Optimization of Patch Antennas on Ferrite Substrate Using the Finite Element Methods

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1 Introduction

The nonreciprocal properties of ferrites have been used to control printed circuits and antennas. The material properties of ferrites are mainly controlled by the direction and strength of an externally applied magnetic field, thus enabling control of various antenna radiation and scattering characteristics. These unique properties of ferrite materials provide many desirable features such as tunability, polarization diversity, beam steering, and radar cross section (RCS) control. On the other hand, because of the additional variables such as bias field, bias direction and saturation magnetization, use of optimization method is suitable for ferrite antennas to obtain desired performance.

In this paper, we will study the effect of biased ferrite substrate on resonant frequency tuning [1] and beam steering [2] of patch antennas. The tools used will be the gradient-based optimization methods in conjunction with finite element - boundary integral (FE-BI) methods. The use of design optimization methods will greatly facilitate the selection of 'best' antennas. Compared with traditional antenna designs, optimization processes not only decrease simulation time, but also save on huge hardware manufacturing costs with the removal of expensive trial and error processes.

2 Resonant Frequency Tuning

One can use the optimizer to predict the resonant frequency of the ferrite patch instead of using a frequency sweep. The optimizer uses the Sequential Quadratic Programming (SQP) method [3], one of the best methods among gradient-based

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optimization techniques. The problem statement can be formulated as follows:

$$\begin{array}{ll} \text{Find } f_* & \text{which minimizes } |\text{Imag}(Z_{in}(f))| \\ \text{subject to} & f_L \leqslant f \leqslant f_U \end{array} \quad (1)$$

where Z_{in} is the frequency-dependent input impedance and f_L and f_U refer to the lower and upper bounds for the frequency. Here we use the definition that the antenna reaches resonance when the imaginary part of the input impedance is zero. In practice, the following objective function can also be used:

$$\text{Find } f_* \text{ which maximizes Real}(Z_{in}(f)) \quad (2)$$

The optimization process requires several iterations where the input impedance computations are needed. These analyses are carried out using the Finite Element - Boundary Integral method (FE-BI). Because of the tensor properties, ferrites introduce a great deal of complexity into the FEM formulation when solving radiation problems. A more robust solver employing the General Minimal Residual (GMRES) method produces convergent results where the Bi-Conjugate Gradient (BiCG) method fails [4].

As an example, we study an antenna similar to that in [1], with $L = W = 0.61$ cm, $h = 0.127$ cm, and $\epsilon_r = 15$. We place the antenna in a 1.22 cm $\times$ 1.22 cm cavity and a probe feed is located at the mid point of an edge. For the isotropic case, the resonance should occur around 5.5 GHz. The antenna is biased parallel to one of the edges of the patch (not normal to the patch as in [1]). We solve the optimization problem (1) for various values of the bias field strength H_0 and saturation magnetization $4\pi M_s$. The results are plotted in Figure 1-2 for x-bias (bias field perpendicular to the edge where the feed is located) and y-bias (bias field parallel to the edge where the feed is located), respectively. It is seen that the resonant frequency of the antenna shifts to a higher frequency as H_0 or $4\pi M_s$ increases. Also, the resonant frequencies for the y-bias are higher than those for x-bias. This provides more tuning flexibility. Other ferrite parameters may also play a role in determining the resonant frequency.

3 Beam Steering

The purpose of this optimization problem is to develop a low-profile ferrite-loaded microstrip antenna with beam steering capability. A convenient way to achieve pattern control is to put the antenna patch sandwiched between an upper ferrite superstrate layer and a lower dielectric substrate layer [2], as shown in Figure 3. With zero bias, the main beam of the H-plane pattern is normal to the antenna patch. When some bias field is applied, the main beam can be shifted depending on the values of the bias field, the ferrite properties and the layer thickness. From an optimization point of view, the question is: how could we control the pattern to obtain a given beam shift θ_0?

For the simplest case, we can consider the thickness of the ferrite superstrate as a single design variable while fixing the size of the patch and the external biasing field, just as in [2]. This optimization model can be stated as follows:

$$\text{Minimize } |\theta_* - \theta_0| \tag{3}$$

where $\theta_* = \arg \underset{\theta}{max}$ Relative Power.

The optimization can be carried out in the same way as in the previous problem by using the gradient-based SQP method combined with FEM. Numerical results will be shown at the meeting. We note that for the most general case of this problem, we can have as many design variables as possible, such as antenna patch size, the thicknesses of the substrate and superstrate, feed location, the bias field, etc., with the objective of obtaining a given beam shift θ_0 and a desired resonant frequency f_0. Such a problem will be multi-objective and can be solved by generating a set of Pareto optimal solutions.

References

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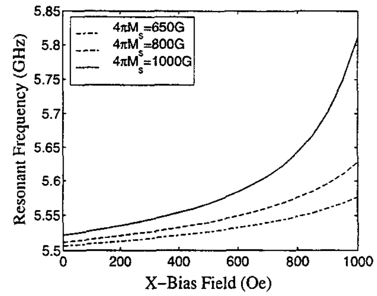

Figure 1: Resonant frequency of the patch in Section 2 as a function of the bias field and saturation magnetization (x-bias).

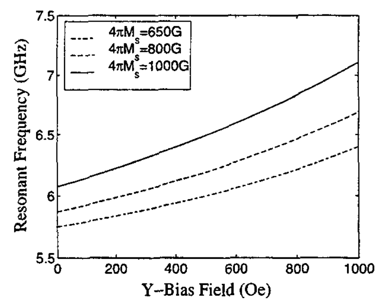

Figure 2: Resonant frequency for the patch in Section 2 as a function of the bias field and saturation magnetization (y-bias).

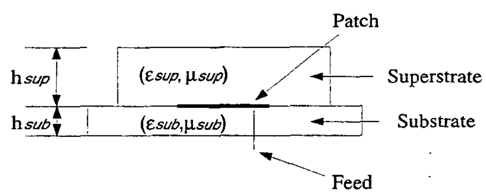

Figure 3: Geometry of the cavity-backed patch antenna for the beam steering optimization problem.