PUBLICATION 2

Near-zero permittivity substrates for horizontal antennas

Performance enhancement and limitations

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an EYDF amplifier, the amplified spontaneous emission intensity can be more than 40 dBm suppressed over the tunable range, and the power conversion efficiency can achieve 10.5%. The tunable laser is a potential candidate for communication and optical measurement.

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NEAR-ZERO PERMITTIVITY SUBSTRATES FOR HORIZONTAL ANTENNAS: PERFORMANCE ENHANCEMENT AND LIMITATIONS

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ABSTRACT: *In this letter the advantages offered by ε-near-zero materials as substrates for horizontal dipole antennas near a ground plane are theoretically studied. From the previous work it is known that substrates with extremely low values of permittivity dramatically enhance radiation from horizontal currents over a ground plane. On the other hand, as reported in this letter, frequency dispersion and the finite size of the substrate limit the achievable enhancement in antenna performance.* © 2008 Wiley Periodicals, Inc. Microwave Opt Technol Lett 50: 2674–2677, 2008; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/mop.23739

Key words: *dipole antenna; conducting surface; near-zero permittivity; dispersion; quality factor*

1. INTRODUCTION

Antenna miniaturization is one of the most difficult challenges for antenna designers due to the low radiation resistance and high reactive field level (stored energy), which are inherent features of electrically small antennas. Moreover, horizontal antennas designed to operate in the vicinity of a ground plane suffer from these problems even more, since the currents induced to the ground plane tend to cancel out the radiating ones. High reactive energy accumulated in the vicinity of a small antenna and low radiation resistance allow in practice only extremely narrow operational bandwidth and low efficiency of the antenna.

From the above discussion it is clear that one needs to find antenna solutions that would enhance radiating power and lower the amount of stored electromagnetic energy. One known approach is to use permeable material loadings [1–3]. That approach is limited by dispersion and losses in available magnetic materials. More recently, when possibilities to realize artificial materials with exotic properties (metamaterials) have been discovered, possibilities of using media with $\varepsilon_r < 1$ and $\mu_r < 1$ were considered. In particular, in [4], the effect of substrates with various material parameters were studied in the case of a horizontal dipole over a ground plane (see Fig. 1). From the radiated power P_r analysis one could detect not only the radiation enhancement in the presence of permeable and negative-index materials, but also a notable enhancement with materials having permittivity close to zero. Prior to [4], near-zero materials have been studied to enhance the directional properties of antennas [5–7].

Calculations in [4] revealed that in the dispersion-free low-epsilon case the internal stored energy was roughly at the same level of magnitude as compared with the air-filling case. This lead to low quality factor values and rather broadband operation. However, in [4] the effect of dispersion of the low-epsilon material was left out of the scope of the study, although it is known to play a major role in antenna applications of metamaterials [2, 3]. In this article, we provide more insight to potential performance of antennas using artificial low-epsilon materials and study the effect of dispersion and the size of the substrate on the antenna performance.

2. THEORY

To understand the enhancement in radiated power of a horizontal dipole in the case of a low-permittivity substrate, one can analyze the surface impedance of the slab Z_s seen by a horizontal electric dipole. In the case of a low-surface impedance, the reflection coefficient from the impedance boundary is close to -1, which means cancellation of radiation. On the other hand, a high-surface impedance is preferable, since radiation from the dipole can be

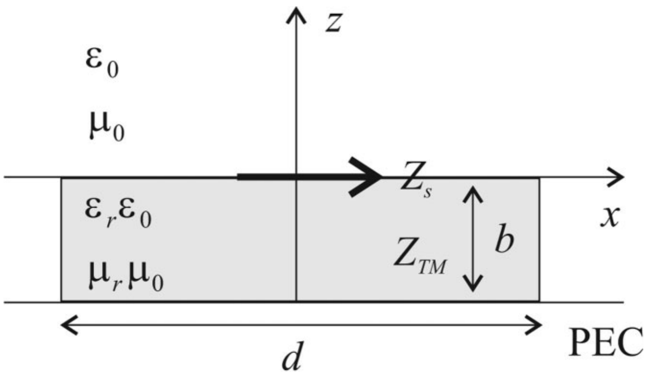

Figure 1 Electric dipole on a conductor-backed slab

enhanced. A horizontal dipole over a material slab on a ground plane (see Fig. 1) generates a wide spectrum of spatial harmonics, and we need to consider surface impedance for plane-wave components with arbitrary tangential wavenumbers k_t. The surface impedance can be written as (e.g., [8])

$$Z_s = jZ^{\mathrm{TM}}\tan(\beta b), \tag{1}$$

where b is the thickness of the slab and β is the vertical component of the propagation constant given by

$$\beta^2 = \omega^2 \varepsilon\mu - k_t^2. \tag{2}$$

Z^{TM} is the wave impedance of TM waves in the slab:

$$Z^{\mathrm{TM}} = \sqrt{\frac{\mu}{\varepsilon}}\sqrt{1 - \frac{k_t^2}{\omega^2\varepsilon\mu}}. \tag{3}$$

For the spatial harmonic propagating in the vertical direction ($k_t = 0$), and for electrically thin slabs the permittivity ε cancels out: The slab impedance becomes $Z_s \approx j\mu\omega b$. Thus, if the thickness b is small compared to the wavelength, the slab impedance is small and acts as an electric conductor, unless a high-permeability substrate is used. However, if the tangential wave number k_t is nonzero (all other spatial harmonics, propagating in oblique directions or evanescent fields), the tangent function is finite and for the case when ε tends to zero, the surface impedance becomes infinite and acts as a magnetic conductor enhancing the antenna radiation. Although the enhancement is smaller than for the ideal case of a perfect magnetic conductor ground plane, it can be very significant. The results presented in publication [4] strongly support this hypothesis.

3. EFFECT OF FREQUENCY DISPERSION

In publication [4], calculations in the dispersion-free low-epsilon case showed that the stored energy W was roughly of the same magnitude as compared to the air-filling case. Thus, the enhancement in radiated power P_r, which is easily computed numerically from the far-field data as

$$P_r = \frac{1}{2}\sqrt{\frac{\varepsilon_0}{\mu_0}}\int_0^{2\pi}\int_0^{\pi}(|E_\theta|^2 + |E_\varphi|^2)r^2\sin\theta\,d\theta\,d\varphi, \tag{4}$$

led to a low radiation quality factor Q, since

$$Q = \frac{\omega W}{P_r}, \tag{5}$$

and to a wide antenna bandwidth.

However, in [4] dispersion of the material parameters and its effects on the stored energy and the radiation Q were left out of the scope. In practice, dispersion plays an important role. Like permeability in high microwave frequencies, near-zero permittivity is realized with passive artificial composite materials. As one possible realization, one can use meshes of thin metal wires, possibly loaded by inductors to reduce structural dimensions. It is well known, that frequency dispersion of the material parameters cannot be neglected in calculation of the stored energy, if the permittivity and/or permeability values are smaller than unity (e.g., [9, 10]). For these materials, the stored energy is calculated as

$$W = \frac{1}{4}\mathrm{Re}\int_{\text{sphere}} dV\left(\frac{\partial(\omega\varepsilon)}{\partial\omega}|\mathbf{E}|^2 + \frac{\partial(\omega\mu)}{\partial\omega}|\mathbf{H}|^2\right). \tag{6}$$

This formula assumes that the substrate losses can be neglected. While the permittivity values can approach zero, the coefficient $\frac{\partial(\omega\varepsilon)}{\partial\omega}$ is always larger than unity.

Thus, dispersion leads to increased stored field energy in the substrate. In estimating the antenna quality factor we integrate the energy density over the smallest sphere that can completely enclose the antenna. The energy stored outside this volume can be estimated using the spherical-mode expansion of the antenna fields. In paper [4] it is shown that the energy stored outside the antenna sphere is small compared to the internal energy, and in this study it is neglected.

In antenna design low-loss substrates are clearly preferable, which suggests the use of non-resonant microstructures for the realization of near-zero permittivity materials. In this case the dispersion can be usually well approximated by the Drude law as

$$\varepsilon = \varepsilon_0\left(1 - \frac{\omega_p^2}{\omega^2}\right), \tag{7}$$

where ω_p is the plasma frequency. If the permeability is nondispersive (we assume nonmagnetic substrates in this study), we get for the field energy

$$W = \frac{1}{4}\mathrm{Re}\int_{\text{sphere}} dV\left[\varepsilon_0\left(1 + \frac{\omega_p^2}{\omega^2}\right)|\mathbf{E}|^2 + \mu_0|\mathbf{H}|^2\right]. \tag{8}$$

4. RESULTS

In the case of a microstrip antenna loaded with artificial magnetic materials studied in [2], it was found that the bandwidth enhancement due to magnetic properties of the substrate was negated by the effect of increased stored energy due to material dispersion. In the present case of low-epsilon substrate the favorable effect on increased radiation depends on the size of the substrate. In paper [4] the size of the low-ε substrate was considered infinite. However, empirically one can expect considerable decrease in the radiated power as the substrate size becomes smaller. If the antenna system is assumed to be similar to the case presented in the earlier work [4] (a horizontal dipole over a material-coated ground plane), the radiated power curves presented in Figure 2 can be drawn showing the decrease in the radiated power as the length d of the substrate is decreased from infinity to the quarter of the wavelength in free space. The normalized distance k_0b to the ground plane equals 0.1, and the primary radiator is a quarter-wavelength dipole. In the simulations, the dipole was metal strip with width 0.0033λ and fed in the center with ideal current source. In Figure 2 the ground plane is considered infinite and the radiated power is normalized to the power radiated by the same dipole in free space without the ground.

The internal stored energy of the same antenna is presented in Figure 3. In the calculations, the internal energy was numerically evaluated from the field data simulated with HFSS software and the dispersion factor was included. In all the simulation cases the feed current was considered constant and the stored energy was normalized to the stored energy of a similar dipole in free space.

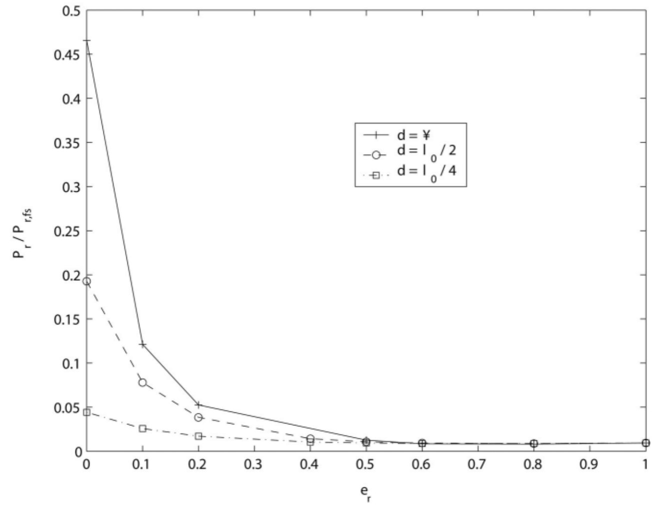

Figure 2 Radiated power for different sizes of low-ε substrate

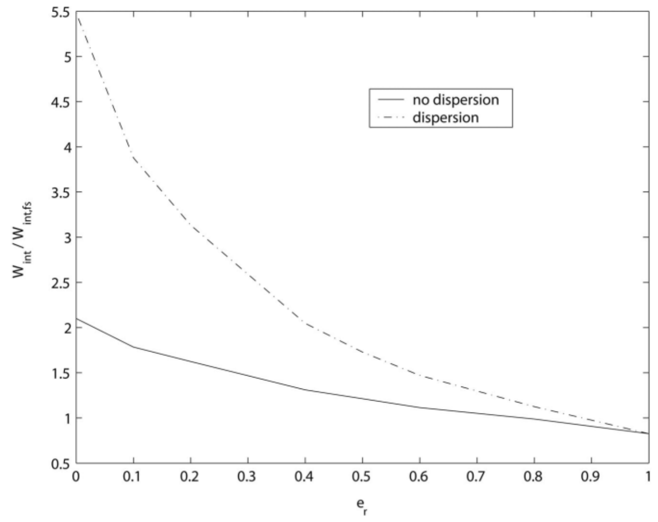

Figure 3 Stored reactive energy

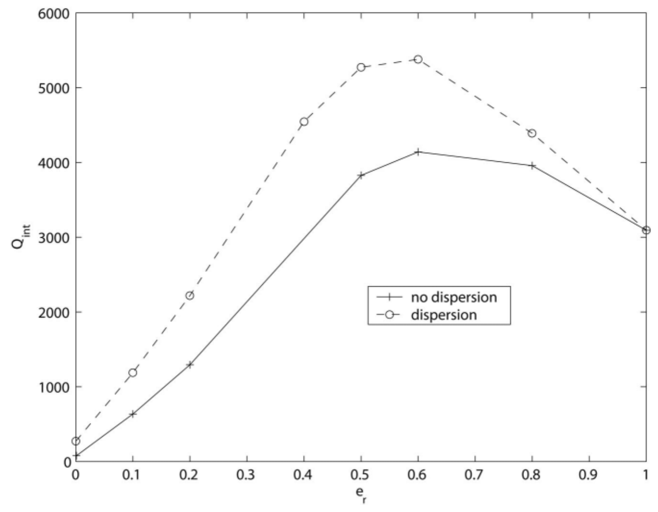

Figure 4 Radiation quality factor in the case of an infinite substrate

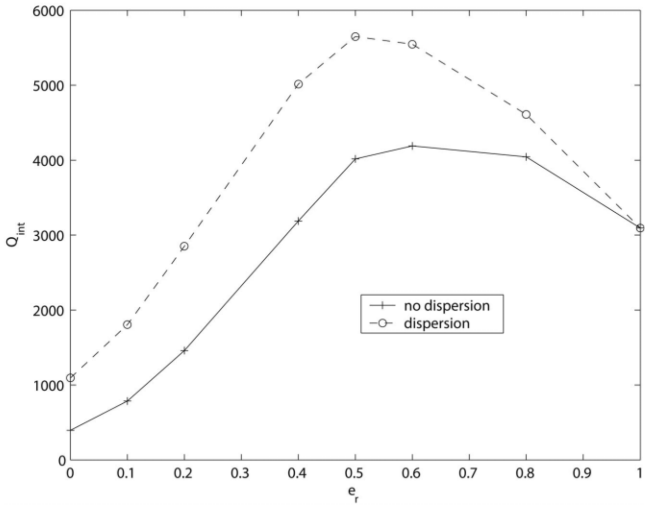

Figure 5 Radiation quality factor in the case of a λ/2 × λ/2 substrate

As can be seen from Figure 3, the internal stored energy increases notably due to dispersion of the substrate permittivity.

From the radiated power and the stored energy data, the radiation quality factors for different sizes of dispersive low-epsilon substrates can be plotted (Figs. 4–6). The radiation quality factors first increase as ε decreases, but start to decrease sharply as ε gets closer to zero. For the case where dispersion is included in the analysis, the values are expectedly higher as compared to the dispersion-free situation. However, the size of the substrate (which determines the radiated power) plays a major role. For an infinite substrate (see Fig. 4) and for a substrate measuring λ/2 × λ/2 (see Fig. 5), even for the dispersive case, lower quality factors are possible than in the air-filling case. However, if the substrate is quarter wave in length (see Fig. 6), just filling the volume under the radiating dipole, the quality factor is higher as compared to the air-filling case.

5. CONCLUSIONS

In the earlier work it was shown, that in addition to permeable substrates under a horizontal current element, low-epsilon materials lead to higher radiation resistance and widening the antenna bandwidth [4]. However, the size of the substrate was considered

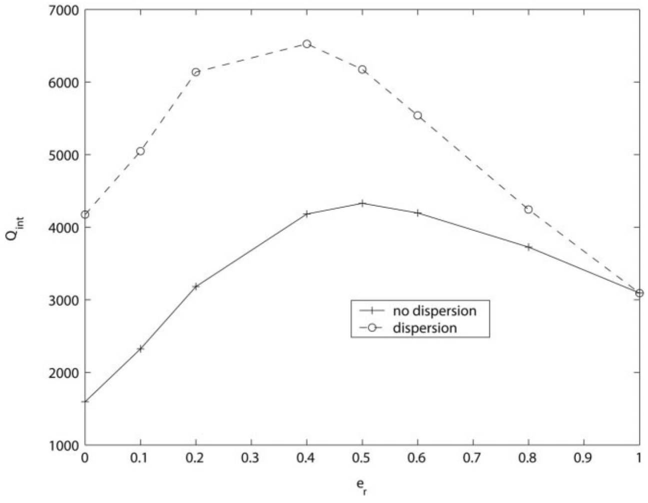

Figure 6 Radiation quality factor in the case of a λ/4 × λ/4 substrate

infinite and the frequency dispersion of the material was neglected. In this article, we have taken the dispersion effects into account and have shown that the size of the substrate plays a major role in radiation enhancement. The radiated power of a dipole has been found to decrease drastically as the low-epsilon substrate size decreases. Also, the stored energy of the element increases notably with material dispersion. As a result, low-epsilon substrates measuring $\lambda/4 \times \lambda/4$ has a higher radiation Q compared to the air-filled case. On the other hand, substrates of the size of $\lambda/2 \times \lambda/2$ have been found to give notable enhancement in the radiation performance of the antenna.

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SMALL HANDSET ANTENNA FOR FM RECEPTION

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ABSTRACT: *A passive internal handset antenna for FM reception is presented using electromagnetic simulations as well as laboratory experiments. Received signal for the antennas have been demodulated and the quality of the audio signal evaluated. Results have been compared with a long antenna (λ/4) confirming that the proposed solution is a good candidate to migrate to a full wireless FM system that may be integrated into a handset phone.* © 2008 Wiley Periodicals, Inc. Microwave Opt Technol Lett 50: 2677–2683, 2008; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/mop.23774

Key words: *handset antennas; FM antennas; small antennas*

1. INTRODUCTION

Up to the moment and during several years the design of antennas for handset and wireless devices in CDMA, GSM, UMTS, Bluetooth, among other bands, has evolved and numerous publications on this topic appeared [1–14]. None the less to our knowledge, there is no scientific literature to design passive embedded antennas for handset/wireless device at FM band (100 MHz). At the beginning of this research, a benchmarking has been done to confirm that nowadays there are no commercial mobile phones that include a wireless FM system having an internal FM antenna. Therefore it is a challenge to design such an antenna.

In this article, we present a miniature FM internal antenna for mobile terminals that obtains reasonable levels of bandwidth and radiating efficiency. To prove its behavior, three prototypes have been simulated using a commercial code and then implemented. Each prototype is representative of a particular handset platform.

In Section 2 the precedents of the antenna design is presented. Some of the problems about miniaturizing an antenna are indicated and it is shown how efficiency and bandwidth are critically affected when trying to fit a FM antenna into a phone case. A common solution to overcome the bandwidth (BW) difficulties is also commented and its drawbacks are explained. In Section 3 the antenna design is presented. The benefits of using this technique are clearly remarked because it improves both efficiency and BW without increasing the antenna dimensions ($l_{\max} \approx \lambda/30$). In Section 4 the measurements of received power and gain of three prototypes are shown. The results are also compared with the ones obtained using a larger antenna ($\lambda/4$ monopole over a ground plane). Section 5 summarizes and concludes the work.

2. BACKGROUND

When the operating frequency of a mobile wireless device is at a lower part of the spectrum such as FM, $\lambda/4$ antennas as PIFA or monopole become not practical. Nevertheless when the operating frequencies of the devices are above 800–900 MHz these designs are valid since λ is shorter than 350 mm, so antennas with lengths of 87 mm ($\lambda/4$) can be packed into a small space [1]. However commercial FM spectrum is placed between 88 and 108 MHz (λ of 3061 mm at 98 MHz). At these frequencies, a design of a $\lambda/4$ monopole antenna would require a wire of 765 mm! In this case, a typical $\lambda/4$ monopole would not be a practical solution because

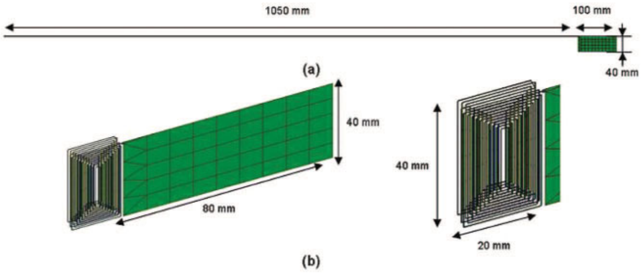

Figure 1 (a) Straight/reference monopole (wire length = 1050 mm, wire width = 0.5 mm), (b left) packed monopole (wire length = 2262 mm, wire width = 0.25 mm) and (b right) zoom of the antenna: 40 × 20 × 5 (h) mm^3. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]