Microstrip Patch Antenna Design Using Artificial Material Loadings

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***Abstract*— Patch antennas filled using different material loadings, both homogeneous and dispersive, are reviewed in order to assess its *FBW* value. A compact formulation proposed by Yaghjian and Best [1] to compute the *FBW* of antennas is successfully applied.**

I. Introduction

Conventional microstrip patch antennas can be easily miniaturized by increasing the electric permittivity (ε_r) although, in this way, the fractional bandwidth (*FBW*) is dramatically decreased [2]. For this reason the use of metamaterials as artificial antenna substrates is studied as an alternative method to efficiently miniaturize patch antennas, accounting not only the electric permittivity (ε_r) but also magnetic permeability (μ_r). In addition, a compact *FBW* formulation proposed in [1] is applied to compute the maximum achievable bandwidth of patch antennas for both homogeneous and dispersive metamaterial substrates. This formulation is used both in simulated and measured data.

II. FBW Formulation

The maximum bandwidth of an antenna under test can be obtained through different procedures. Yaghjian and Best [1] introduced the *matched VSWR bandwidth*, that can be defined at each and every frequency (for a small enough fixed reflection coefficient value). That means that exists both in the resonant $((\partial X_0(\omega_0)/\partial\omega)|_{\omega_0}>0)$ and in the antiresonant $((\partial X_0(\omega_0)/\partial\omega)|_{\omega_0}<0)$ frequency ranges. The maximum *FBW* formulation is defined as:

$$FBW(\omega_0) \approx \frac{4\sqrt{\beta}R_0(\omega_0)}{\omega_0\,|Z_0^{'}(\omega_0)|} \qquad (1)$$

$$\text{with } \sqrt{\beta} = \sqrt{\frac{\alpha}{1-\alpha}} = \frac{S-1}{2\sqrt{S}} \le 1 \qquad (2)$$

where Z'_0 is the first derivative (with respect to the frequency) of the antenna input impedance after tuning, R_0 is the input resistance of the antenna after tuning, ω_0 the radian frequency at which the antenna is tuned and S the desired *VSWR* value. Note that, in this case, tuning the antenna means to make zero the reactance $X_0(\omega_0)$ =0, by means of using an external series inductance or capacitance.

With this formulation, it is possible to obtain a value of the antenna bandwidth at frequencies where the antenna is actually not properly working. In this way, from a given antenna design one can not only know whether that antenna is going to perform a good bandwidth at its matching frequency, but also if it is going to perform a better bandwidth at other frequencies.

Our aim is to apply this formulation to the design of microstrip patch antennas loaded with artificial materials.

III. Patch Antenna Design

It is well known that the Chu limit relates the maximum *FBW* and the electrical size of an antenna [3]. In addition, the size (L) of a patch antenna depends on the working frequency ($f_0 = c/\lambda_0$) and the electromagnetic material properties of the substrate [2]:

$$L \approx \frac{\lambda_0}{2\sqrt{\varepsilon_r\mu_r}} \qquad (3)$$

In such a case, miniaturized patch antennas will be achieved when using high-$\varepsilon_r\mu_r$ substrates.

A. Non-Dispersive Substrates

Patch antennas with homogeneous, non-dispersive and lossless substrates are simulated (using Ansoft's HFSS) varying their material parameters (ε_r, μ_r). These antennas are designed to operate around 2.45 GHz, thus obtaining different sizes depending on the different material loadings (ε_r, μ_r), which are listed in Table I.

TABLE I

Material parameter variation: Antenna Dimensions

Patch filling	h [mm]	$L = W$ [mm]	L/λ
Air	3	53.7	0.44
ε_r =0.5, μ_r =1	3	67.5	0.55
ε_r =3, μ_r =1	3	35.4	0.29
ε_r =1, μ_r =0.5	3	74.73	0.61
ε_r =1, μ_r =3	3	35.9	0.29

Note that the antennas are designed to be as better matched as possible at 2.45GHz. This is accomplished varying both the patch size and the feeding position. The obtained input impedances of each antenna are gathered in Table II.

TABLE II

INPUT IMPEDANCE FOR EACH ANTENNA AT THE WORKING FREQUENCY

Patch filling	$R_0(f_0)$ [Ω]	$X_0(f_0)$ [Ω]	$\|Z_0(f_0)\|$ [Ω]
Air	58.0	-5.5	58.2
$\varepsilon_r = 0.5$, $\mu_r = 1$	45.6	7.0	46.1
$\varepsilon_r = 3$, $\mu_r = 1$	58.7	-5.5	58.9
$\varepsilon_r = 1$, $\mu_r = 0.5$	43.1	5.4	43.4
$\varepsilon_r = 1$, $\mu_r = 3$	52.1	9.4	52.9

The simulated reflection coefficients (S_{11}) are plotted in Fig. 1. The *FBW* is computed using Eq. (1) and the results for each case are plotted in Fig. 2, while considering *S* equal to -10dB.

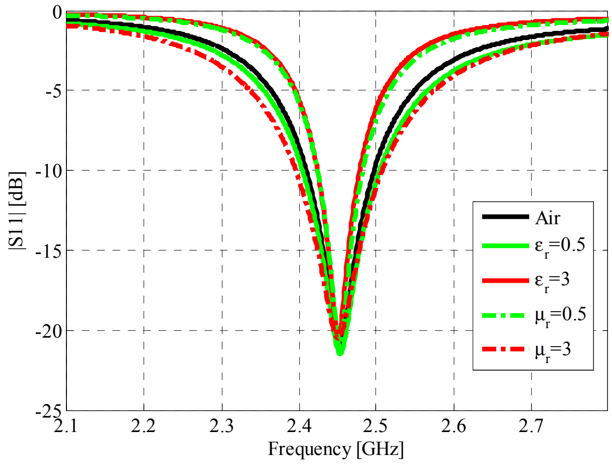

Fig. 1 Simulated reflection coefficient S_{11} for different patch antenna fillings: homogeneous case.

Note that the reflection coefficients in Fig. 1 are simulated considering a reference impedance Z_{ref} equal to 50Ω. The actual antenna input impedances at 2.45GHz have a value very close to 50Ω, because they are designed to be matched with respect to 50Ω at the frequency of operation, as it is presented in Table II.

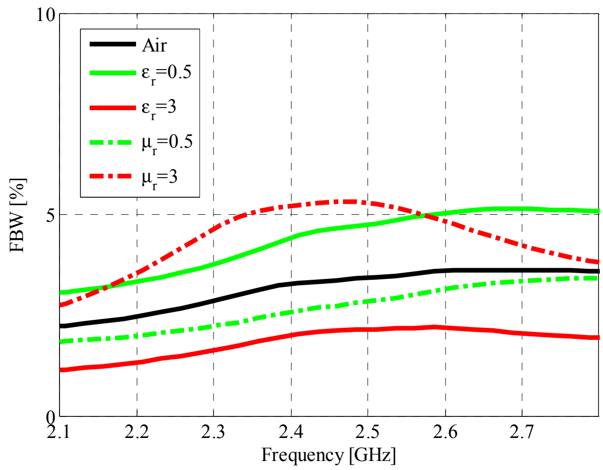

Fig. 2 Computed FBW_{-10dB} for different patch antenna fillings: homogeneous filling case.

It is observed that when increasing the relative permeability μ_r the *FBW* is also increased, as expected from [4]. This result outperforms the result obtained in [5] for the same substrate characteristics, where the impedance bandwidth for the air case was always higher than for the high-μ_r.

For values of 0< (ε_r, μ_r) <1, the *FBW* behaviour is reversed, achieving their highest values for the lower values of relative permittivity ε_r. The only inconvenience is that the antenna size is increased in such cases (for ENZ -Epsilon Near Zero- and MNZ -Mu Near Zero- materials).

Note that Fig. 2 shows the *FBW* over a wide frequency range: from 2.1GHz to 2.8GHz. In some cases, for instance the ε_r =0.5 case, better *FBW* values are obtained at frequencies different from 2.45GHz. The reason is that the *matched VSWR bandwidth* formulation obtains the bandwidth for the antennas tuned at each frequency f_k (i.e., with $X_0(f_k)$=0) and using as reference impedance the value of the input resistance $R_0(f_k)$ when the antenna is tuned. The studied antennas are almost resonant at f_0 (2.45GHz), and hence tuned at this frequency. However, any antenna is resonant at a limited number of frequencies and is not tuned at each and every frequency. Since the considered antennas are only tuned (and with $Z_{ref}=R_0(f_0)$=50Ω) at 2.45GHz in the frequency range considered, it is reasonable to observe that the *FBW* shown in Fig. 2 and obtained applying Eq. (1) is higher for frequencies different from the working one. In that case, the value of the reference impedance necessary to obtain the indicated *FBW* value may be quite different from 50Ω ($R_0(f_k)$≠50Ω).

Table III exposes a comparison between the *FBW* values obtained through two different methods: the ones extracted from a direct measurement on the S_{11} coefficient (from Fig. 1 with Z_{ref}=50Ω), and the ones extracted from the application of the *matched VSWR bandwidth* formulation (from Fig.2).

TABLE III

FBW VALUES COMPARISON

Patch filling	FBW [%] Direct measurement	FBW [%] Eq.(1) formulation
Air	3.5	3.3
$\varepsilon_r = 0.5$, $\mu_r = 1$	4.0	4.7
$\varepsilon_r = 3$, $\mu_r = 1$	2.2	2.1
$\varepsilon_r = 1$, $\mu_r = 0.5$	2.3	2.7
$\varepsilon_r = 1$, $\mu_r = 3$	4.5	5.3

The bigger discrepancies are found for the ε_r =0.5 (μ_r =1) and the μ_r =3 (ε_r =1). These are precisely the cases where the antennas are worst tuned at f_0 (Table II), and therefore the big discrepancies are explained.

B. Dispersive Substrate

It has been proved how the effect of using an homogeneous material with a permeability value higher than one as a loading of a microstrip antenna enhances its *FBW* while, in addition, its size is reduced.

A metasubstrate composed of spiral resonators (*SR*s) [6] printed on RO4003C dielectric layers is considered as dispersive lossy patch antenna filling (Fig. 3) to obtain an antenna matched at the considered 2.45GHz working frequency. Such artificial material substrate is commonly referred as metasubstrate.

In this design, the unit cell is slightly different than the one used in the work of P.J. Ferrer et al. [6]. Its dimensions have been adjusted in order to obtain the material resonance at a higher frequency to assure a μ_r >1 value at 2.45GHz. The dimensions of the unit cell used are gathered in Fig. 4.

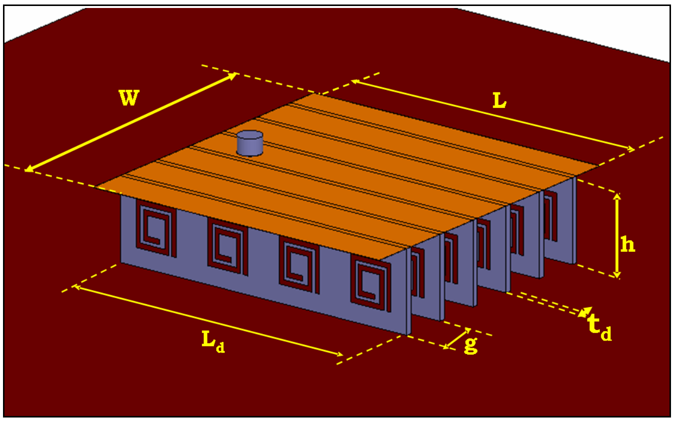

Fig. 3 Detail of the simulated antenna metasubstrate under the copper patch. The structure shown in the sketch is placed above a ground plane with W_{GP} = L_{GP} = 250 mm. The dielectric thickness is t_d = 0.8 mm, L_d = L = W = 40 mm and g = 6 mm.

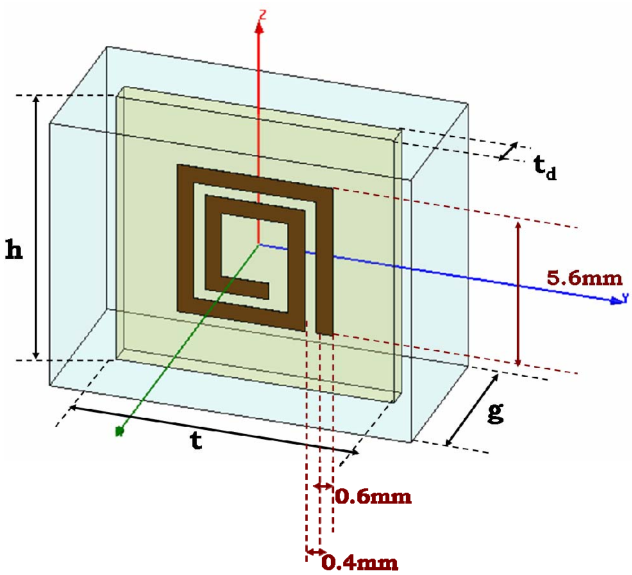

Fig. 4 Dimensions of the unit cell of the SR. Unit cell height h = 10mm, unit cell thickness t = 10mm, gaps between consecutive strips of spirals g = 6mm and dielectric thickness t_d = 0.8mm. The dimensions of the spiral resonator are the major side width (5.6mm), the line width (0.6mm) and the line gap (0.4mm). Port 1 is defined in the negative part of the y axis, while Port 2 is defined in the positive part of the y axis.

1) Dispersive Material Characterization

Periodic boundary conditions (*PBC*) are used to simulate the considered unit cell of *SR*s as an infinitely periodic material. The asymmetric arrangement of the spirals after applying image theory to the unit cell has no influence on the final macroscopic performance (*S*-parameters) as shown by P.J. Ferrer et al. [7]. The magnitude and phase of the simulated S-parameters are shown in Fig. 5 and Fig. 6, respectively.

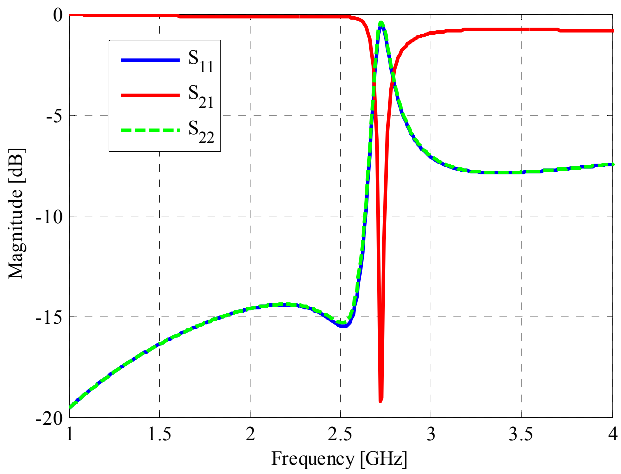

Fig. 5 Magnitude of the simulated *S*-parameters of the spiral resonators.

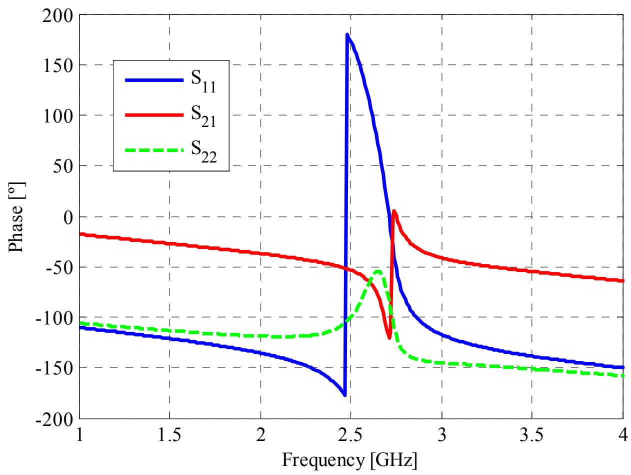

Fig. 6 Phase of the simulated *S*-parameters of the spiral resonators.

The phase of the reflection coefficient S_{11} crosses 0º at 2.71GHz, which is considered the resonant frequency, with a magnitude of -1.05dB. The phase of the S_{22} parameter is around -83.35º with a magnitude of -0.85dB at the resonant frequency. From the S_{11} point of view, the material acts as a *PMC* (perfect magnetic conductor) in a narrow frequency band around the resonant frequency. The resonance is also evidenced in the strong magnitude reduction of the S_{21} parameter.

From the formerly described *S*-parameters and using the method for effective medium parameters retrieval proposed by Li et al. [8], the effective permittivity and the effective permeability of the medium are shown in Figs. 7 and 8, respectively.

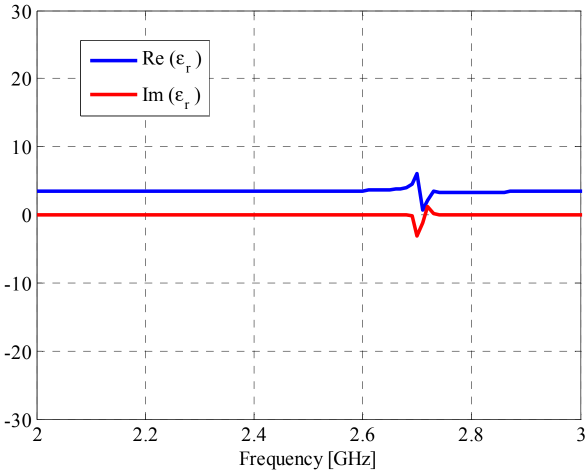

Fig. 7 Retrieved effective relative permittivity ε_r.

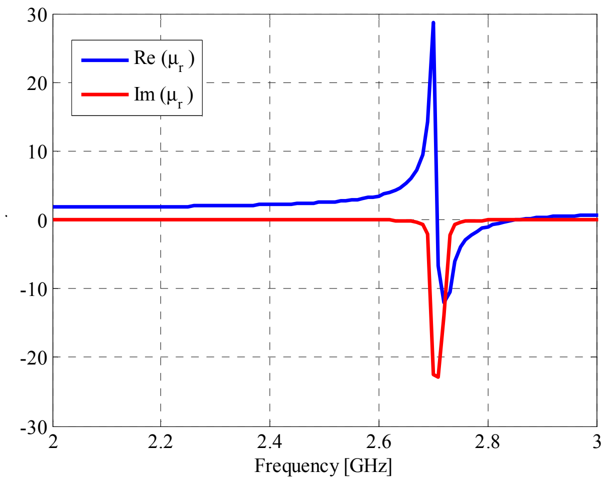

Fig. 8 Retrieved effective relative permeability μ_r.

The parameter extraction is useful to characterize the material in terms of resonance frequency. However, different parameter extraction methods are found in the literature and the magnitudes of the retrieved ε_r and μ_r differ between methods. In addition, what is being characterized is the material itself and not the material once placed inside the antenna acting as its substrate. Therefore, it has no sense to use the ε_r and μ_r values at 2.45GHz as a reference to predict the antenna performance once filled with the material.

It is known that to obtain higher *FBW* antenna values the appropriate part of the ε_r-μ_r curve in which the antenna must operate is neither too far from the resonance of the material (μ_r values are low) nor too close to the material resonance (in the material resonance the material bandwidth is very narrow). Therefore, the ideal is to have a smooth permeability value variation (having low losses) in a dispersive medium [9]. In our case, the material resonance (2.71GHz) is far enough from the working frequency (2.45GHz).

2) Dispersive Material Filled Antenna Behaviour

The antenna filled with the material characterized in the former subsection is simulated. Note that the simulation is done as a full-wave, that is, considering the whole structure (Fig. 3).

The simulated reflection coefficient and the computed Yaghjian *FBW* for the metasubstrate filled patch antenna as well as for a couple of non-dispersive substrate loadings are plotted in Fig. 7 and Fig. 8.

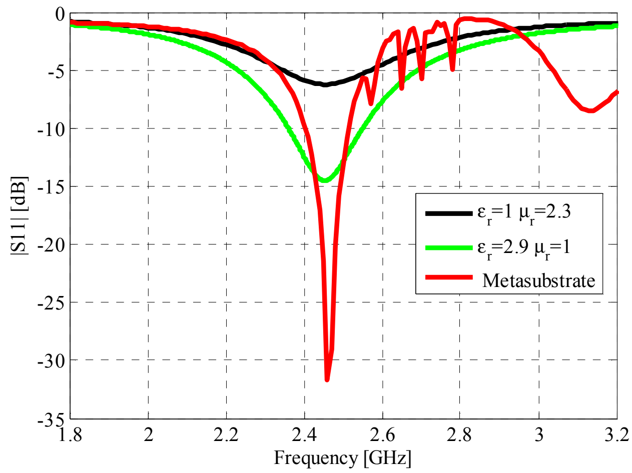

Fig. 7 Simulated reflection coefficient S_{11} for different patch antenna fillings: dispersive (metasubstrate) and non-dispersive (ε_r=1, μ_r=2.3 and ε_r=2.9, μ_r=1).

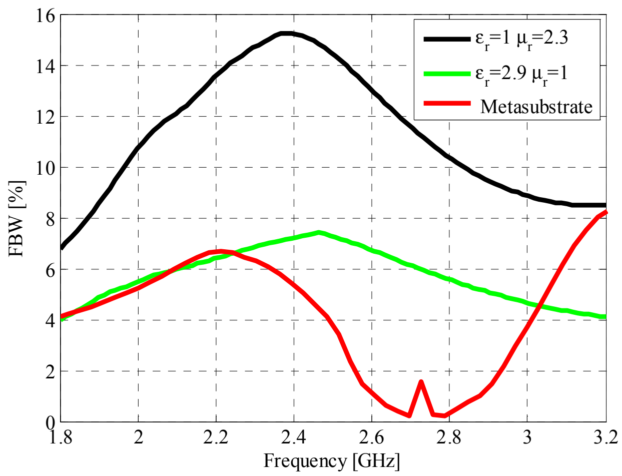

Fig. 8 Computed FBW_{-10dB} for different patch antenna fillings: dispersive (metasubstrate) and non-dispersive (ε_r=1, μ_r=2.3 and ε_r=2.9, μ_r=1).

This time the patch size is fixed to a smaller size than the one in the *Air* reference case in section *A*, *L*=*W*=40mm (L/λ=0.32), although the substrate thickness is higher *h*=10mm, as depicted in Fig. 3. With the help of the metasubstrate, the matching frequency is again adjusted at

2.45GHz. Hence, by using the metasubstrate, we physically miniaturize the antenna.

Note that the height of the substrate is higher in the dispersive case (h=10mm) than in the homogeneous one (h=3mm), and hence some improvement in the FBW due to that fact is expected to happen comparing with the non-dispersive simulated cases. For that reason it has been necessary to simulate non-dispersive substrates matched at 2.45GHz to fairly compare the results between the non-dispersive and the dispersive cases. Since the antenna size and feeding point are maintained to compare both cases under the same conditions, the matching level of the antenna filled with the non-dispersive substrates is not as good as it could be. In addition, the increase in height of the substrate makes more difficult to match the antenna with high values of ε_r and μ_r.

Compared with the homogeneous μ_r=2.3 case, the use of the metasubstrate dramatically reduces the FBW of the antenna (in approximately a 10%). However, materials with such values of permeability do not exist in nature. For that reason a second comparison with non-dispersive substrates is carried out. Compared with the homogeneous ε_r=2.9 case, which is a normal value for a dielectric material, the use of the metasubstrate reduces around a 2.8% the FBW value at 2.45GHz, because of its dispersive nature. Hence, no apparent advantage on using the metasubstrate is found, apart from a reduction in the weight of the antenna (which can be a design restriction in some applications) because we are using a material lighter than a solid dielectric slab. Nonetheless, the FBW reached with metasubstrates is not a narrow bandwidth for many practical applications.

Therefore, the reduction of the antenna bandwidth when filled with dispersive metasubstrates is assessed (Fig. 8) and the results predicted by authors as Ikonen et al. [5] are confirmed applying the Yaghjian and Best FBW formulation. The FBW value achieved in the metasubstrate case at 2.45GHz is not the best that the antenna can achieve in the studied frequency band. At approximately 2.2GHz the antenna FBW has an optimum value. However, since the antenna is matched at 2.45GHz it can be assured that at this frequency no better FBW than the obtained in Fig. 8 can be achieved. In addition, if one may decide to work at 2.2GHz where the FBW is higher, the reference impedance would have to be the resistance value R_0(2.2GHz), which is different from 50Ω.

The goodness of magnetodielectric substrates would be noticed if the objective were to miniaturize the antenna. In that application, the miniaturization factor obtained with magnetodielectrics would reach such a value that the required permittivity of a possible alternative dielectric material would be too high (around ε_r=10). Dielectric materials with very high values are expensive. The improvement in miniaturization factor using magnetodielectrics can be obtained by means of increasing the SR density for the same SR considered in this work. The SR density is increased including more SRs per strip, decreasing the height of the substrate and reducing the gap between consecutive strips of spirals. Another SR or magnetic resonator can be designed to continue increasing the miniaturization factor (reducing the working frequency).

IV. CONCLUSIONS

The use of non-dispersive high permeability substrates leads to efficient antenna miniaturization with a high FBW, even outperforming the case of the air as dielectric substrate. In the dispersive case, high permeability helps to miniaturize the antenna while the FBW is worsened with respect to the non-dispersive case, although the resulting FBW values make the antenna still practical.

Yaghjian and Best FBW method of computation is applied for the first time to patch antennas. In particular, the method is successfully applied to microstrip patch antennas filled with lossy dispersive metasubstrates corroborating results obtained by other authors [5]. This method implies the use of a different reference impedance Z_{ref}=R_0 for each frequency.

Prototypes with artificial metasubstrates have been fabricated to assess the simulated results, leading to a proper patch antenna miniaturization while maintaining its FBW. The results will be shown at the conference.

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