SMALL UNI-PLANAR ANTENNA SUITABLE FOR BODY WEARABLE APPLICATIONS

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ABSTRACT

We present a small, low cost printed antenna suitable for wireless systems operating below 1 GHz. The antenna is based on a meander line slot loaded with a short circuit and is fed by a co-planar waveguide (CPW) transmission line to provide a uni-planar solution. We have prototyped and tested a 430 MHz version of the antenna and the resulting radiator provides a near omni-directional radiation pattern with a bandwidth of approximately 5 %. We also explore versions of the antenna that can be integrated into a platform suitable for body wearable applications.

INTRODUCTION

There is a pressing need for the development of small radiators that can not only be efficiently integrated with RF components, but can also be integrated within the clothing/armor of a soldier ensemble. These antennas must meet the RF communications requirements for the wireless system such as efficiency and bandwidth, operate within health related guidelines (Specific Absorption Rate; SAR) and also be consistent with low cost manufacturing techniques. In addition, the environment in which the antennas are to be typically mounted is extremely electromagnetically hostile; near ammunition, radios, hydration packs and other essential gear which unfortunately can severely limit the performance of the antenna.

Given the limited real estate available for the radiator in a body wearable platform, the problem at hand is probably the most challenging for an antenna engineer to solve. Fortunately there is a wealth of related information and experience derived from the development of antennas for handset terminals for cellular systems that can assist in addressing this problem. For example, size reduction techniques and fabrication procedures incorporated in the commercial communications market are applicable to these military based systems, assuming large bandwidths are not required. Also, techniques that reduce the radiation directed towards the user may also applicable.

There are probably three general classes of radiators that are directly applicable to the development of small antennas: shorted patches/Planar Inverted F-antennas (PIFAs) [1, 2]; meander line or folded monopoles [3]; and folded slot antennas [4, 5]. Each class has its own relative advantages and drawbacks, especially when developing antennas for operating below 500 MHz. PIFA based solutions can be extremely small and also provide inherent shielding to the user [6] however because the antenna is a two layered structure, to achieve even relatively small bandwidths the thickness needs to be greater than 0.03 λ_0 (where λ_0 is the free-space wavelength at the operating frequency). The two layered structure also complicates the overall fabrication of the antenna as the layers must be connected by a via.

Meander line monopoles can give small, relatively efficient radiator solutions however the performance (in particular the return loss response) is very sensitive to its surrounding environment and also the size of the required ground-plane. This is related to how the radiating fields are created for this antenna; between the meandering monopole and the ground-plane. A very useful property of the meander line monopole however is that it can be developed in a uni-planar format (if the feed is CPW) and therefore can have a low manufacturing cost.

The final class of small antenna is the folded slot. Here the typical $\lambda/2$ antenna is folded back on itself to provide a compact version. The number of folds depends on the dielectric constant of the material used to realize the radiator and uni-planar versions can be easily developed. Of the three classes of radiators suitable for creating small structures, the folded slot is probably the largest in surface area. Even using size reduction techniques typically applied to PIFA-based antennas [2], the overall area of the folded slot is appreciably bigger than the other radiators. A summary of the characteristics of each class of antenna is presented in Table I where more ticks (✓) are an indication of a better solution. As can be seen, no one technology possesses the most outstanding performance in all categories.

Proc. IEEE Military Communications Conference (MILCOM), Washington, DC, Oct 2006.

Table I. Comparison of characteristics of small printed antennas

Antenna	Area	Pattern	BW	Ease of Fab.	Independ. of Environ.
Shorted patch	✓✓✓	Near-omni	✓	✓	✓✓✓
Printed monopole	✓✓	Near-omni	✓✓	✓✓✓	✓
Folded slot	✓	Near-omni	✓✓✓	✓✓	✓

In this paper, we present the results of a prototyped thin, uni-planar printed antenna suitable for body wearable applications that is electrically small and as a consequence has near omni-directional radiation pattern. The radiator combines the principles of all the three classes of antennas summarized in Table I. The antenna is based on a folded meander line slot radiator and uses a short circuit near the feed location to provide a good impedance match at the frequency of operation. The low cost antenna has a 10 dB return loss bandwidth of approximately 5 % and a gain of near 0 dBi. In this paper we present the typical performance (return loss, radiation patterns, and gain) of this form of radiator. We also discuss how the numerous design parameters impact the return loss and radiation performance of the new small antenna and from this investigation, establish how the optimum performance of the radiator can be achieved. We also discuss how the antenna can be developed into a body wearable version and discuss some of the trade-offs associated with such an application, including the use of Electromagnetic Bandgap (EBG) structures to improve the radiation performance and reduce SAR.

The outline of this paper is as follows. We first detail the configuration of the antenna and how the radiator can be designed. We then present the return loss and radiation performance of a prototype version of the antenna. In the next section we describe how body wearable versions of the new small antenna can be implemented and investigate the compatibility of the radiator with three basic radiation control techniques: a back plate [7], a reflector element [8] and EBG technology [9].

ANTENNA CONFIGURATION AND DESIGN

Figure 1 shows a schematic of the top-view and side-view of the radiator. The proposed structure is based on the concept of a shorted spiral-like patch antenna that we first introduced in [10]. This radiator was based on two principles: (i) the shorted patch concept [2] where a shorting pin located in close proximity to the feed can dramatically reduce the overall size of the radiator; and (ii) the use of a folded spiral-like structure for the patch antenna so that we could maximize the current path of the resonant structure. Looking carefully at the shorted patch concept presented in [10] and applying the principle of reciprocity, we postulated that we should be able to create a similarly small radiator based on a slot design. The advantage of this new form of radiator is that it should be relatively independent of the material used to etch the radiator (as most slots are) and also, the antenna does not need to be thick to yield reasonable bandwidth. In addition, the proposed antenna will only require a single layer etching process and therefore should be low in production cost.

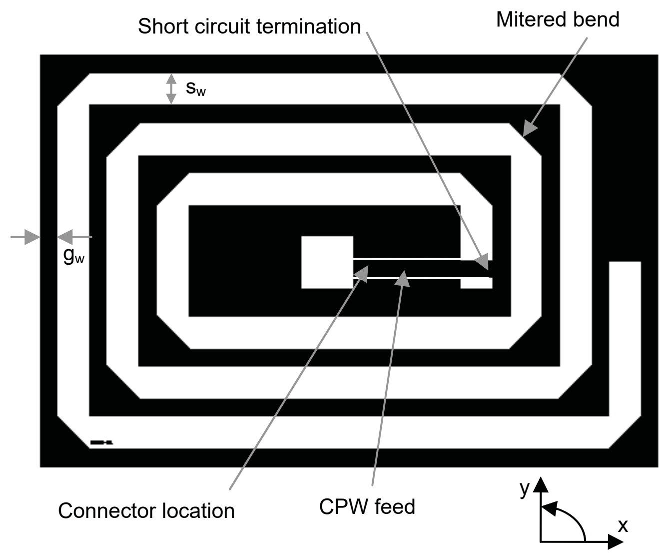


Figure 1. Schematic of meander line slot with short circuit

Figure 1 highlights the important features of the new shorted meander line slot antenna. In this configuration the feed, a coplanar waveguide transmission line, is located at the center of the radiator. The CPW line is designed for 50 Ω and acts as a uni-planar interconnect between the RF devices and the radiating element. As can be seen from Figure 1, the hot electrode of the CPW transmission line extends beyond the radiating slot and forms a short circuit with the perpendicular section of the ground-plane. The slot of width, s_w, expands from the center of the antenna in a spiral-like manner. The bends in the slot are mitered to reduce the parasitic capacitance associated with the bend, thereby ensuring that the resonant frequency of the antenna is as low as possible. The length of the slot, together with the location of the short circuit, governs the frequency of operation of the antenna. This is similar to the design principles associated with the spiral-like shorted patch;

the length of the meander line controls the resonant frequency of the antenna and the location of the shorting pin determines the level of impedance matching at that frequency. The conductor gap between the meandering slot, g_w, was chosen to be thin such that the overall area associated with the antenna could be minimized.

To predict the performance of the proposed antenna structure and also establish design trends and trade-offs, we used a full-wave analysis based on the Spectral Domain Integral Equation technique [11]. There is a shortcoming with this analysis procedure for analyzing small antennas; namely that it assumes the ground-plane and any dielectric layers extend infinitely in the lateral directions. However in spite of this assumption, we have shown in the past that full-wave analysis codes are useful in determining the general performance of small radiators and can still accurately predict the return loss performance of a small antenna even when the ground-plane and dielectric laminates have been truncated [2].

We prototyped the concept highlighted in Figure 1 and Figure 2 shows a photograph of the resulting radiator. The antenna has been developed on 1.6 mm thick FR4 due to the low cost of this material. For this substrate material, a 50 Ω CPW transmission line requires a hot electrode that is 3 mm wide and the slot gaps between the hot electrode and the ground-planes to be 0.3 mm wide. The operating frequency for the radiator was chosen to be approximately 430 MHz, and so the length of the slot and the position of the short circuit were optimized accordingly. The overall length of the slot (unfolded) is 29", and the width (s_w) is 6 mm. The gap between adjacent sections of the slot is 3 mm.

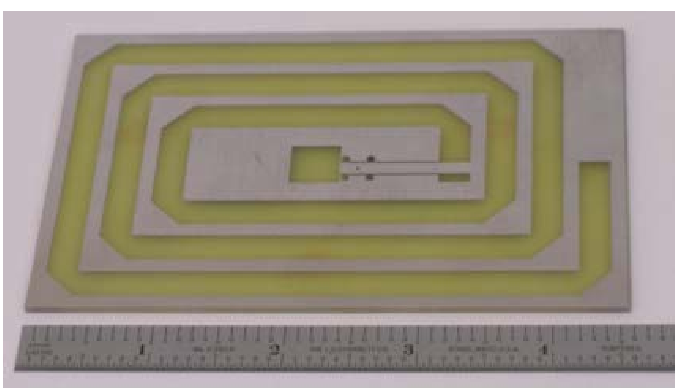


Figure 2. Photograph of prototyped antenna

In the prototyped antenna the short circuit is approximately 2.5 mm from the edge of one of the feed slot lines and is easily formed by extending the hot electrode of the CPW line. As for the case of the spiral-like shorted patch, to achieve maximum size reduction and good matching at the input port the feed and short circuit location need to be near one end of the radiating slot. The overall size of the antenna presented in Figure 2 is 4.5" × 3". To characterize the antenna we connected an RG 316 cable to the hot and ground electrodes of the CPW feed line.

RESULTS AND DISCUSSION

The predicted and measured return loss performance of the proposed small, uni-planar antenna is shown in Figure 3. As mentioned before, the theoretical results were achieved using a full-wave analysis based on a spectral domain implementation of the Method of Moments. In the analysis we use sub-domain basis functions to accurately model the magnetic fields across the slot and the CPW transmission line. To carry out the measurements, the antenna was placed on a foam block within an anechoic chamber to minimize any coupling between the radiator and the surrounding environment. As can be seen from this plot, very good agreement between theory and experiment was achieved. The measured 10 dB return loss bandwidth for the radiator is 25 MHz compared to a predicted bandwidth of 35 MHz, however the minimum return loss for the measured case is better by almost 2 dB. The reasonable bandwidth, in excess of 5.5 %, is due to the bandwidth of the slot primary radiating element which inherently has more bandwidth than a patch antenna.

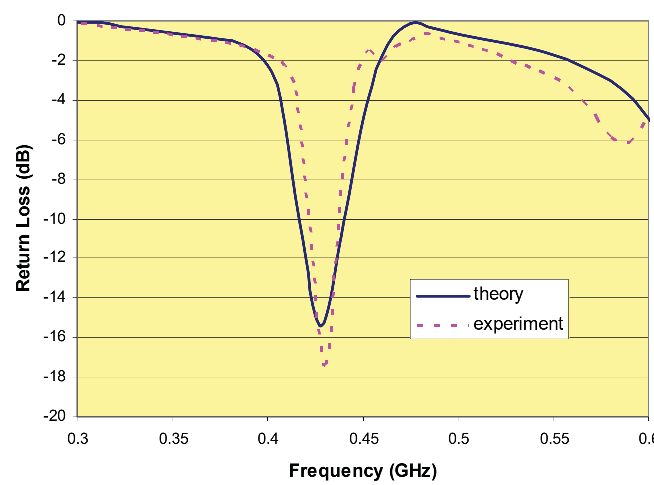
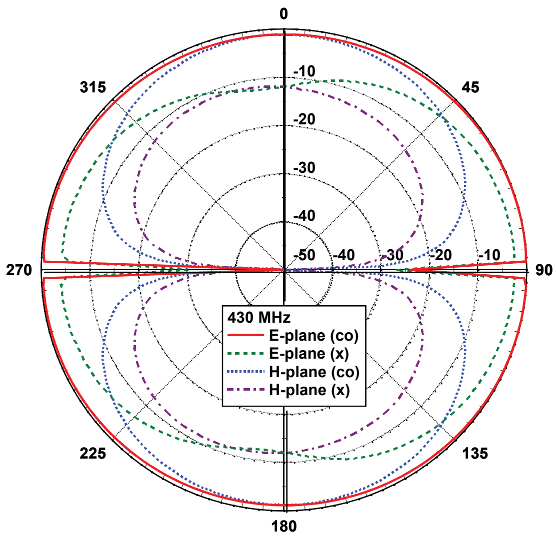
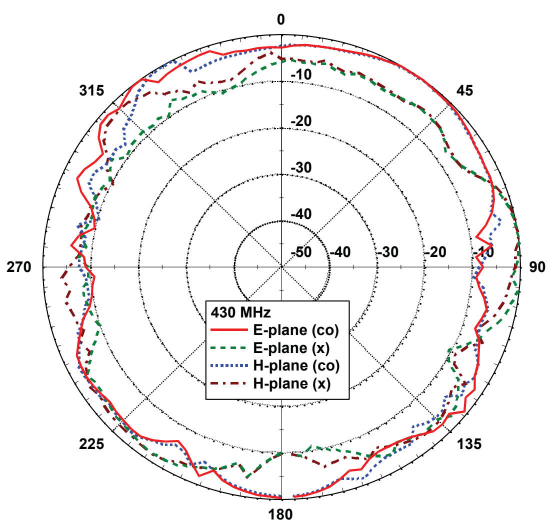


Figure 3. Return loss performance of antenna

The predicted and measured principal plane radiation patterns (E-plane, ϕ = 0° and H-plane, ϕ = 90°) are shown in Figure 4. The coordinates with respect to the radiator are shown in Figure 1. The radiation pattern measurements were carried out at an outdoor antenna range at NAVAIR in Patuxent River, MD. As can be seen from these results the patterns are in reasonable agreement, with higher cross-polarization levels, particularly towards endfire (θ = ± 90°), and scalping of the co-polar patterns in the measured patterns observed compared to the predicted results. These are characteristics that are typically observed for small antennas with truncated ground-planes. The measured gain was approximately 0 dBi with an uncertainty of ± 2 dB. Such an uncertainty is typical for the measurement of small radiators where the impact of the feeding cable can play a role in the resulting gain.



(a)



(b)

Figure 4. Radiation patterns of proposed antenna: (a) Predicted and (b) Measured

BODY WEARABLE VERSIONS

Investigations into body wearable antenna platforms are becoming extremely popular because of the opportunity to remove all the obtrusive radiators currently utilized for communications and also to provide a fully integrated solution with body wearable electronics. In such applications, the antenna system should be able to be readily integrated within the Land Warrior or Future Force Warrior tactical combat gear and provide communications connectivity independent of the position/orientation of the soldier.

Naturally there are several issues related to the development of body wearable radiators and perhaps the most public of these is the associated health related concerns. It is imperative that any body wearable antenna satisfy the published SAR guidelines outlined in [12] to ensure the user is not at risk. Having said this, if a technique is used that reduces the amount of radiated energy towards the user then some form of diversity (for example, a two antenna system) must be incorporated if omni-directional coverage is required. This in turn will increase the complexity of the antenna platform.

As mentioned before, PIFA-based solutions have inherently better SAR performance because of the integrated ground-plane which help shields the user from the radiator [6]. For uni-planar radiator solutions, there are three approaches that can be used to reduce radiation towards the user: (i) a back plate [7]; (ii) a reflector element [8, 13]; or (iii) a metamaterial/electromagnetic bandgap structure [9]. Each approach has its merits and disadvantages and we will discuss these with respect to small antennas for body wearable applications.

Back Plate Configuration

Probably the most common procedure to reduce radiation in a given direction is to use a ground-plane shield, or back plate. In its conventional form the plate is located $\lambda_0/4$ from the radiating element. At a frequency of 430 MHz this would require a distance of 6.9" between the radiator and the back plate, which would make the overall solution unwieldy and therefore unsuitable for body wearable applications. The back plate can be positioned closer to the radiating element, however as the separation distance becomes smaller the ground-plane tends to 'short' the radiator resulting in an inefficient antenna. A rule of thumb is that the ground-plane should be no closer than 0.06 λ_0, although this will require the antenna to be re-designed, and at 430 MHz the overall thickness is still too large; approximately 1.7".

Reflector Element

The reflector element approach has been successfully applied to printed slot antennas to reduce the radiation in a given direction [8, 13]. Here the reflector element (usually a thin elongated patch) is designed to cancel the radiated fields from the slot below the ground-plane. Excellent field cancellation can be achieved using this configuration, even with spacer thicknesses of less than 0.1 λ_0 and truncated ground-planes [13]. In fact this approach has recently been applied to UWB (ultrawideband) body wearable antenna platforms [14] and showed significant improvement in SAR values.

There are however several issues with attempting to apply the reflector element approach to applications operating below 1 GHz. Firstly, at these frequencies the physical thickness of this technique is too large for a body wearable application. Also, applying the reflector element technique to electrically small antennas may not work, as the size of the ground-planes for these antennas is very small. Although it has been shown that the reflector element can improve the front-to-back ratio of a printed antenna mounted on a truncated ground-plane of size less than $2\lambda_0 \times 2\lambda_0$, for small antennas (such as the one presented in Figure 2) the ground-plane is significantly smaller and therefore the reflector element structure may reduce the power that is radiated away from the user.

Electromagnetic Bandgap Structures (EBGs)

There is another technology that can improve the isolation between an antenna and its surrounding environment without compromising the efficiency of the radiator. This technology is commonly referred to as an Electromagnetic Bandgap structure. An EBG structure, metamaterial, Artificial Magnetic Conductor, or high impedance ground-plane, is a lossless, reactive surface that inhibits the flow of tangential electric surface current. This approximates a zero tangential magnetic field and results in a high equivalent surface impedance over a limited band of frequencies. This property of an EBG structure has two consequences: wire antennas (electric currents) can be placed in close proximity to the EBG material without adversely affecting the input impedance of the antenna; and both transverse magnetic (TM) and transverse electric (TE) surface waves are effectively 'cut off' over a range of frequencies. EBG structures can also be readily realized using low cost printed circuit board fabrication procedures.

One potential issue related to an EBG structure is the overall size required to make these surfaces effective; essentially the behavior of the EBG structure is based on the interactions between adjacent cells and therefore the larger the number of cells, the more effective the structure. This can be a problem when there is limited available real estate for the structure, particularly when trying to integrate EBG surfaces with wireless communication devices/radiators that operate in the lower microwave frequency spectrum (less than 1 GHz). Having said this, the structure presented in [9] was only three cells wide and was still able to operate effectively over the band of interest at 2.4 GHz. However the size of the cell is a critical issue if EBG structures are to be integrated with other RF components for applications below 1 GHz.

Figure 5 shows a photograph of a compact EBG structure that we recently developed [15]. The concept is based on the uni-planar metamaterial developed by Itoh [16], however in the new configuration we were able to increase the series inductance of the unit cell and therefore lower the frequency of operation by folding the thin transmission line within the unit cell itself. Using this technique we were able to create EBGs that can operate in the lower microwave frequency range and are also not too much larger than the radiator itself.

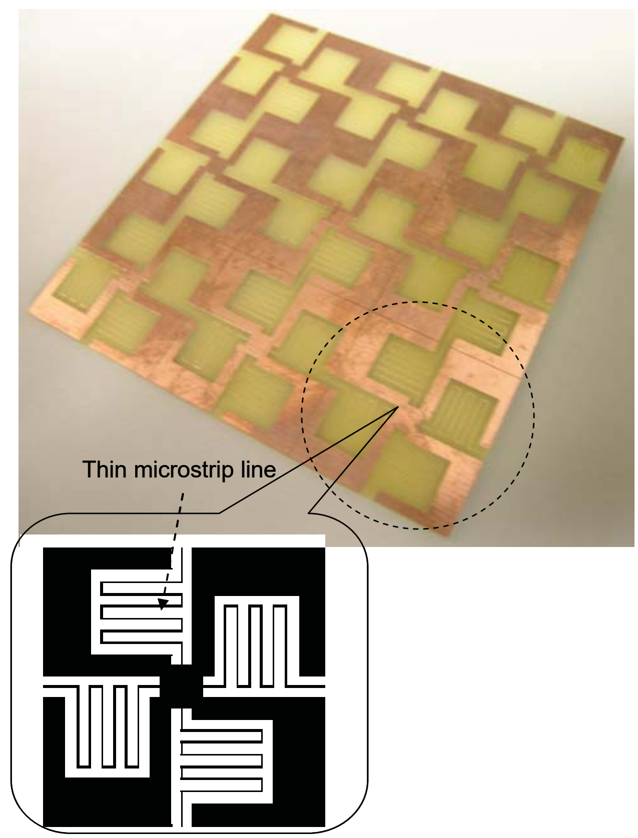


Figure 5. Compact EBG structure [15]

Figure 6 shows the resulting improvement in front-to-back ratio when an EBG structure is integrated with a small radiator operating around 400 MHz. As can be seen from the radiation patterns, the EBG reduces the power directed towards the user by approximately 7 dB. Of course the integrated antenna/EBG is a complicated electromagnetic structure and while in this case there is less power directed toward the user, some of the power may be lost within the structure. Additional investigation into this form of radiator will be given at the presentation.

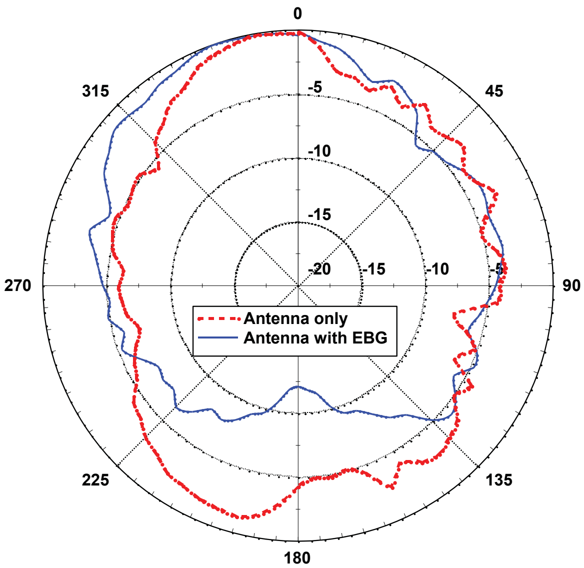


Figure 6. Radiation pattern performance of antenna integrated with EBG

CONCLUSIONS

We have presented a small uni-planar antenna suitable for operating below 1 GHz. The new antenna is a printed meander line slot with a short circuit and has reasonable bandwidth (approximately 5 %) at its operating frequency and provides near omni-directional radiation patterns. We prototyped a version of the small radiator at 430 MHz and measured its return loss performance and radiation response. We have also investigated how a body wearable version of the small antenna may be realized that reduces radiation directed towards the user.

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