

A proposed model for frequency tuned antennas used in mobile communication systems

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ABSTRACT

The antenna is considered as one of the most fundamental elements in wireless communication systems, especially in mobile devices. Desirable specifications of antennas include covering wide range of operating frequencies, while maintaining high quality of system performance over the whole range of operating frequencies. Therefore, the ability of tuning the resonant frequency of the antenna without altering its physical dimensions would be highly recommended in up-and-coming designs of antennas in mobile devices. This research work proposes a model for tuning the operating frequency of the inverted F-antenna over a reasonably wide range of frequencies, via altering the electromagnetic properties of its ferrite material. In this proposed model, it will be shown that the electronic control of the permeability of the ferrite material of the antenna leads effectively to a significant shift in its resonant frequency, and hence to an overall improvement in the performance of the communication system.

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1. INTRODUCTION

The recent advances in modern communications technology, resulted in an accelerating need for reliable and efficient components used in the implementation of wireless communication systems. The antenna is one of the most vital components in mobile devices, and hence, an efficient and reliable design of the antenna that fulfils the modern design requirements, is one of the main objectives for enhancing the overall quality of the mobile communication systems.

The wide spread of mobile communication devices, especially, smart phones, constitutes a major motivation for extensive research work on internal antenna designs that can be incorporated into these devices. Consequently, various techniques, and technologies were established to deal with different aspects of antenna designs. One of the main and important design aspects is the capability of the antenna to cover wide range of operating frequencies without altering its shape and physical dimensions. The techniques developed to achieve this goal can be categorized into three main techniques: (1) mechanical techniques, (2) usage of electronic tuning circuits, and (3) alteration of electromagnetic properties of the antenna material, such as its permeability, permittivity, and conductivity [1, 2].

Mechanical techniques include adjusting the physical dimensions, or the shape of the antenna. The disadvantages of these techniques include intolerable time delay, unreliability, and short life time of the system, due to the mechanical movements of the system. Alternatively, controlling the electromagnetic properties of the antenna material, enables shifting the resonant frequency of the antenna, without the need

for adjusting its shape or physical dimensions [3-6]. This research work focuses mainly on controlling the permeability of the antenna ferrite material, which in turn leads to a significant shift of the resonant frequency of the antenna over a relatively wide range of frequencies.

The main concept of electromagnetic frequency tuning has been discussed in the literature. For example, [7] presents a method for an electronic frequency tuning of the planar inverted F-antenna (PIFA), using an electronic tuning circuit, composed of a radio frequency switch, besides other discrete passive elements, that are entirely integrated into the antenna, and without using external wiring. This method enables the dual band PIFA antenna to function successfully in four frequency bands. Moreover, various methods of resonant frequency tuning of inverted F-antennas (IFA) are discussed in [8], where capacitors and short pins with various positions are used in these designs.

Additional methods for tuning the resonant frequency of PIFA are introduced in [9-12]. These methods rely on the re-configuration of the physical antenna dimensions, instead of controlling the electromagnetic properties of material of the antenna. In [13] a procedure for designing a small dual-band IFA using a series resonator is introduced. This resonator is positioned at the right end of the IFA to provide adjustable loading effects proportional to the required resonant frequency of the antenna. On the other hand, [14] suggests a tuning circuit composed of a microfluidic impedance incorporated into a planar inverted F-antenna (PIFA). This microfluidic impedance is used in conjunction with a simple double-stub, where the impedance is adjusted by modifying the stub length via injecting a liquid metal alloy to the microfluidic channels of the impedance. While, [15-17] suggest inserting an L-shaped slot with different dimensions into the dual band planar inverted F- antenna design, in order to tune its operating frequency.

Various approaches for enhancing the performance of planar inverted F-antennas are presented in [18-27]. These approaches include using: (1) liquid metal as switching mechanism to reconfigure high frequency patch antennas, (2) a reconfigurable RF impedance tuner integrated with broadband antennas, (3) a stub to enhance the performance of dual band PIFA, and (4) a PCMCIA card to design printed PIFA. This research work focuses on proposing an efficient model for tuning the resonant frequency of the inverted F-antenna by controlled alteration of the electromagnetic properties of its ferrite material, while the shape and physical dimensions of the antenna are intact.

In the proposed model of the antenna, a controllable static magnetic field is applied through the ferrite material of the antenna to alter its permeability, and hence a shift in the resonant frequency of the antenna occurs due to this change in the permeability. The controllable shift of the resonant frequency of the antenna provides a reasonable flexibility in operating the antenna over a significantly wide band of frequencies, which in turn enhances the overall performance of the communications system.

2. THEORY AND DISCUSSION

Ferrite materials are made from mixtures of magnetic metallic oxides, such as iron oxide (Fe_3O_4) and nickle oxide (Ni_2O_3). Due to the electromagnetic characteristics of ferrites, they can be employed in various industrial applications. Ferrites are distinguished by having high resistivity, high relative permeability at low operating frequencies, and high relative permittivity of 10 or more. In this paper, the proposed model of the inverted F-antenna is made completely of nickle oxide (Ni_2O_3). The electromagnetic behavior of ferrites is thoroughly investigated in many research articles e.g. [2, 3]. A brief literature overview on ferrites characteristics is briefly discussed in this section.

At atomic level, the magnetic dipole moment is generated by the rotations of the electrons in the ferrite materials about the axis of the static magnetic field H_0 , which is mainly responsible for their electromagnetic properties. Figure 1 illustrates the generation of dipole moment (m) by the electron spin. When a uniform static magnetic field H_0 is applied through the ferrite material, the electrons will start to rotate about the axis of the static magnetic field at a frequency of $\omega_0 = 2\pi\gamma H_0$ (called Larmor frequency), where γ is the gyromagnetic ratio of a rotating particle or system, and it is defined as the ratio of its magnetic moment to its angular moment. For example, nickle oxide has a gyromagnetic ratio: $\gamma = 2.8 \text{ MHz/Oersted}$.

The wave characteristics of a circularly polarized electromagnetic wave, normally incident on the ferrite medium, such as the wave impedance Z , and the propagation constant k , are related to the medium permeability μ , in the form of the ferrite medium tensor. By determining the eigenvalues of the ferrite medium tensor, it can be shown that the permeability μ of the ferrite material depends on the static bias magnetic field H_0 , the operating frequency ω , and the saturated magnetization M_s . By varying the frequency of the incident wave ω , the permeability μ can be changed, particularly in the vicinity of the Larmor frequency (ω_0). This process results in gyromagnetic resonance [2, 3].

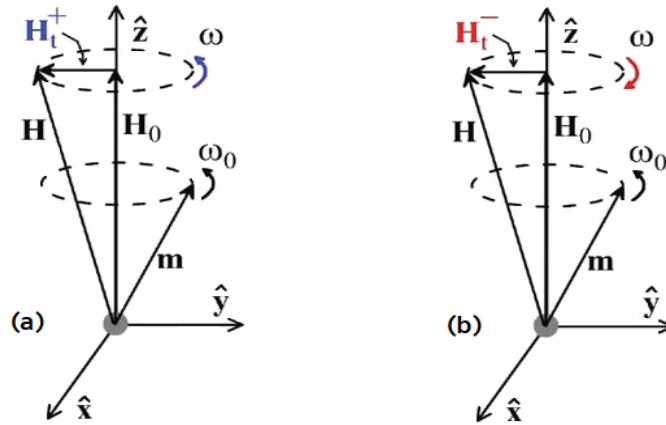


Figure 1. Process of dipole moment generation (m), under uniform static magnetic field H_0

In this situation, the range of alteration of the ferrite permeability, which results in the resonant frequency shift, can be estimated by using the effective permeability μ_{eff} . The magnitude of μ_{eff} depends on the magnetic field component of the electromagnetic RF signal, and on the magnitude of the uniform static magnetic field H_0 . Accordingly, three scenarios exist: (1) longitudinal bias with $\mu_{eff}=\mu\pm\delta$, (2) transverse bias with $\mu_{eff}=(\mu^2-\delta^2)/\mu$, and (3) parallel bias with $\mu_{eff}=1$. It should be noted that in the case of longitudinal and parallel biases, the electromagnetic waves can propagate. However, in the case of transverse bias, μ_{eff} will have a negative value, and hence the waves will not be able to propagate. This occurs when the frequency of the RF electromagnetic wave lies within the range $\sqrt{f_0(f_0+f_m)} < f < (f_0+f_m)$.

When the magnetic field applied to ferrite material has high intensity, the spins of electrons are allied together to form a relatively large unified dipole moment, which results in what is called magnetization saturation M_s . The density of the magnetic flux required to align the spins of all the electrons in the ferrite material can be represented by the magnetization saturation M_s . Moreover, a forced spin of magnetic moment can be generated by an extra relatively small RF alternating magnetic field with a radian frequency ω . Consequently, the tensor of Polder permeability [4] is created such that:

$$[\mu] = \begin{bmatrix} \mu & j\delta & 0 \\ -j\delta & \mu & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{1}$$

where μ denotes the ferrite material permeability, and δ is an intermediate variable, given as:

$$\mu = \mu' - j\mu'' = 1 + \frac{\omega_m(\omega_0 + j\omega_L)}{(\omega_0 + j\omega_L)^2 - \omega^2} \tag{2}$$

$$\delta = \frac{-\omega_m\omega_0}{(\omega_0 + j\omega_L)^2 - \omega^2} \tag{3}$$

where $\omega_m=8\pi^2\gamma M_s$, and $\omega_L=\pi\gamma\Delta H$. Ferrite materials including lithium oxides, magnesium oxides, and nickle oxides, are commercially available in various shapes, e.g. sheets and bars. In general, the magnetization saturation levels of these ferrites lie in the range $300 \text{ Gauss} \leq 4\pi M_s \leq 5000 \text{ Gauss}$, and with a magnetic resonance range of $10 \text{ Oersted} \leq \Delta H \leq 900 \text{ Oersted}$. At radio frequencies, all the frequencies f_m , f_L , and f_0 are quantified in MHz, and they can be expressed as: $f_m=8\gamma\pi M_s$, $f_L=\pi\gamma\Delta H/2$, and $f_0=\gamma H_0$. When the polarization of the magnetic flux H , and the uniform static magnetic field B is circular, where the clockwise and counterclockwise polarizations are denoted by (+) and (-) signs respectively, then the applied magnetic field B can be represented in terms of the magnetic flux H as:

$$\begin{bmatrix} B_+ \\ B_- \\ B_z \end{bmatrix} = \mu_0 \begin{bmatrix} \mu_+ & 0 & 0 \\ 0 & \mu_- & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} H_+ \\ H_- \\ H_z \end{bmatrix} \tag{4}$$

where, $\mu_-=(\mu-\delta)$, and $\mu_+=(\mu+\delta)$.

Figure 2 illustrates the behavior of μ_- and μ_+ versus the frequency of the RF magnetic field. It is obvious that μ'' exhibits a peak at f_0 , which indicates the resonant frequency of the clockwise waves. Moreover, significant attenuations in the magnitude of the clockwise waves are noticeable, compared to the attenuations of the counterclockwise waves, especially, when the RF magnetic field frequency lies in the range $\sqrt{f_0(f_0+f_m)} < f < f_0+f_m$, (which can be approximated as $f_0 < f < f_0+f_m$). As stated earlier, in this range of frequencies, the waves can't propagate due to the negative value of the real part (μ') of the ferrites permeability. Consequently, this controlled alteration of the ferrite permeability can be utilized in designing antennas with tunable resonant frequencies.

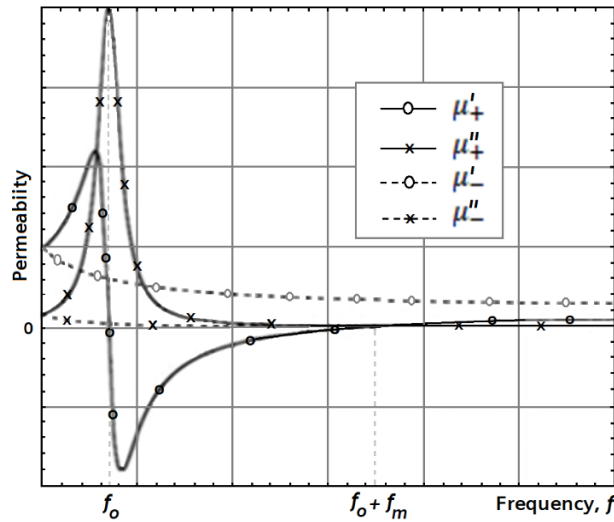


Figure 2. Permeability on nickle oxide versus frequency of the RF magnetic field

In the magnetic saturation phase of the ferrite material, the following approximations can be taken into consideration: $\mu \cong \mu_0$, and $\mu_{\text{eff}} \cong 4\pi\mu_0\gamma M_r/f$, where M_r indicates the residual magnetization in the ferrite material immediately as soon as the uniform static dc magnetic field H_0 is switched off [3, 4]. Figure 3 depicts the relative change in the ferrite permeability δ , which in turn determines the frequency tuning range of the antenna versus the frequency of the RF magnetic field.

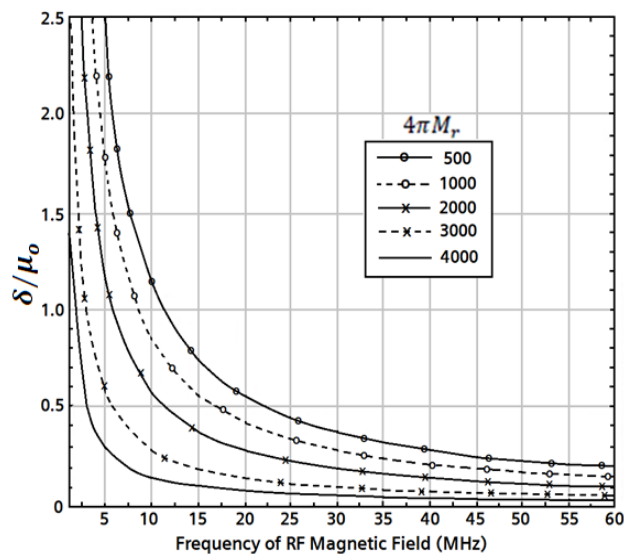


Figure 3. Relative change in ferrite permeability δ , versus frequency of the RF magnetic field [1]

From Figure 3, it can be concluded that the relative change in the ferrite permeability δ decreases exponentially, as the RF magnetic field frequency increases, and hence, the maximum frequency tuning range of the antenna decreases accordingly. The static uniform magnetic field H_0 can be generated and controlled by an electromagnet connected to an adjustable dc voltage source. Therefore, the resonant frequency of a ferrite micro-strip batch antenna, which is placed inside the core of the electromagnet, can be controlled by varying the current in the coil of the electromagnet, which results in adjusting the static magnetic field H_0 . Figure 4 shows the resonant frequency of the inverted F-antenna versus the uniform magnetic field H_0 (Magnetic bias), for a rectangular ferrite micro-strip patch antenna [5]. This approach provides a reasonable flexibility in controlling the resonant frequency of the antenna.

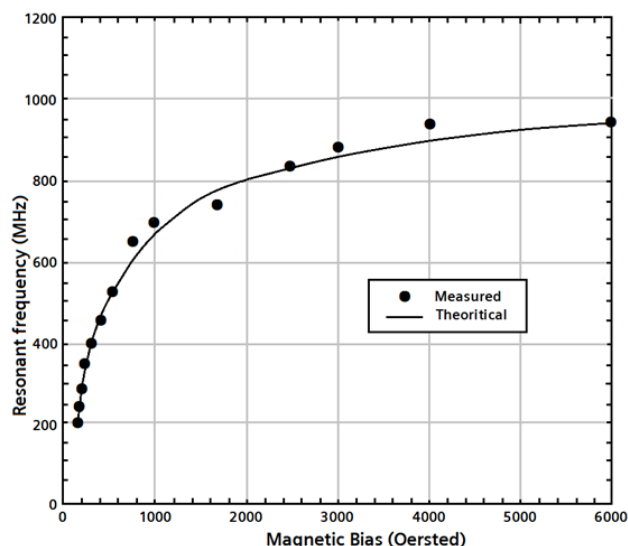


Figure 4. Resonant frequency versus uniform static magnetic field H_0

3. RESULTS AND DISCUSSIONS

A proposed model for a ferrite-based inverted F-antenna is presented in this section. Figure 5(a) shows a typical 2.4 GHz micro-strip Inverted F-antenna, where it is supposed to be placed inside the coil depicted in Figure 5(b), in order to provide full exposure to the static magnetic field H_0 produced by the coil. On the other hand, Figure 6 depicts a typical radiation pattern for the antenna, with vertically polarized electromagnetic waves. It is worth mentioning that simulation results show that the radiation pattern of the antenna, and its gain are not significantly affected by shifting the resonant frequency. However, the radiation pattern, and the antenna gain are mainly dependent on the geometrical shape, and the physical dimensions of the antenna, which are left intact in the proposed model of the antenna. Figure 7 depicts the reflection at the feed-point of the antenna at two different resonant frequencies (2.4 GHz and 3.15 GHz). It can be noticed that at the resonant frequencies of 2.4 GHz and 3.15 GHz, the reflections at the feed-point have minimum values at around 2.41 GHz, and 3.16 GHz respectively, where the antenna has minimum impedances, and minimum SWR's these frequencies as well.

Based on the theoretical analysis presented in sections 2, and on MATLAB simulation results, Figure 8 illustrates the resonant frequency of the antenna versus the static uniform magnetic field H_0 , in two cases: (a) with the whole antenna is made of the ferrite material, and (b) with only the substrate is made of the ferrite material. It can be seen that case (a) provides better performance than case (b).

From Figure 8, it can be seen that when the whole antenna is made of nickel oxide, the resonance frequency of the IFA can lie within the range from 2.41 GHz to 3.15 GHz by adjusting the magnetic bias from 0.2 KOersted to 6.0 KOersted, which resembles a frequency shift of 31%. While when only the substrate is made of nickle oxide the resonance frequency of the IFA can lie within the range from 2.41 GHz to 3.09 GHz by adjusting the magnetic bias from 0.2 KOersted to 6.0 KOersted, which resembles a frequency shift of 28%. It can be concluded that when the whole antenna is made of ferrite material it provides wider range of operating frequencies compared to the case when only the substrate is made of ferrite material. However, in both cases a reasonable improvement in the antenna performance can be observed, which in turn results in an overall improvement in the performance of the wireless systems.

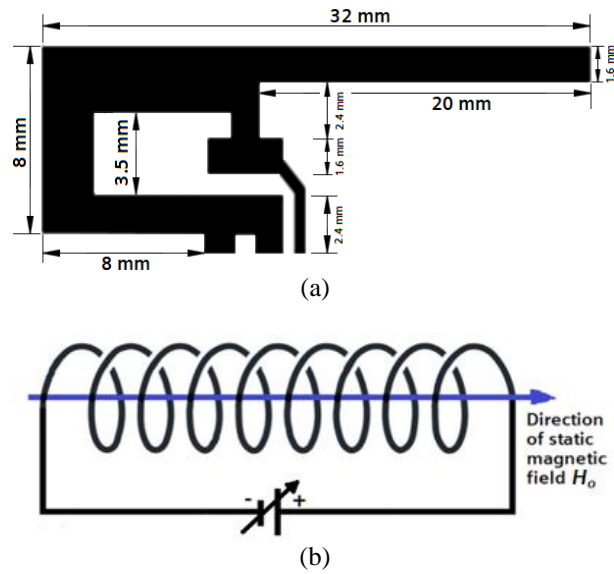


Figure 5. (a) 2.4 GHz inverted F-antenna model, (b) source of static uniform magnetic field

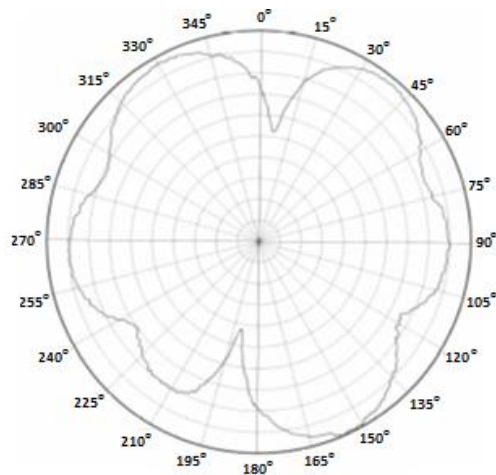


Figure 6. Radiation pattern of a typical 2.4 GHz inverted F-antenna

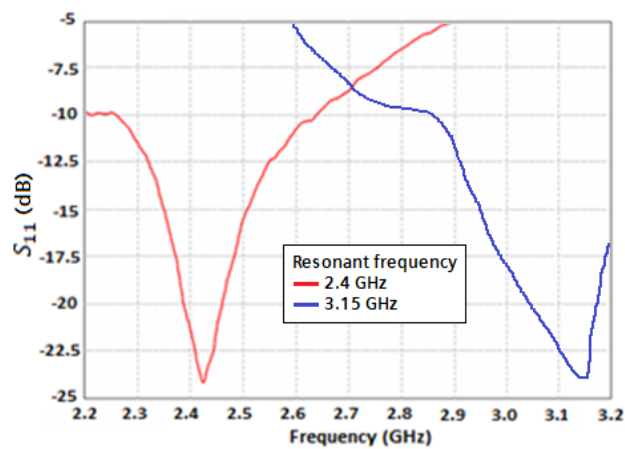


Figure 7. Reflection parameters at the feed-point of inverted F-antenna, with 2.4 GHz and 3.15 GHz resonant frequencies

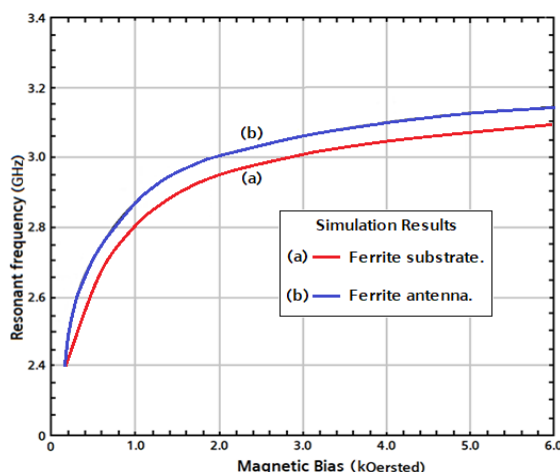


Figure 8. Resonant frequency shift for 2.4 GHz inverted F-antenna, versus the magnetic bias H_0

4. CONCLUSION

In this research work, a model for electronic tuning of the resonant frequency of ferrite-based inverted F-antenna is introduced. The proposed model is based on shifting the resonance frequency of the IFA antenna via controlled alteration of the magnetic permeability of its ferrite material. It is found that the frequency of the antenna resonance frequency can be tuned within the range from 2.41 GHz to 3.15 GHz by rising the magnetic bias from 0.2 KOersted to 6.0 KOersted, which resembles a frequency shift of 31%. This shift in resonant frequency is achieved electronically, which results in a significant improvement in the overall performance of the communication system, without altering the shape or the physical dimensions of the antenna.

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