Paper

Electrically Small Microstrip Antenna Based on Magnetodielectric Materials

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Abstract—An electrically small microstrip patch antenna based on high permittivity dielectric and magnetodielectric materials (MDM) is investigated in this paper. The basic parameters of microstrip patch antennas based on high dielectric and magnetodielectric materials are compared with other solutions. The analysis shows that an MDM-based patch surface is 7.14 times smaller when compared with a suspended plate antenna. The use of MDM improves bandwidth and offers perfect impedance matching between the material and free space, over a much wider bandwidth.

Keywords—electrically small antenna, magnetodielectric material, microstrip antenna.

1. Introduction

Electrically small antennas (ESAs) have become popular these days due to their reduced size and ability of being integrated on a chip. Such antennas are mainly used in wireless, mobile communications, for instance in detection and radio identification applications, as well as in medical instruments and video equipment [1]. The key advantage of ESAs is that the dimensions of the antenna are much smaller than their operating wavelength. As it is the case for any aerial (and the same applies to ESAs), efficient radiation occurs when the operating frequency matches the antenna's resonance.

Because ESAs are small in general, their bandwidth is limited [2]–[4]. Their radiation resistance, meanwhile, is usually much smaller than the ohmic loss on the radiating elements. Thus, their radiation efficiency is suppressed. Traditional on-chip ESAs often rely on spiral-shaped metallic structures, a solution which usually makes the bandwidth and the loss issues even worse. To improve the performance of ESAs, many efforts have been made to identify better approaches to their design and fabrication.

Currently, high dielectric constant and low-loss materials are usually used as substrates in the fabrication of miniaturized antennas. Although a high degree of miniaturization may be achieved using high permittivity dielectric materials, some problems are encountered here:

- existence of a highly confined field around the substrate results in narrow band and lower efficiency of the RF components, such as the antenna,
- impedance in a high permittivity medium is low, which makes it difficult to design proper impedance matching between the source and the antenna.

Magnetodielectric materials (MDM) offer a promising way forward in terms of miniaturization of the antenna and designing ESAs that are capable of overcoming the above mentioned issues [5]–[7].

2. Problem Statement

Microstrip patch antennas (MPA) are popular, low-cost, low-profile aerial structures used when the specific application requires a broadside radiation pattern with a high

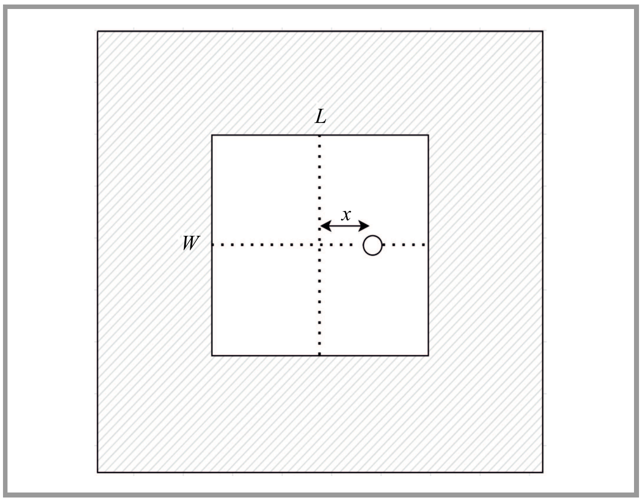

Fig. 1. Schematic view of a coax-fed microstrip patch antenna.

front-to-back ratio. In this paper, miniaturization of an MDM-based patch antenna is presented and a comparative analysis with its high dielectric permittivity counterparts is performed. Figure 1 shows the patch fed below from a coax along the resonant length, where L and W represent patch dimensions, while x denoting the point of coaxial feed [8].

In general, wavelength in the patch substrate material and impedance are interrelated, as shown in Eqs. (1) and (2) [9], where:

$$\lambda = \frac{\lambda_0}{\sqrt{\varepsilon_r \mu_r}} \ , \tag{1}$$

$$Z = Z_0 \sqrt{\frac{\mu_r}{\varepsilon_r}} \ . \tag{2}$$

The MPA radiates from the currents induced on the patch. Equivalently, the magnetic currents around the periphery of the patch and from surface waves induced in the dielectric slab. The surface waves radiate when they reach the edges of the substrate and their emission contributes to the normal patch radiation. The fringing fields from the patch to the ground plane readily excite the lowest-order surface-wave TM_0 mode that has no low frequency cutoff. A dielectric slab of any thickness supports this mode. Surface-wave radiation is controlled by limiting the substrate area or by adding etched photonic bandgap patterns to the open areas of the substrate. However, generally, surface waves are undesirable. As the substrate thickness or dielectric constant increase, the power ratio of surface waves increases as well. The antenna's impedance bandwidth includes directly radiated power and surface-wave power [7].

The antenna quality factor Q_T is a combination of the space-wave radiation Q_R, surface-wave radiation Q_{SW}, as well as dielectric $Q_d = \frac{1}{\mathrm{tg}\delta}$, magnetic Q_m, and conductor $Q_c = h\sqrt{\pi f \mu_0 \sigma}$ factors, such as:

$$\frac{1}{Q_T} = \frac{1}{Q_R} + \frac{1}{Q_{SW}} + \frac{1}{Q_d} + \frac{1}{Q_c} + \frac{1}{Q_m} \ , \tag{3}$$

where $\mathrm{tg}\delta$ is the dielectric loss tangent, σ is the patch conductivity.

The antenna's bandwidth is related to the quality factor:

$$BW = \frac{1}{\sqrt{2}Q_T} \ . \tag{4}$$

The MPA bandwidth can be calculated depending on substrate parameters (h height, ε_r dielectric constant and μ_r magnetic constant) and λ_0 free space wavelength, according to [9]:

$$BW = \frac{96\sqrt{\frac{\mu h}{\sqrt{\varepsilon}\lambda_0}}}{\sqrt{2}(4+17\sqrt{\varepsilon\mu})} \ . \tag{5}$$

MDM allows to miniaturize the antenna by the same factor as a high permittivity dielectric material, however using moderate values of ε_r and μ_r. As seen from Eqs. (1), (2) and (5), by adding a magnetic material into dielectric substrate and making the values of ε_r and μ_r nearly equal, an improvement in substrate properties may be expected. The effect of adding magnetic material into dielectric material reduces strong field confinement and the medium becomes far less capacitive, but only in terms of its dielectric features. Thus, the use of MDM allows to miniaturize the antenna, improve its bandwidth and achieve perfect impedance matching between the material and the free space, over a much wider frequency range. The MPA size may be calculated using Eqs. (6) and (7) [8], [9]:

Antenna width:

$$W = \frac{c}{2f\sqrt{\varepsilon_r \mu_r}} \ . \tag{6}$$

Antenna length:

$$L = \frac{c}{2f\sqrt{\varepsilon_{eff}\mu_{eff}}} - 2\Delta L \ , \tag{7}$$

where

$$L = 0.412h \frac{\varepsilon_{eff}\mu_{eff} + 0.3}{\varepsilon_{eff}\mu_{eff} - 0.258} \cdot \frac{\frac{w}{h} + 0.262}{\frac{w}{h} + 0.813} \ ,$$

h is substrate height, $\varepsilon_e ff$ is effective dielectric constant.

Feed point:

$$x = \frac{L}{\pi} \sin^{-1} \sqrt{\frac{R_i}{R_e}} \ , \tag{8}$$

where R_i is input resistance, $R_e = \frac{\eta\lambda_0}{\pi W\left[1 - \frac{(kh)^2}{24}\right]}$ resistance at the edge, η is radiating efficiency.

Substrate sizes:

$$W_s = W + 12h \ , \quad L_s = L + 12h \ . \tag{9}$$

3. Results and Discussions

Microstrip antennas are researched under free space (suspended plate antenna) conditions, with a high permittivity dielectric and MDM set at 2.4 GHz.

Here, a full-wave numerical analysis based on FEM/MoM is conducted to investigate MPAs with different substrate materials in order to minimize antenna size. The considered aerials are designed in the FEKO environment.

Suspended plate antenna sizes ($\varepsilon_r = \mu_r = 1$) are calculated using Eqs. (6)–(9), when the distance between the patch and the ground (substrate height) h is 1.6 mm:

- patch size $w = 61$ mm, $L = 58.4$ mm,
- feed position from the center $x = 9$ mm,
- ground plane size $w_g = 89$ mm, $L_g = 91.5$ mm.

VSWR of the antenna in the 2.38 … 2.42 GHz band is lower than 2 (VSWR $<$ 2), $BW = 40$ MHz, relative bandwidth is $\delta = 1.66\%$, and at 2.4 GHz VSWR $= 1.06$ (Fig. 2), gain in 2:1 VSWR band varies within the 9…9.17 dBi range (Fig. 3) and beamwidth is in the θ plane at 2.4 GHz $2\theta_{0.5} = 62.19°$ as in φ plane $2\varphi_{0.5} = 68.64°$ (Fig. 4).

Next, the Rogers RO3210 dielectric was used as a high permittivity substrate, with its parameters equaling: $\varepsilon_{r1} = 10.2$, $h = 1.6$ mm, $\text{tg}\delta = 0.0027$. The antenna's size and feed point are calculated based on Eqs. (6)–(9):

- patch size $w = 25$ mm, $L = 18.3$ mm,
- feed position from the center $x = 3$ mm,
- substrate size $w_s = 47.8$ mm; $L_s = 41.1$ mm.

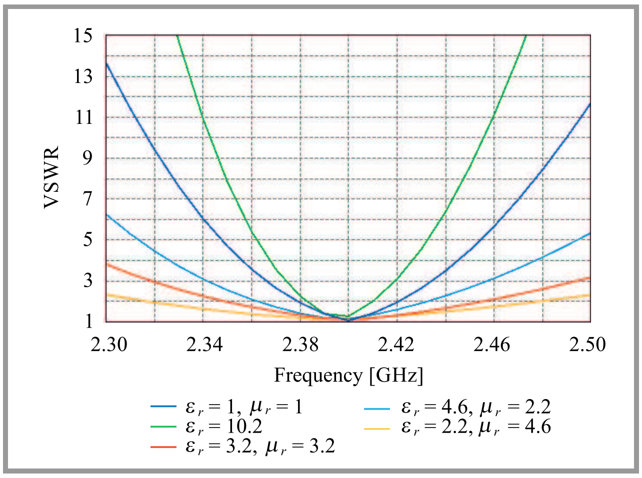

Fig. 2. VSWR of the antenna for different substrates.

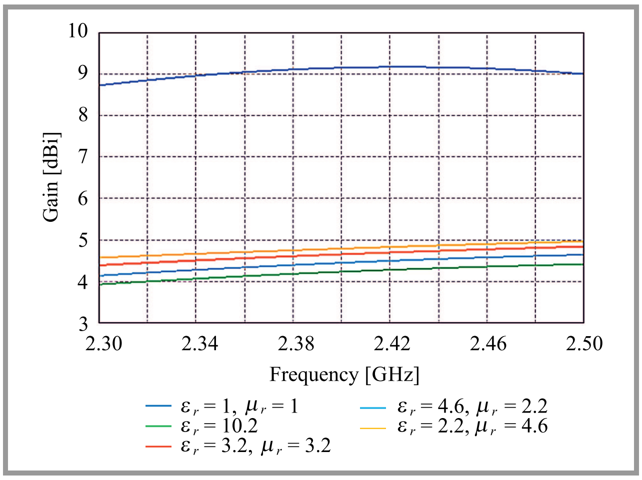

Fig. 3. Gain of the antennas for different substrates.

Using RO3210, the antenna's 2:1 VSWR frequency band is $2.383\ldots2.41$ GHz, $BW = 27$ MHz, relative bandwidth is $\delta = 1.12\%$. At the central 2.4 GHz frequency, VSWR $= 1.02$ (Fig. 2), gain in 2:1 VSWR band varies within the $4.25\ldots4.88$ dBi range (Fig. 3), and beamwidth at 2.4 GHz is, in θ plane, $2\theta_{0.5} = 102.9°$, in φ plane $2\varphi_{0.5} = 99.97°$ (Fig. 4).

For comparison with high dielectric MPA parameters, the characteristics of the MDM material are chosen, thus $\mu_r\varepsilon_r$ is equal to the permittivity of the selected high dielectric material $\mu_r\varepsilon_r = 1 \cdot \varepsilon_{r1}$.

At first $\mu_r = \varepsilon_r = 3.2$ are chosen as the applicable parameters, the height and loss tangent are the same: $h = 1.6$ mm, $\text{tg}\delta = 0.0027$. Using formulas (6)–(9), the antenna sizes and feed point are calculated as:

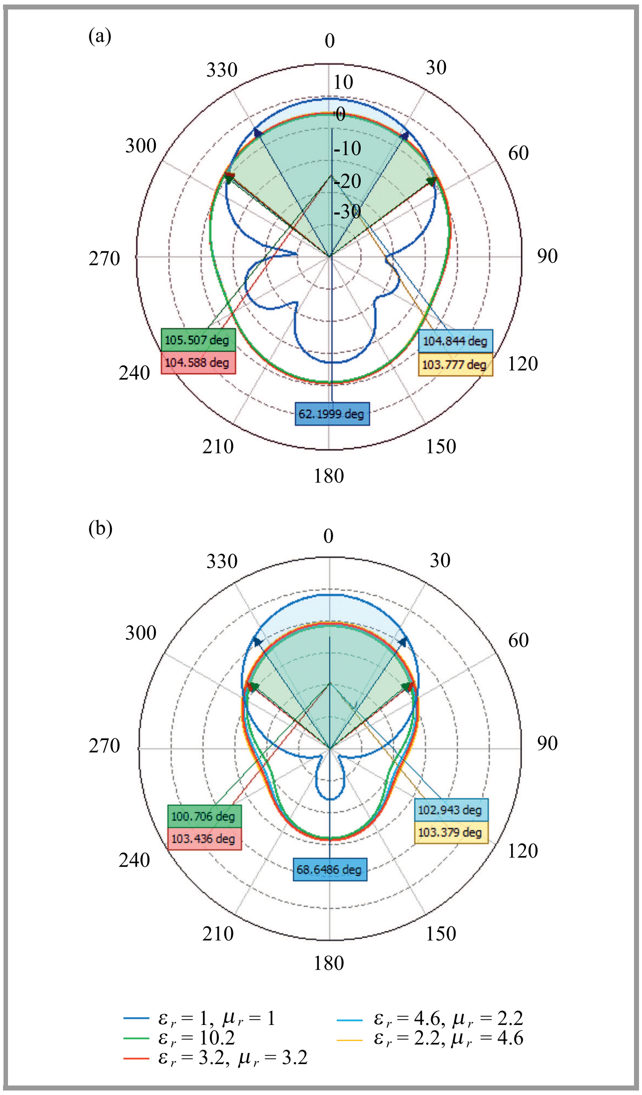

Fig. 4. Antenna radiation pattern at 2.4 GHz in (a) θ and (b) φ plane for different substrates.

- patch size $w = 26.3$ mm; $L = 19$ mm,
- feed position from the center $x = 5$ mm,
- substrate size $w_s = 47.8$ mm; $L_s = 41.1$ mm.

The MDM based antenna's 2:1 VSWR frequency band is $2.349\ldots2.455$ GHz, hence its absolute bandwidth is $BW = 106$ MHz, relative bandwidth is $\delta = 4.41\%$ and at central 2.4 GHz frequency VSWR $= 1.1$. The antenna's gain in the 2:1 VSWR band ($2.349\ldots2.455$ GHz) varies within the $4.9\ldots5.2$ dBi range (Fig. 2), beam width in θ plane at 2.4 GHz $2\theta_{0.5} = 101.9°$, in φ plane $2\varphi_{0.5} = 101.84°$.

In the second stage, the $\mu_r > \varepsilon_r$ case is considered with $\mu_r = 4.6$ and $\varepsilon_r = 2.2$ as substrate parameters. Substrate height is the same at $h = 1.6$ mm. Antenna sizes are identical as in the case with $\mu_r = \varepsilon_r = 3.2$, feed position from the center is $x = 6.5$ mm. Under such conditions, the antenna's 2:1 VSWR frequency band is $2.316\ldots2.479$ GHz (absolute bandwidth is $BW = 153.1$ MHz, while relative bandwidth is $\delta = 6.37\%$). At the central 2.4 GHz frequency VSWR $= 1.1$ (Fig. 2). The antenna's gain in the 2:1 VSWR band

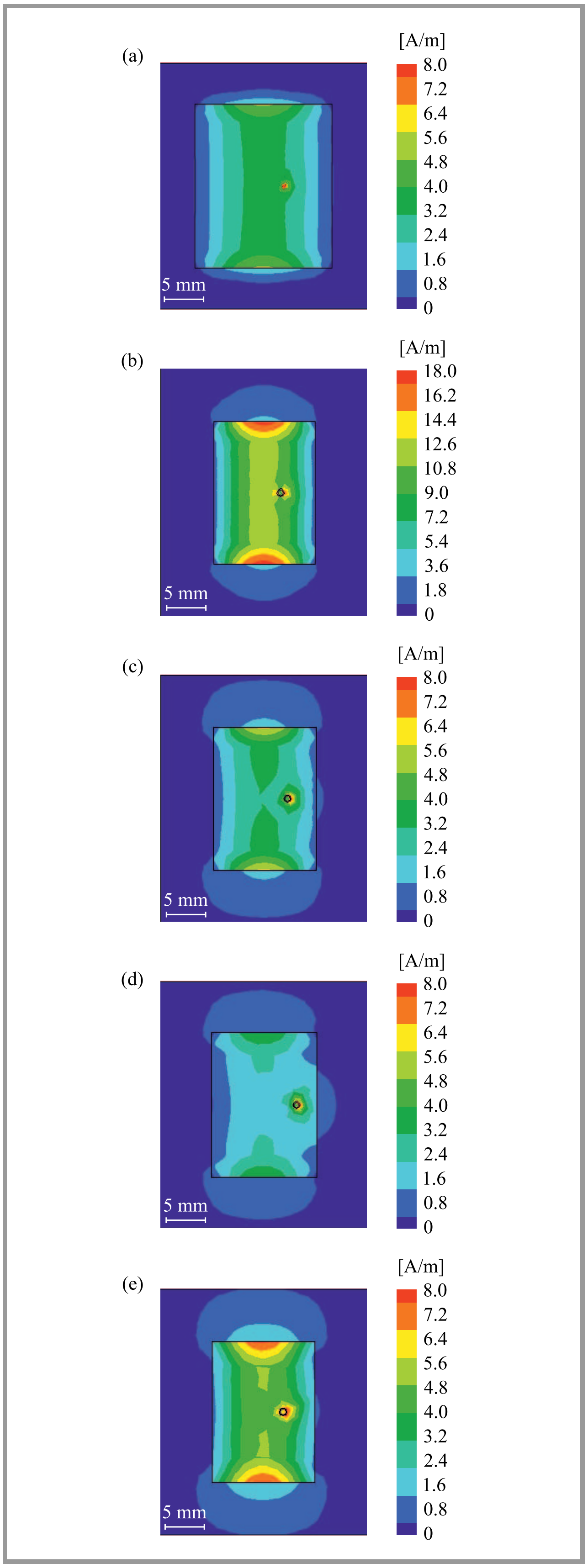

Fig. 5. Antenna surface current distribution for different substrates: (a) $\varepsilon_r = \mu_r = 1$, (b) $\varepsilon_r = 10.2$, $\mu_r = 1$, (c) $\varepsilon_r = \mu_r = 3.2$, (d) $\varepsilon_r = 2.2$, $\mu_r = 4.6$, (e) $\varepsilon_r = 4.6$, $\mu_r = 2.2$.

(2.316…2.479 GHz) varies within the 4.9…5.3 dBi range, beamwidth: in θ plane at 2.4 GHz $2\theta_{0.5} = 101.4^\circ$, in φ plane $2\varphi_{0.5} = 101.7^\circ$ (Fig. 4).

In the third stage, the $\mu_r < \varepsilon_r$ case is studied with $\mu_r = 2.24$ and $\varepsilon_r = 4.6$ as substrate parameters, and the same height $h = 1.6$ mm is considered. Antenna sizes are the identical as those in the case of $\mu_r = \varepsilon_r = 3.2$, feed position from the center $x = 3.8$ mm. The antenna's 2:1 VSWR frequency band is 2.362…2.432 GHz, while absolute bandwidth is $BW = 70$ MHz and relative bandwidth is $\delta = 2.91\%$. At the frequency of 2.4 GHz, VSWR = 1.1 (Fig. 2). The gain in the 2:1 VSWR band (2.329…2.474 GHz) varies within the 4.95…5.1 dBi range (Fig. 3), beamwidth at 2.4 GHz: in θ plane $2\theta_{0.5}$ is 102.3°, in φ plane $2\varphi_{0.5}$ is 101.9° (Fig. 4).

Surface current distribution is shown in Fig. 5. It may be observed that an increase in permittivity creates a highly confined field around the substrate. The increase of permeability results in a decrease in surface current. The existence of a highly confined field around the substrate results in a narrow band.

4. Conclusion

By performing numerical calculations, we have compared conventional microstrip patch antennas based on a high dielectric permittivity substrate with a new aerial based on a magnetodielectric material.

MDM allows to miniaturize the antenna's size by the same factor as high permittivity dielectric material. By using moderate values of ε_r and μ_r and by comparing the results with a suspended plate antenna, we have concluded that the patch surface may be thus reduced 7.14 times.

The antenna's quality factor varies depending on substrate permittivity and permeability. With high permittivity dielectric materials, the existence of a highly confined field around the substrate results in the narrowing of the band. In MDM-based antennas, strong field confinement is reduced, and the medium one becomes far less capacitive, but only in the dielectric part. Thus, the use of MDM results in the miniaturization of the antenna, improvement of its bandwidth and allows to achieve perfect impedance matching between the material and free space over a much wider bandwidth.

Consequently, an electrically small antenna with a wider bandwidth is achieved using MDM in the case of $\mu_r > \varepsilon_r$.

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