Efficient Dual-Band Meandered Loop Antenna for RF Energy Harvesting Applications at FM and GSM Bands

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Abstract

This paper presents an efficient dual-band meandered loop antenna for RF energy harvesting applications. The proposed antenna operates at FM (95 MHz) and GSM (925 MHz) bands and consists of a modified folded dipole antenna. The modified loop antenna with meandered load and the additional layer can function at both FM and GSM frequency bands with a proper gain. Furthermore, this modification leads to achieving an electrically small antenna with a maximum dimension of 35 cm × 35 cm at the FM band. The fabricated antenna reveals two distinct resonant frequencies with a favourable reflection coefficient. Thus, it can eliminate the need for an impedance matching circuit. Moreover, the peak antenna gains of 1.1 and 3.2 dBi at FM and GSM with an omnidirectional pattern are achieved, respectively. Hence, the proposed antenna can be an appropriate candidate for RF energy harvesting and wireless power transfer.

1. Introduction

Radiofrequency energy harvesting (RFEH) technology has been attracted significant attention due to its ability to reduce costs related to replacing batteries and making an unlimited lifetime source [1]. Utilizing RFEH supports us in using the wide availability of RF bands in an environment all day, where several electromagnetic waves survey [2-4]. Measured results and analysis indicated that the FM broadcasting band is well suited to harvesting. This band provides a stable RF scavenge source with a suitable ambient power level at various locations. It is worth noting that compared to other frequency bands (e.g. cellular networks and Wi-Fi), FM (88-108 MHz) band offers the advantage of omnipresence, lower free space pass loss, deeper penetration, and low-cost electronic components. Comparatively, few works have been focused on the lower side of the radiofrequency spectrum [5]. Moreover, GSM-900, which is responsible for the global system for mobile communications in an urbanized environment, can be a good candidate for RFEH.

Microstrip antenna is promising to be a good candidate to operate at various frequency bands. Due to its advantages such as low weight, low profile planar configuration, low fabrication costs and capability to integrate with microwave integrated circuits technology, the microstrip antenna is well suited for applications such as RF energy harvesting, wireless communications system, cellular phones, pagers, radar systems and satellite communications [6]. In this regard, the main part of rectennas reported in [7-8] is the microstrip as an antenna. Moreover, since the ambient RF signals may propagate in any direction, the omnidirectional receiver antenna can be an appropriate choice in rectennas [9,10]. Thus, a microstrip antenna with an omnidirectional pattern is functional in RFEH systems. It is noticeable that the antennas at the HF or VHF frequency band such as FM radio tend to be large due to having high wavelength; hence miniaturization techniques leading to size reduction and maintaining performance should be considered [11,12]. Meander line antennas have been proposed to be promising techniques to reduce the resonance frequency. The principle of a meander line structure to antennas is the application of slow-wave performances. The main feature is the smaller phase velocity compared with free space; therefore, the resonance frequency is lowered, resulting in the antenna size reduction. Suffering from low gain could be one of the main drawbacks of the compact antenna, thus requiring a gain enhancement method in ambient RF harvesting applications. Studies show that the gain and, similarly, the bandwidth of an antenna can be enhanced by varying its structural geometry [13]. As a result, adding a meander line and changing the geometry of the microstrip antenna make a desirable compact antenna for RFEH.

This paper presents an efficient dual-band meandered loop antenna at FM and GSM bands with a maximum dimension of 35cm×35cm. The dual-function is achieved by a modified dual-band omnidirectional folded dipole microstrip antenna. Designing antenna at desired bands with an acceptable trade-off between dimension and performance is done by adding meander load and Mica-Muscovite as a second substrate to microstrip folded dipole. Mica Muscovite is a usual rock mineral found in sedimentary rocks, which is added to the antenna's substrate. The proposed antenna is simulated in CST Microwave Studio, fabricated and tested for validation.

The rest of the paper is organized as follows: Section 2 describes the antenna's conceptual design and measurement results. Finally, the conclusion section summarizes the achieved findings and demonstrates their potential implications.

2. Proposed Antenna Design, Simulation and Measurement

The aim is to design a low-profile and self-matched antenna with the desired gain operating at two bands, especially FM broadcasting. Since antennas operating at the FM band tend to be extremely large, miniaturization techniques are required to achieve size reduction while maintaining the required gain. To address this, a folded meander line antenna was considered as it is proposed to be one of the promising techniques to lower the resonance frequency with enhanced gain and radiation resistance. The initial version of the antenna depicted in figure 1 (a) was designed based on the geometry folded dipole antenna [13]. This conventional antenna, as illustrated in figure 1 (b), was modified to be as a meandered load folded antenna, mounted on the RO4003C with a dielectric constant of ε_r = 3.38, loss tangent of $tan\delta$=0.0027 and thickness of t_s=0.8 mm, with the design parameters listed in table 1. Note that the geometric center of the metal coincides with the geometric center of the substrate. To lower the resonant frequency in constant dimension while maintaining the antenna's proposed properties, some changes in the antenna design have been made.

In the first step, it has been found that meandering the line in the load section could enlarge the conducting line length and consequently, it can decrease the resonant frequency and increase the antenna efficiency. Although adding loops to the antenna can make its electrical length larger and consequently lower the resonant frequency, this work definitely increases the maximum dimension of the antenna. Therefore, the antenna will not remain electrically small at the proposed frequency. The antenna resonant frequency is calculated as follow,

$$f_r = \frac{1}{2\pi\sqrt{LC}} \quad (1)$$

where f_r is the resonant frequency. Also, L and C are the equivalent series inductance and capacitance, respectively. Based on our antenna design, the inductance of a straight conductor of each thin flat section in the antenna is defined by equation [14] that is estimated below,

$$L_{(uH)} = 2 \times 10^{-4} l_c [ln \frac{2l_c}{d+t_c} + 0.5 + 0.2235(\frac{d+t_c}{l_c})] \quad (2)$$

Where l_c, d and t_c are the conductor's lengths, width and thickness in millimeters, respectively.

In the next step, Mica Muscovite, a usual rock-forming mineral found in igneous, metamorphic and detrital sedimentary rocks, is added to the rear of the antenna substrate. As illustrated in figure 2, when a layer is added to the substrate, it changes the overall effective electric permittivity of the total structure; therefore, it is able to change the resonant frequency. The total effective electrical permittivity of microstrip with two substrates is calculated as below [15]:

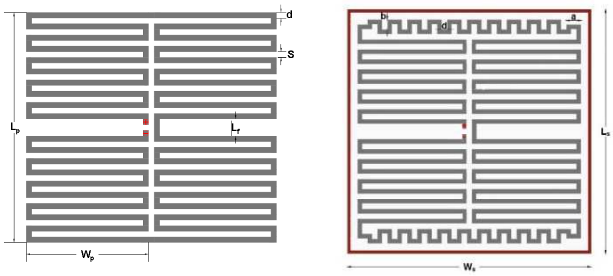
$$\varepsilon_{eff} = \frac{d_1+d_2}{\frac{d1}{\varepsilon_{r1}}+\frac{d2}{\varepsilon_{r2}}} \quad (3)$$

Where:

ε_{r1} and ε_{r2} are relative electrical permittivity of two substrates.

$$\begin{cases} d_1 = \frac{K(k_1)}{K'(k_1)} \; ; and \; d_2 = \frac{K(k)}{K'(k)} - \frac{K(k_1)}{K'(k_1)} \\ k = \frac{1}{\cosh\frac{\pi W}{4h}} \end{cases} \quad (4)$$

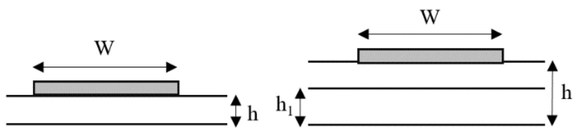
K is the complete elliptic integral of the first kind and $K' = \sqrt{1-K^2}$.



(a) (b)

Figure 1. The geometry of (a) the conventional meandered folded dipole and (b) proposed meandered folded dipole.

Having equations (3) and (4), Mica Muscovite with the dielectric constant of ε_{r1}= 7.9, loss tangent of $tan\delta$=0.001 and thickness of t_m=10 mm, is used to degrade the total relative electrical permittivity of structure. In other words, by adding this layer, the total resonant frequency can be reduced. In figure 1 (b) additional layer is illustrated with brown color.



(a) (b)

Figure 2. Microstrip lines on (a) single or (b) double dielectric substrate.

In addition, the loss resistance R_{Loss} of a meander line antenna is computed by equation [13] below,

$$R_{Loss} = \frac{l_e\sqrt{\pi\mu f_r}}{2(d+t_c)\sqrt{\sigma}} \quad (5)$$

That, l_e is the line length (when extended), $\boldsymbol{\sigma}$ is conductivity, and $\boldsymbol{\mu}$ is permeability. A standard unit defines all parameters. In (5), with reducing resonant frequency while other parameters are fixed, loss resistance is decreased; hence efficiency is enhanced.

Therefore, these two changes were followed for the proposed antenna to resonate at a lower frequency while keeping the performance relatively unchanged.

According to faraday's cage law, a grid plane comprises lines in metal with a gap about much shorter than wavelength acts as a PEC (perfect electrical conductor) plate [16]. As can be seen in figure 2 (b), the proposed antenna is not only included strip lines with $S \leq \frac{\lambda}{43}$ but also it is vertically symmetric; hence the upper loops perform as the positive polarity of the dipole, while the lower parts act as the negative polarity. Thus, the antenna approximately resonates similar to a wavelength dipole at the GSM band. In other words, the wavelength at 925 MHz is about 32.4 cm which is roughly equal to the total length of the proposed antenna (L_p).

Table 1. Dimension of the antenna in figure 2 (UNIT: mm)

Parameter	Dimension	Parameter	Dimension
L_s	350	S	7.5
W_s	350	L_f	22.5
L_p	337.5	d	7.5
W_p	165	a	22.5
N	18	b	15

A designed antenna was fabricated and measured to validate the above analysis and simulation results. A photograph of the fabricated antenna is shown in figure 3. Simulations were conducted in CST Microwave Studio, and measurements were carried out to demonstrate the performances of the proposed dual-band meander line folded dipole antenna.

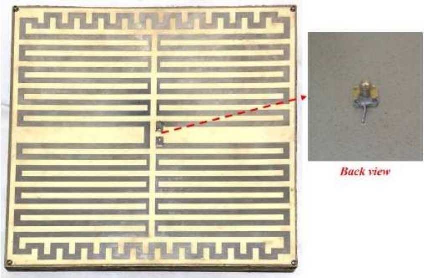


Figure 3. Photograph of the fabricated antenna front and back (feed) view.

The simulated reflection coefficient of three-step modifications with a conventional folded dipole at the FM frequency band is depicted in figure 4. The measurement results are also added to this figure to verify the analysis. It can be seen that the conventional antenna resonates at 137.8 MHz. After the second modification, the resonant frequency is lowered due to meandering the loaded lines and degrading the conducting line width. Hence, the frequency-shifted from 137.8 to 118.4 MHz. Furthermore, the reflection coefficient moves to 95 MHz by adding the Mica Muscovite layer to Rogers 4003C. In other words, the resonant frequency moves toward the lower frequency in the proposed version.

The same procedure was followed, and simulation and measurement results of the reflection coefficient in the second operation band are illustrated in figure 5. As can be seen, the antenna resonates at 925 MHz. It is worth mentioning that the antenna maintains about 5 and 6 MHz impedance bandwidth around 95 and 925 MHz, respectively.

Figure 6 shows the simulated and measured normalized radiation patterns for E- and H-field, respectively. Based on the simulated and measured pattern, the proposed antenna is a suitable candidate to receive/transmit electromagnetic waves from/to most directions for several applications such as RF harvesting and wireless communications.

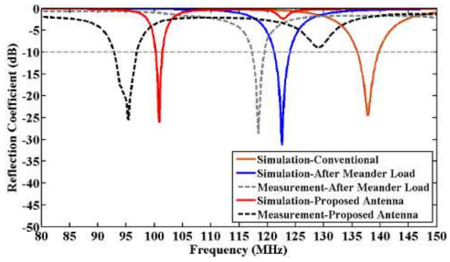


Figure 4. Simulated and measured the reflection coefficient of the antenna at the FM frequency band.

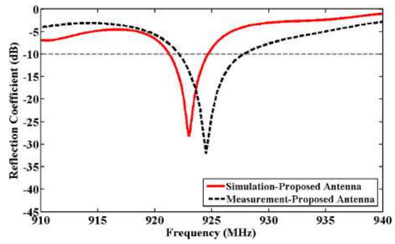


Figure 5. Simulated and measured the reflection coefficient of the antenna at GSM-900MHz.

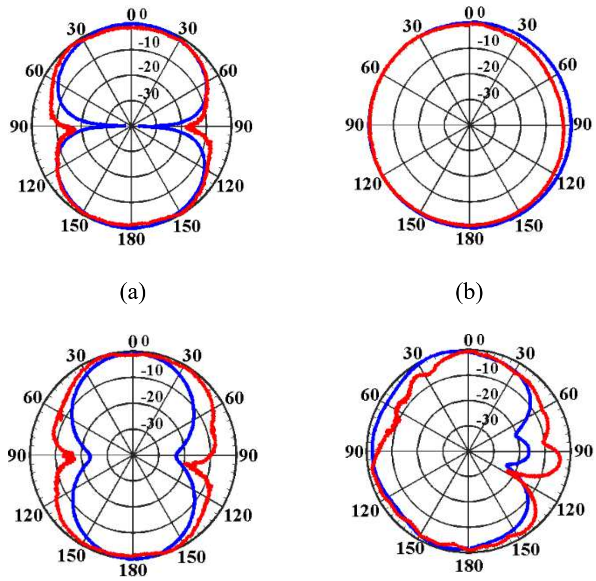


Figure 6. Simulated (Blue) and measured (Red) antenna radiation pattern (a) E-plane at 95 MHz and (b) H-plane at 95 MHz (c) E-plane at 925 MHz and (d) H-plane at 925 MHz.

The *ka* of the proposed antenna at 95 MHz is 0.48; thus, the antenna is electrically small at the FM band. In this criteria, k is the free-space wavenumber, and a is the radius of an imaginary sphere circumscribing the maximum dimension of the antenna [13]. Also, unlike other electrically small antennas with low gain, the measured peak gain is g_a=1.1 dBi at 95 MHz.

Based on the achieved results, it is evident that the performance of the proposed antenna is enhanced by implementing meandered load, reduced line width and

Mica Muscovite compared to the conventional meandered folded dipole type. Since lowering the resonant frequency decreases the resistance loss, the gain has been boosted. Further, the antenna presents g_a=3.2 dBi at its second frequency band.

3. Conclusion

This paper demonstrates an efficient dual-band meandered loop antenna for RF energy harvesting application at FM and GSM bands. The meandered loop antenna with the goal of dual resonant frequency, size reduction, and 1.1 dBi at FM and 3.2 dBi at GSM band gain with the omnidirectional pattern was designed, fabricated and measured. Thanks to the proposed structural changes, such as meandered line load and additional layer, the antenna can resonate at FM GSM bands simultaneously.

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