Antenna Miniaturization Techniques for Applications in Compact Wireless Transceivers

K. Sarabandi, R. Azadegan, H. Mosallaei and J. Harvey
Radiation Laboratory
Department of Electrical Engineering and Computer Science
The University of Michigan, Ann Arbor, MI 48109-2122
Tel :(734) 936-1575, Fax:(734) 647-2106
email: saraband@eecs.umich.edu

Abstract

In this paper two distinct methodologies in achieving miniaturized antennas for wireless applications are described. One method is based on defining novel topology of radiating elements that can easily be incorporated into monolithic circuits and the other method is based on embedding radiating structures within novel electromagnetic materials. Examples of extremely small planar antennas using both methods are demonstrated.

I. Introduction

The demand for commercial and military mobile wireless systems is on the rise. Low power capability and compactness are two highly desirable features of mobile wireless systems. An important component of any wireless system is its antenna. With recent advances in solid state devices and MEMS technology, construction of high performance miniaturized transmit and receive modules have become realizable. These modules together with miniaturized sensors and transducers have found numerous applications in industry, medicine, and military. As mentioned earlier, apart from the need for miniaturization, low power characteristics of such transmitters and receivers is extremely important as well. Whereas significant efforts have been devoted towards achieving low power and miniaturized electronic and RF components, issues related to design and fabrication of efficient, miniaturized, and easily integrable antennas have been overlooked. In this paper novel approaches for antenna miniaturization which are recently developed at the University of Michigan will be presented. Two basic antenna miniaturization methods are followed. These include antenna miniaturization based on: novel architectures (antenna topology), and miniaturization based on novel materials. Interesting results are obtained using both methods. The design aspects and measured results of a class of miniaturized, planar, reconfigurable, slot antennas based on a novel topology are presented in Section II. Using the proposed antenna architecture, design of a miniaturized antenna as small as 0.05×0.05 λ and a fairly high efficiency (about −3dBi is demonstrated. Maintaining the same antenna size a folded slot design is also demonstrated that shows twice as much bandwidth. Conversely maintaining the bandwidth the size can be made as small as 0.03λ×0.03 λ. Since there are neither polarization nor mismatch losses, the antenna efficiency is limited only by the dielectric and Ohmic losses. In Section III, the methodology for antenna miniaturization based on novel materials is described. Antenna miniaturization is accomplished by embedding antenna structures within an artificial magneto-dielectric material. It is shown that in a magneto-dielectric material where the effective permittivity and permeability of the material are equal, antenna structures can be substantially miniaturized without much compromise in antenna efficiency and bandwidth.

II. Design of Miniaturized antennas by the proper choice of Antenna topology

In this section, we study methods that can be used in miniaturization of resonant antennas merely by varying the antenna topology. Effects of miniaturization on antenna matching, bandwidth, and efficiency is also investigated. The end-loading of an antenna has been devised in the earlier designs of *short dipole antennas* such as center loaded (inductive), and top loaded (capacitive) short dipoles [1]. Inductive and capacitive loadings introduce a slow wave structure, which create a jump discontinuity in the standing wave patterns of the voltage and/or current along the dipole. The magnitude of this jump can be related to the size reduction of the antenna. For instance, if the current distribution along the radiating structure can be made to vary from its minimum to its peak value across a lumped element, a quarter wavelength antenna configuration, instead of a half wavelength, can be achieved. Hence appropriate loading of a radiating element can

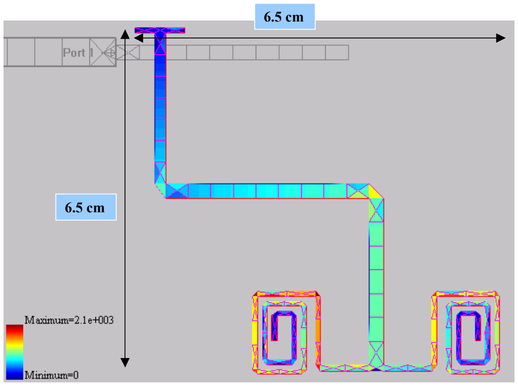

Fig. 1. Quarter wavelength miniaturized antenna.

drastically reduce the size, however, antenna efficiency may be reduced as well. To remedy this deficiency, lumped elements of large dimensions can be created using distributed reactive elements made by open- or short-circuited transmission lines.

The first architecture, which is based on the aforementioned concepts, is a bent quarter wavelength resonant slot antenna [2]. In view of transmission line resonators one can make a quarter-wave resonator by creating a short circuit at one end and an open circuit at the other end. Although creating a physical open circuit for slot lines is not practical, a spiral slot of a quarter wavelength long and short-circuited at the other end behaves as an open circuit at the resonant frequency. Therefore, a radiating quarter-wave slot line short-circuited at one end and terminated by the non-radiating quarter-wave spiral should resonate and radiate electromagnetic waves very efficiently. With this topology the size of the slot dipole can be reduced by approximately 50%. Further reduction can be accomplished by bending the radiating section. This bending procedure should be done in a manner such that no section of the resulting line geometry carries a magnetic current opposing the current on any other sections. Figure 1 shows the geometry of the slot antenna fed by a microstrip line and the distribution of the magnetic current along the antenna. The simulated return loss of this antenna is illustrated in Fig. 2, which shows a perfect impedance match at the design frequency. To validate the design procedure the antenna was fabricated on an FR4 substrate with three different ground plane sizes and their radiation characteristics were measured and summarized in Table I.

Table I. Radiation Characteristics of the antenna shown in Fig. 1.

Ground Plane Size	Resonant Frequency	Gain (dBi)
8.5 cm x 11 cm	568 MHz	–5.0
12 cm x 13 cm	577 MHz	–2.0
22.5 cm x 25 cm	592 MHz	0.5

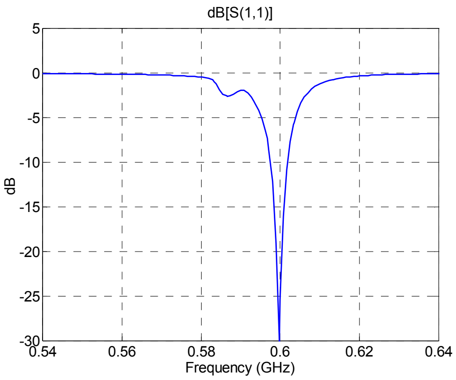

Fig. 2. Return loss of the $\lambda/4$ slot antenna .

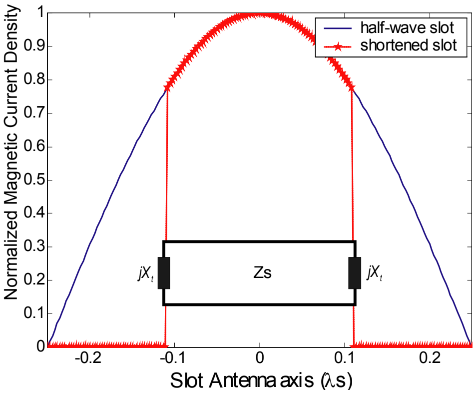

Fig. 3. Magnetic current distribution on a half-wave, and inductively loaded slot antenna.

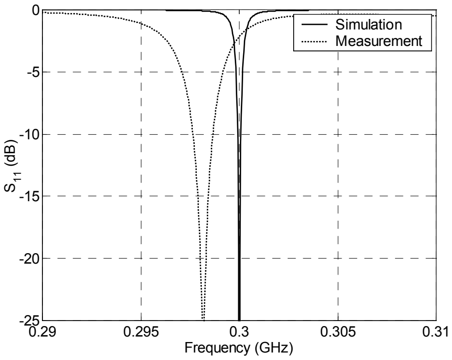

Fig. 5. Miniaturized slot antenna return loss (measurement and simulation)

Another novel procedure for designing a miniaturized slot antenna for almost any arbitrary size has recently been presented [3]. Figure 3 shows the equivalent magnetic current distribution on a standard slot antenna as well as a loaded antenna. If the antenna is terminated in such a way that the current distribution on the reduced size slot resembles that of a half wavelength antenna, both structures resonate at the same frequency. The geometry of this symmetrically loaded miniaturized slot antenna is shown in Fig.4. Illustrated in Fig. 5, is the input return loss of this antenna. Referring to Fig. 5, it is shown that a perfect impedance match can be achieved. This figure shows the simulated (assuming infinite ground plane) and the measured (finite ground plane) return loss of the antenna. The gain of this antenna was measured to be –3dBi when the antenna was made on a $0.18\lambda_0 \times 0.18\lambda_0$ ground plane.

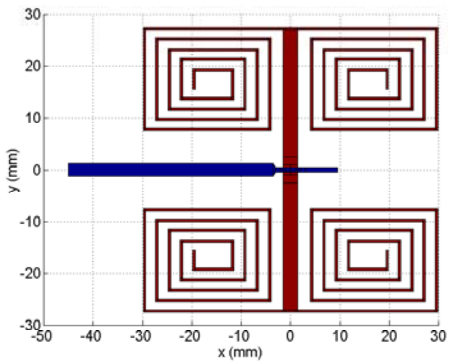

Fig. 4. Symmetric inductive loading of slot antenna.

Miniaturized antennas are inherently narrow band. This narrow bandwidth is a result of a high concentration of electric and or magnetic fields within the antenna structure. In other words, the physical aperture of miniaturized slot antenna is much smaller than that of a half wavelength antenna, which results in a very high radiation resistance. Therefore, the antenna can only be matched to a 50Ω line over a very narrowband of frequency. One method to improve the bandwidth is to increase the physical size of the aperture. To do this without increasing the area occupied by the antenna a novel folded slot antenna is proposed. Figure 6 shows the proposed folded slot that basically occupies the almost the same area as the previous design. Figure 7 shows both the simulated and measured return losses as a function of frequency. Comparison of Figs. 5 and 7, clearly indicates an increase in the –10 dB return-loss bandwidth of the miniaturized antenna. Table. II, summarizes the comparison between both simulated and measured bandwidths of these two antennas.

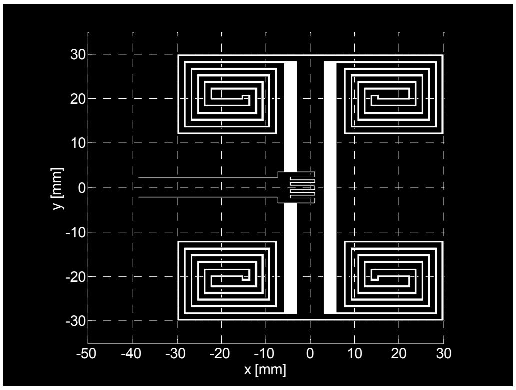

Fig. 6. Capacitively fed miniaturized folded slot antenna geometry.

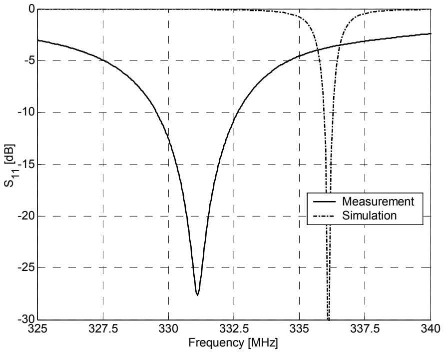

Fig. 7. Miniaturized folded slot antenna return loss (measurement and simulation).

Table. II. Comparison between miniaturized slot and miniaturized folded slot antennas

Antenna Type	Size	BW (%)		Gain (dBi)		Directivity (dB)
		sim	meas	Sim	meas	
Miniature slot	$0.05\lambda_0 \times 0.05\lambda_0$	0.058	0.34	1.0	–3.0	1.9
Folded slot	$0.067\lambda_0 \times 0.067\lambda_0$	0.12	0.93	1.0	–2.7	1.8

III. Antenna Miniaturization utilizing Dielectric and Magneto-Dielectric Meta-Materials:

Antenna miniaturization by embedding an antenna structure within a high permittivity material has been attempted in past [4]. The major drawback of this method is entrapment of a large amount of EM energy within the near-field region due to the existence of impedance contrast between the dielectric material and surrounding air region. Strong resonance behavior of this type of antenna structure only allows impedance match over a very narrow bandwidth. Also because of this strong resonance, the antenna efficiency is expected to be low. Fig. 8(a) depicts the geometry of a rectangular patch antenna with dimensions $13.33\,mm \, X \, 16.67\,mm$ on a finite substrate with relative dielectric constant $\varepsilon_r = 25$ loss tangent $\tan\delta_l = 0.001$, thickness $t = 3.33\,mm$, and size $50\,mm \times 50\,mm$ ($\approx 0.26\lambda_0 \times 0.26\lambda_0$). The resonant length is about a tenth of the free-space wavelength. In this work, a Finite Difference Time Domain (FDTD) technique [5] is applied to accurately characterize the patch antenna with finite size ground plane. The results are presented in Fig. 9. The resonance frequency is determined to be at $f_0 = 1.56\,GHz$ and the bandwidth is about $0.64\,\%$. The antenna has a low efficiency of about $77\,\%$. The performance of this antenna can be extremely enhanced if one uses a magneto-dielectric meta-material [6] substrate with the same relative permittivity and permeability parameters. In this case the wave impedance in the material and its surroundings is the same whereas the index of refraction is rather high. The geometry of the antenna on a meta-material substrate with $\varepsilon_r = \mu_r = 5$ ($\tan\delta_l = 0.001$) is shown in Fig. 8(b). Note that the substrate has the refraction index $n = 5$ (miniaturization factor is $1/10$, similar to the dielectric substrate with $\varepsilon_r = 25, \mu_r = 1$) and intrinsic impedance equal to η_0. The thickness and electrical size of the meta-material substrate is chosen to be same as the dielectric patch antenna considered before. Since in this case both air and magneto-dielectric material have the same intrinsic impedance a small portion of EM waves is trapped in the meta-material and the bandwidth as demonstrated in Fig. 10 is significantly improved to about $7.94\,\%$. The antenna efficiency is about $99\,\%$. Therefore, the magneto-dielectric substrate offers significant advantage for antenna miniaturization compared to the commercially available patch antennas on high permittivity ceramic materials.

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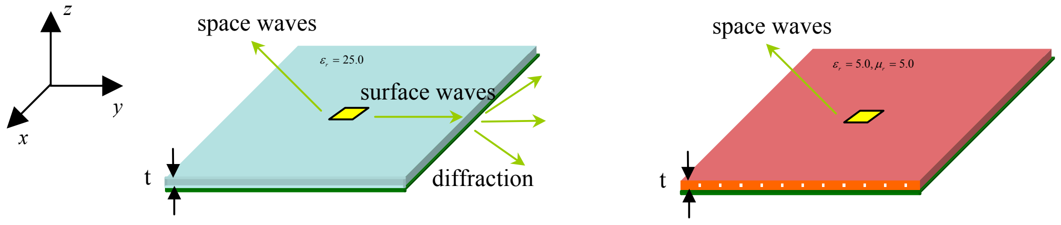
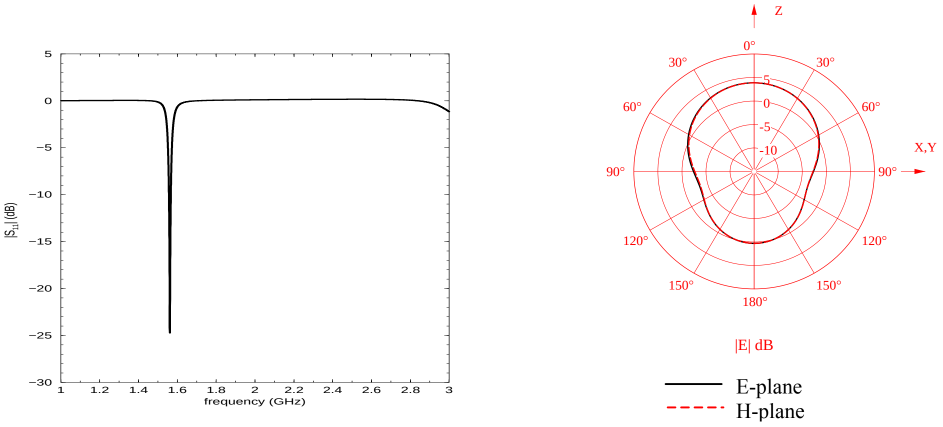


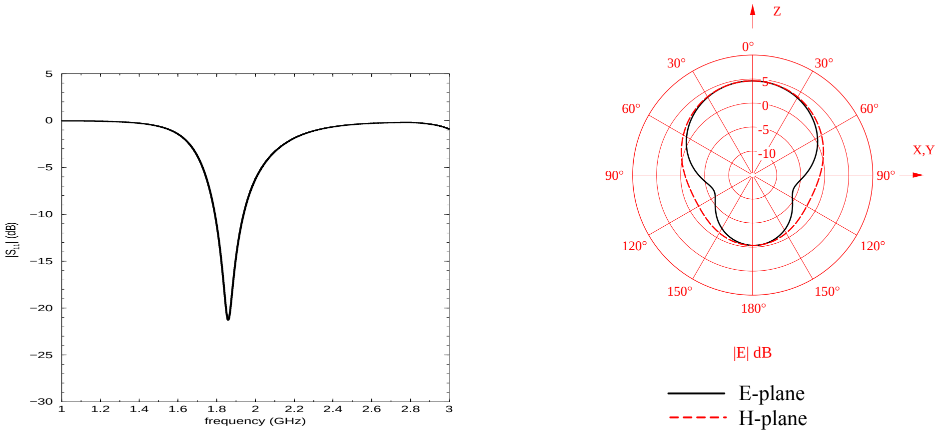
(a) (b)

Fig. 8: Patch antenna on the substrate material, (a) Dielectric substrate, (b) Magneto-Dielectric substrate.



(a) (b)

Fig. 9: Patch antenna on the dielectric substrate, (a) Return loss, (b) Radiation pattern.



(a) (b)

Fig. 10: Patch antenna on the magneto-dielectric meta-material substrate, (a) Return loss, (b) Radiation pattern.