \frac{-1 \pm \sqrt{1 + 4\pi^2(\epsilon_r - 1)}}{2\pi(\epsilon_r - 1)} \quad (1)$$

$$h_{FSS} = h_0 \frac{\epsilon_r \chi_i^2}{\eta_0^2 + \chi_i^2} \quad (2)$$

With these equations for our particular case considering as superlayer the rubber with ϵ_r=5.85 we obtain a value of h_{FSS}=12.66mm and jχ=j159.26Ω. A canonical FSS with the latter impedance can be easily implemented following the equations in [13]. We have fixed the periodicity of the strips to p=$\lambda/6$=5mm and a strip width of w=0.2523mm is required.

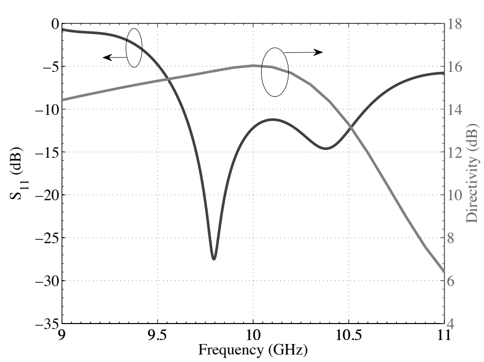
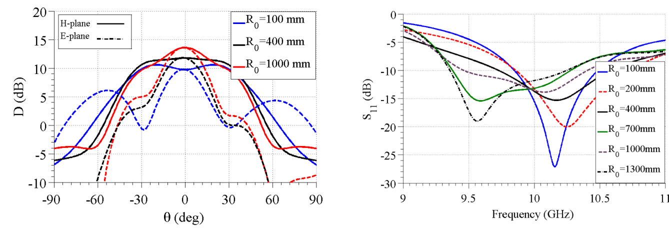


Fig. 7. S_{11} and Directivity of the flat antenna with FSS superlayer.

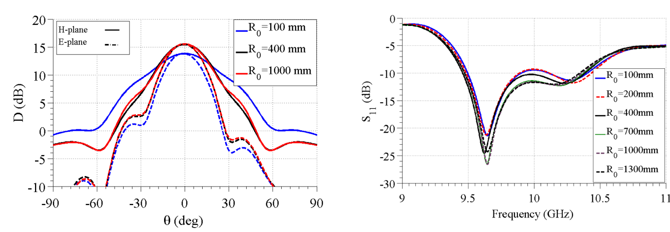
Simulation results, with same total antenna size as for the dielectric case (80 mm) for the matching and directivity as a function of frequency are represented in Figure 7. For the flat structure an increase in the antenna directivity is observed being now 16dB at 10GHz and the obtained bandwidth for the matching is 11.5%.



(a) Radiation pattern at 10GHz. (b) S_{11}.

Fig. 8. Effect of bending the antenna with FSS superlayer in E plane

A similar study about the effect of the bending in the two main planes is presented in Figs. 8 and 9. For this structure we can observe different sensitivities with respect to the plane where the bending is applied. When the antenna bends in E-plane the variations in the matching and radiation pattern are more noticeable than when the same bending is applied in H-plane. Actually only large radius of the cylinder in E-plane give as result a good antenna performance and even in this case there is some loss of directivity. The FSS is not isotropic and has a clear different behaviour in the two main planes and that explains these results. The electric field radiated by the patch is aligned with the strips of the FSS and any small bending in that plane affects the antenna performance. As a consequence, for this version of the antenna, the bending in E plane should be avoided.



(a) Radiation pattern at 10GHz. (b) S_{11}.

Fig. 9. Effect of bending the antenna with FSS superlayer in H-plane

V. Experimental Results

Two prototypes have been manufactured and measured, one with a rubber superlayer and the other with the equivalent FSS. A picture of the feeding patch antenna that is common to the two prototypes is shown in the inset of Fig. 11. In the same figure, the antenna with the superlayer of rubber (the black part) and the intermediate felt layers (in pink) is shown.

For the experimental cases, we have measured the two antennas bent on their H-plane with a radius of 400 mm. To provide this bending, a structure made of PVC was manufactured as it can be seen in Fig. 10 with the FSS prototype. For this verification, the FSS was made in kapton (ϵ_r=3.6, tanδ=0.02, thickness 0.0.25 mm) instead of using a textile material. The flexible kapton allows bending as it can be seen in the figure. A textile version of this FSS can be made via embroidering or other manufacturing technique.

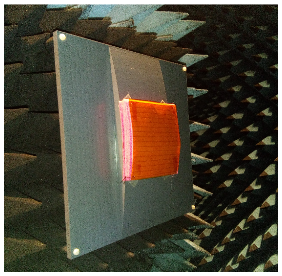


Fig. 10. Bent FSS prototype with the designed physical support in PVC.

The measured S_{11} (Figure 11) and the gain as a function of frequency (Figure 12) are represented for the two experimentally verified cases, together with the comparison with the feeding patch antenna. In all cases the antenna is bent. The matching bandwidth of the antenna is similar to simulations in both cases. The gain of the dielectric structure is almost identical to the simulated cases, whilst for the FSS case the measured gain is smaller than expected, probably due to tolerances in the manufacturing of the antenna.

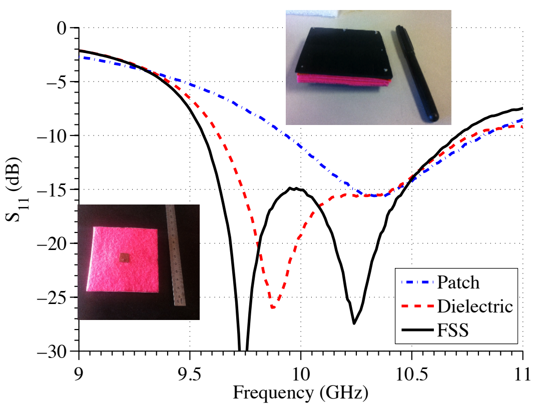


Fig. 11. Comparison of the experimental S_{11}.

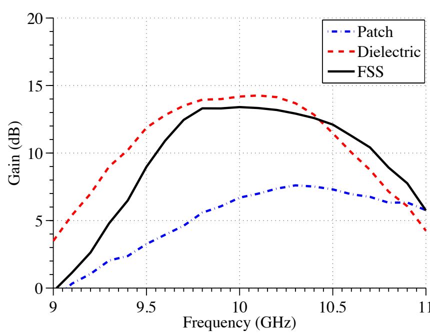
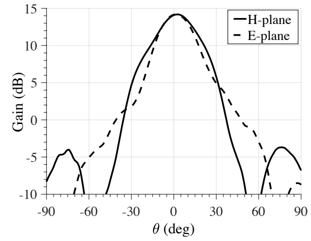


Fig. 12. Comparison of the experimental gain as a function of frequency.

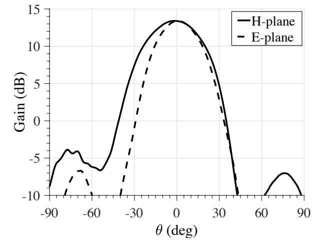
Finally the measured radiation patterns for the two antennas at 10GHz and in the two main planes are included in Fig. 13.

VI. Conclusions

A medium-directivity simple wearable antenna based on the use of Fabry-Pérot concept has been proposed. The antenna performance has been studied in terms of bending in both planes for realistic applications showing a good robustness in terms of both matching and directivity. However the classic design is limited by the scarcity of textile materials providing a good range of permittivity values and thicknesses.



(a) Dielectric prototype.



(b) FSS prototype.

Fig. 13. Measured radiation patterns at 10GHz.

A second version of the same antenna replacing the superstrate by an equivalent metallic inductive FSS has been presented. This allows more flexibility in terms of targeted directivity but the bending in E plane is more critical. Experimental results have confirmed the viability of these designs providing a new way of designing a textile antenna.

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