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ANTENNAS ON HIGH IMPEDANCE GROUND PLANES: ON THE IMPORTANCE OF THE ANTENNA ISOLATION

G. Poilasne

University of California at Los Angeles, CA 90024, USA
Now at Photonic RF Corp., Los Angeles, CA 90024, USA

Abstract—Photonic Band-Gap materials (PBG) are periodic structures composed of dielectric materials or metal. They exhibit frequency bands for which no propagation mode can propagate. Unfortunately, they are bulky and their period has to be at least a quarter wavelength. One extension of the PBG structures is called High impedance ground planes (High Z). Their period is much smaller and they exhibit frequency bands in which no surface wave can propagate. Their electromagnetic characteristics make them particularly interesting for antenna applications. On the one hand, they reduce the interaction between an antenna and its backward surroundings, with smaller size than usual ground planes. On the other hand, they can be used for planar antenna solutions, as the radiating element can be placed right on the top of the ground plane. After a presentation of the steps which lead to High Impedance ground planes, the electromagnetic characteristics of such ground planes are presented. Then, some antenna applications illustrate the interest of such structures.

1. HIGH IMPEDANCE GROUND HISTORY

In the first part of this paper, the extension from photonic band-gap materials to high impedance ground planes is presented.

1.1. Photonic Band-Gap Materials

Photonic band-gap materials are periodic structures composed of dielectric or metallic materials. They exhibit frequency bands for which no propagation mode exists just like semi-conductors exhibit energy levels at which no electron can be [1]. This behavior is based on the periodicity of the dielectric constant of the structure. Only metallic structures will be studied in this paper.

Two kinds of metallic structures can be considered. Either the structure possesses a metallic continuity along the electric field direction or the structure is discontinuous. In the first case, the band structure of the PBG is composed of a first band-gap, linked to the metallicity, starting from 0 Hz until a cut-off frequency, called plasmon frequency. This frequency depends on the metallic photonic band-gap material (MPBG) physical characteristics, especially the period and the wire diameter or the strip width. A propagation band composed of Fabry-Perot propagation modes follows this band-gap. These modes correspond to the reflection on the interface of the finite structure. Then, band-gaps and propagation bands alternate. Those characteristics are also described in [2]. The reflection coefficient of

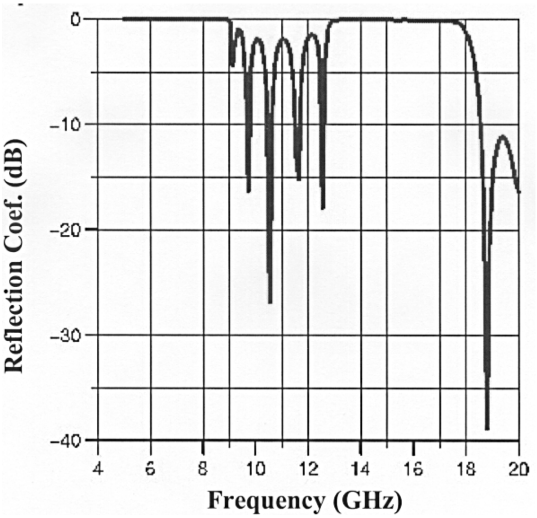

Figure 1. Reflection coefficient of a Photonic Band-Gap materials composed of continuous wires.

a MPBG structure composed of metallic wires in a square lattice is presented in Figure 1. A low level of reflection evidenced a propagation band whereas a band-gap corresponds to a high level of reflection. In the case of a discontinuous structure, as presented in Figure 2, the low frequency range belongs to a propagation band. Then, band-gaps and propagation bands alternate in the same way as they do for continuous structures. This duality between continuous and discontinuous structures can actually be used to switch from pass band to stop band, implementing active devices on the metallic structure. This application will not be developed but the reader can find related information in [3, 4].

In order to reduce the MPBG dimensions, the metallic strips or wires can be embedded inside a dielectric material. The period can be reduced by a factor equal to the square root of the dielectric constant of the material. This also corresponds to increase the capacitance inside the MPBG, which leads to metallo-dielectric structures.

1.2. Metallo-Dielectric PBG

Metallo-dielectric PBG's are an extension of discontinuous structures. By increasing the overall structure capacitance, it is possible to reduce the structure period and therefore the overall dimensions. In order to increase the capacitance, a material with a higher dielectric constant

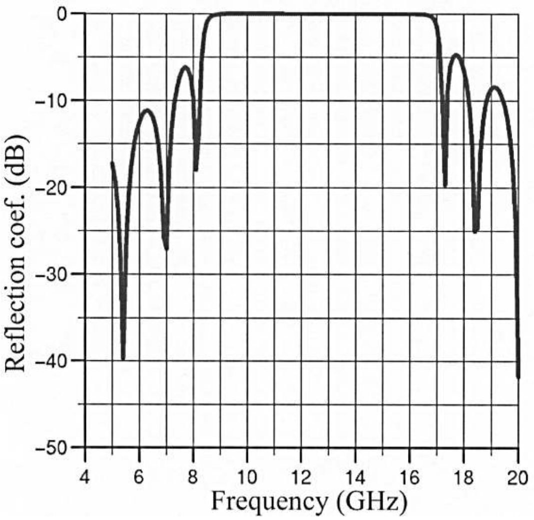

Figure 2. Reflection coefficient of a Photonic Band-Gap materials composed of discontinous wires.

is placed at the metallic discontinuities. The fringing capacitance is then increased. The period can even be more reduced, using facing capacitances. Different structures have already been presented [5, 6]. In this case, the period can be reduced to one thirtieth of the wavelength whereas it is about one half to a quarter wavelength in the case of classical MPBG structures. It has also been shown that such structures suppress surface wave [5]. This feature is particularly interesting for antenna applications. In fact, with regular ground planes, surface waves are diffracted by the edges, which creates ripples on the radiation pattern and increase the interaction between the antenna and its backward surroundings. Moreover, it has been shown that the suppression of the surface wave depends only on the surface of the metallo-dielectric PBG and not on the volume of the structure. Therefore, just a simple ground plane with a periodic structure on its top is needed rather than a full PBG structure.

1.3. High Impedance Ground Planes

Corrugated surfaces are a one-dimensional form of high impedance surfaces introduced years ago [7]. Wavelength corresponding to four times the depth of the slits can not propagate along the surface. In fact, for the corresponding frequency, the short circuit at the bottom of the slit is seen as an open circuit, a quarter wavelength above. Therefore,

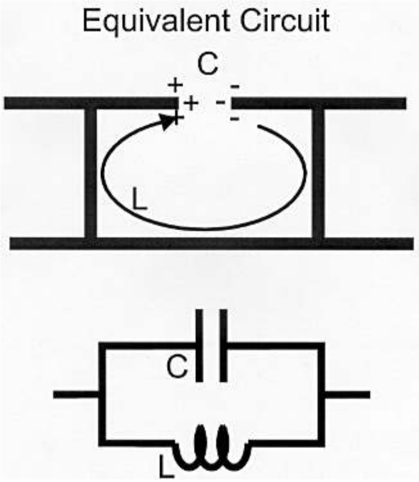

Figure 3. 2 Layer high impedance ground plane and equivalent circuit model.

the metallic blades appear infinite and the wave can not propagate.

High impedance ground planes are two-dimensional periodic structures, which are often called "mushroom field." They are composed of a pattern of patches all connected to a metallic ground plane. As presented in Figure 3, one period of the structure is equivalent to a parallel L-C circuit. This L-C parameters control the center frequency at which the ground plane exhibits a high impedance. In this case, the capacitance corresponds to the fringing capacitance. The inductance is proportional to the thickness of the ground plane. The bandwidth mainly depends on the board thickness. A periodicity of one tenth of the free space wavelength can be obtained. Those results and many others can be found in [8]. As presented for metallio-dielectric, increasing the capacitance can reduce the periodicity. Overlapping the metallic parts and inserting a dielectric material in between is one solution to reduce the periodicity (Figure 4). In that case, the periodicity can be as low as one thirtieth of the wavelength.

2. ELECTROMAGNETIC CHARACTERISTICS OF HIGH IMPEDANCE GROUND PLANES

As introduced previously, the first version of high impedance surfaces is known as corrugated surfaces. High impedance ground planes are their extension to two dimensions. This brings different characteristics, which are described in this section.

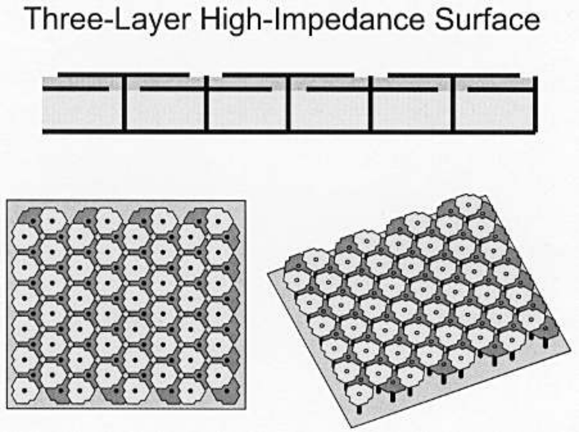

Figure 4. 3 Layer high impedance ground plane.

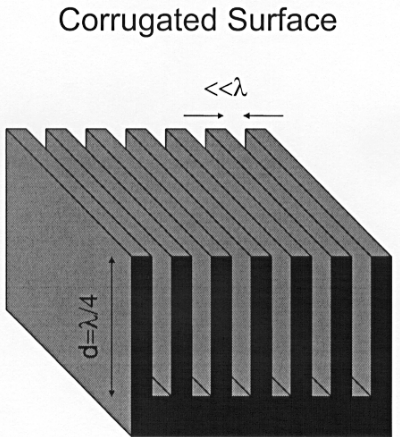

Figure 5. Corrugated surface [7].

2.1. Corrugated Surfaces

Corrugated surfaces are one-dimensional periodic structures as presented in Figure 5. But the period is not so important to determine the resonant frequency. This frequency depends on the depth of the slot in the ground plane. This depth corresponds to a quarter wavelength. The interest in such a structure is the suppression of the surface waves. They are already used in some applications such as very high precision global positioning system, GPS, antennas, which are presented later. Unfortunately, corrugated surfaces are rather large and thick, about

50 mm for the GPS frequency, as the depth of the slots has to be a quarter wavelength. By increasing the capacitance between the periods or slots of the corrugated surfaces, it is possible to reduce the overall dimensions of the structure, especially the thickness, about 12 mm in the solution presented later, keeping the same characteristics [8].

2.2. High Z Equivalent Circuit Model

An easy way to understand high impedance ground planes is to look at their equivalent circuit model. Figure 3 presents one period of a high impedance ground plane with its equivalent circuit model. The period is equivalent to a parallel L-C circuit, where the capacitance is proportional to the period and the inductance is mainly proportional to the thickness of the ground plane, considering that the post is small regarded to the period. Then, using the filter theory, the resonant frequency of the structure is the inverse of the square root of the product of the inductance by the capacitance $f = \frac{1}{LC}$. The relative bandwidth only depends on the thickness. These results are very well described in [8].

Even if this equivalent circuit model is quite accurate to design high impedance ground planes, it has some limitations. The main one comes from the fact that the formula used in [8] are for a structure with a small period regarded to the wavelength. Therefore, the expression of the inductance and the capacitance are not valid anymore when the period gets to large, but the results obtained often remain within a 5 to 10% error when compared to measurements, which is accurate enough for general purpose designs.

2.3. High Z Electromagnetic Characteristics

High impedance ground planes have two important characteristics. The first one corresponds to the fact that they exhibit a high impedance to an incident plane wave. For a regular metallic reflector, the phase of the reflection coefficient is equal to 180 deg as the electric field cancels on the metallic surface (short circuit). In the case of a High Z (high impedance ground plane), the phase of the reflection coefficient remains the same at the resonant frequency. This is actually one way to characterize high Z as presented in Figure 6. When considering a ground plane, it is possible to measure the phase of the reflection coefficient using a network analyzer. This method has already been presented in [8]. It consists in exciting a High Z with a plane wave and by measuring the phase normalized by the measurement of a regular metallic reflector. Results presented in Figure 6 show that the phase of the reflection coefficient is equal to +180 deg for the low frequencies,

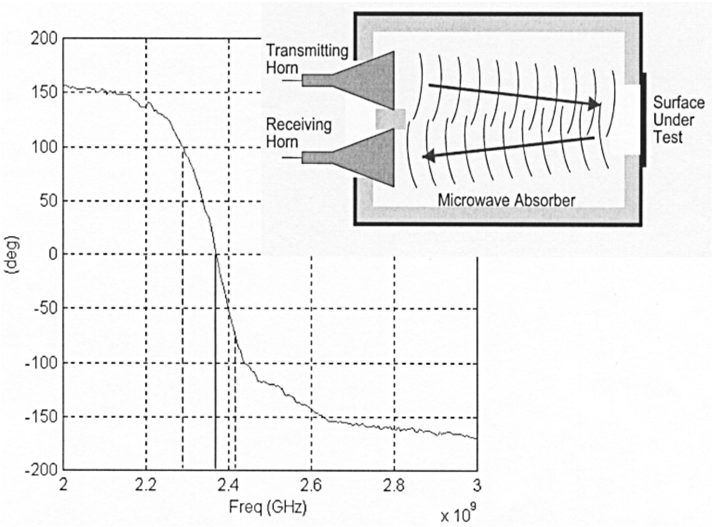

Figure 6. Phase characterization of a high impedance ground plane.

then it decreases and is equal to 0 deg at the resonant frequency to be equal to -180 deg at high frequencies.

The second characteristic corresponds to the suppression of the surface waves. This can be characterized in two ways, using numerical simulations to calculate the band structure, or experimentally using probes to excite TM and TE modes. Figure 7 presents the band structure of a High Z. In the band structure extracted from [9], the low frequency range below the first dotted line corresponds to TM modes which can propagate inside the structure with different wave vectors. The second dotted line corresponds to the first TE modes propagating inside the surface. The frequencies between those two lines are within the band-gap. No mode propagates inside the structure. Outside the structure, TE modes extend in free space as shown by the curve above the TEM line. Which means that the modes would not propagate inside the structure, but would couple to free space modes. As said previously, the band-gap limits can also be obtained experimentally by measuring the transmission coefficient between two probes. For example, a small dipole can excite TM modes with a large **k** vectors and a small loop can excite TE modes. The experimental results presented in Figure 8 show that within a certain frequency range, between 2.3 GHz and 2.7 GHz, no mode can propagate, as the transmission between both probes drops with more than 20 dB. The accurate limits are the TM limits for the low frequencies and the TE

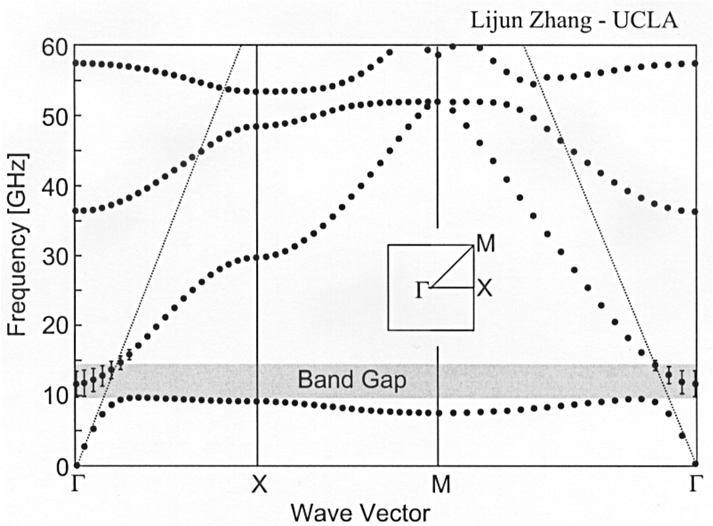

Figure 7. Dispersion diagram of a high impedance ground plane, extract from [9].

limits for the high frequencies. This is due to the fact that, TM modes are cut-off by the band-gap, the other edge is due to the excitation of leaking TE modes. As well as for TE modes, at low frequency, no TE mode should be excited in the substrate, but the probes are not perfect, therefore some TM modes are also excited.

These two characteristics are very interesting for antenna applications. As the ground plane is high impedance, it is possible to place the antenna right on the top rather than a quarter wavelength away as it is the case for metallic ground planes. Therefore, it is possible to use such ground planes for planar and very compact applications. For regular ground planes, the antenna excites surface waves, which are diffracted by the edges and create ripples on the frontward part of the radiation pattern and a backward radiated field. The suppression of the surface waves avoids ripples and reduces the backward radiated field. This reduction is all the more important as it reduces the interaction between the antenna and its backward environment.

3. STUDY OF A HIGH Z ANTENNA

In this section, the electromagnetic characteristics of an antenna flushed on a High Impedance ground planes are studied, especially the return loss and the radiation pattern. Each of these characteristics,

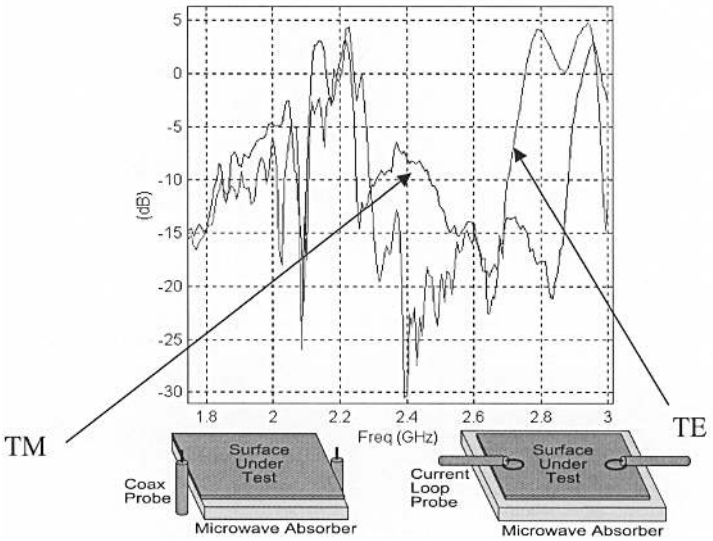

Figure 8. Experimental results of surface wave suppression.

return loss and radiation pattern, actually corresponds to each characteristics of the High Z, respectively the high impedance or magnetic surface behavior and the suppression of the surface waves.

3.1. Return Loss

The magnetic behavior of a high impedance ground plane allows to lie over the ground plane a radiating element with a very a distance between the antenna and the top part of the ground plane of about 1 mm. With a straight dipole, the impedance is too capacitive, this can be observed on the Smith chart, by referencing the phase right at the connection point of the antenna. By introducing a kink in the shape of the dipole, it is possible to compensate this capacitance. The kink actually behaves like an inductance. Unfortunately, no law gives the exact shape of the kink needed. Figure 9 shows the shape of an antenna working between 2.4 GHz and 2.5 GHz, the so-called ISM band, Instrumental, services and medical band. The dimensions of the ground plane are 50 mm by 25 mm. The figure also shows the kink on the monopole. The radiating element is printed on a layer of FR4 of 30 mil thick. Figure 10 presents the return loss when the antenna is optimized. A bandwidth of 8 to 10% can easily be obtained. The frequency range exactly corresponds to the resonant frequency range of the board.

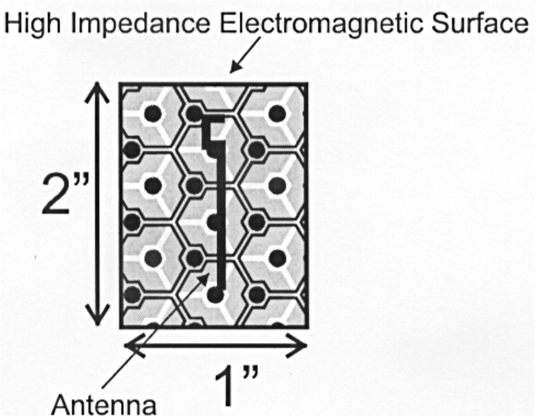

Figure 9. Shape of the antenna on the high impedance ground plane working inside the ISM band.

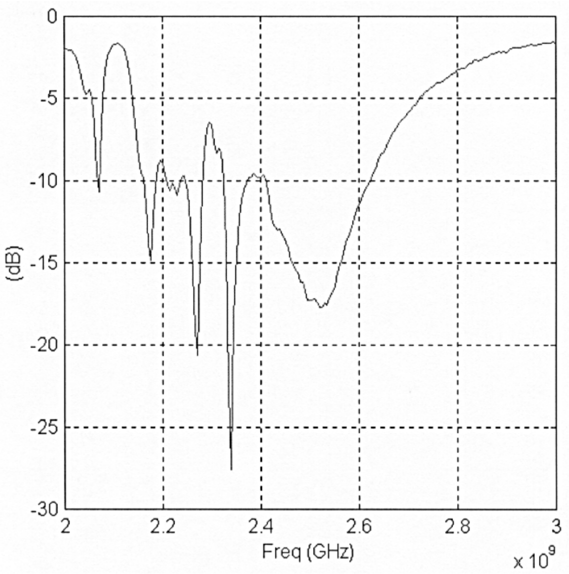

Figure 10. Return loss of the antenna working within the ISM band.

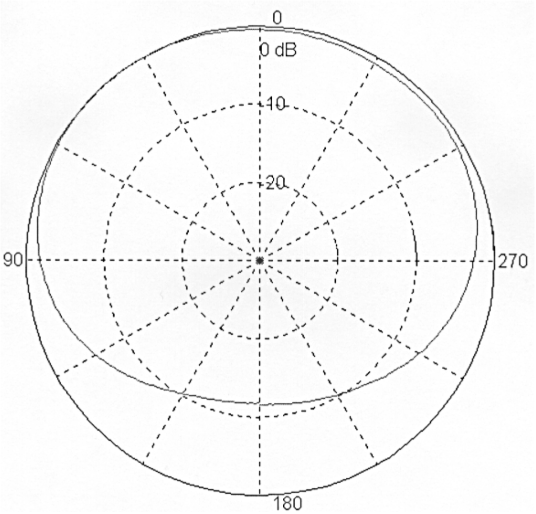

Figure 11. H-plane radiation pattern of the antenna working within the ISM band.

3.2. Radiation Pattern

Figure 11 presents the experimental H-plane radiation pattern of the monopole with the kink, laid down on the 50 mm by 25 mm high impedance ground plane. The radiation pattern is very smooth with a front to back ratio of 10 dB. Those two characteristics are the proof that surface waves are great reduced. The ripples a suppressed as there is diffraction by the edges. Moreover, such a value of front to back ratio is usually obtained with a ground of one wavelength by one wavelength. In this case, the ground plane is 0.4 by 0.2 times the wavelength. This shows that the antenna will have very little interaction with the backward environment. Such a characteristic is very important for different applications described in the following applications.

4. INTEREST OF HIGH Z ANTENNAS FOR HIGH PRECISION GPS

The first application described here is the high precision GPS. This application and the existing solutions are first described. Then, some results obtained with high impedance ground will be given.

4.1. High Precision GPS Applications

High precision GPS is a very promising solution for many applications. By determining very accurately the phase of the signal, it could be possible to have the position any kind of car or trucks with an accuracy of about a few millimeters. With such a precision, the human presence could be suppressed in many applications.

To obtain such accuracy, the antenna has to cover an angle from −60 deg to +60 deg as the satellites in within this range of coverage. But to avoid the multipath, which introduces errors in the measurement, the backward radiated field has to be at least 20 dB below the frontward field. Such requirements can never be obtained if the antenna excites surface waves.

4.2. Existing Antennas

A solution already exists and starts to be used by some companies. It consists of a choke ring within the middle a patch antenna. The choke ring is a kind of corrugated surface shaped in order to go all around the patch antenna. Results obtained with this kind of antenna are very good but the antenna is heavy, a couple kilograms and the cost is really high, about $2000, as the choke ring is modeled in the bulk metal. High impedance ground planes may be a solution to reduce the cost and the dimensions. In fact, high Z can be made of light dielectric material like foam, for a cost of about $200.

4.3. Potential for High Z Antennas

A two-layer structure has been designed in order to work at the GPS frequency. The measurement of the phase of the reflection coefficient shows that the structure resonates at 1.55 GHz as shown in Figure 12. Then, a loop has been placed over the high impedance ground planes and matched to the GPS frequency. The radiation pattern has been measured and is presented in Figure 13. It exhibits a very smooth and regular shape with a −60 deg to +60 deg angular coverage and with a front to back ratio of more than 25 dB.

Still, many issues remain in order to have a good High Precision GPS antenna, the variation of the phase along the angular coverage is one of these. But these first results are very encouraging to pursue further more the research.

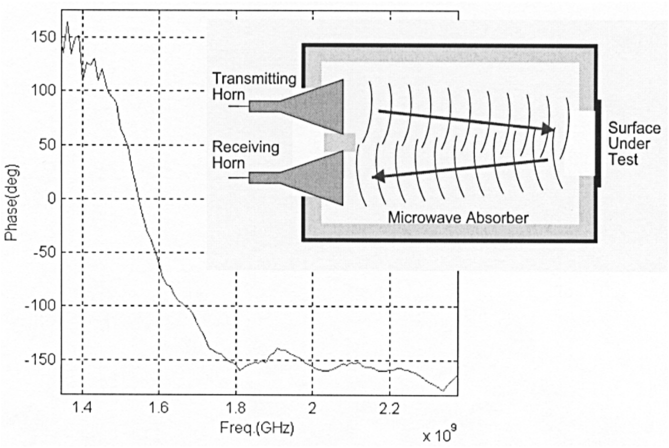

Figure 12. Phase of the reflection coefficient of the structure design for GPS.

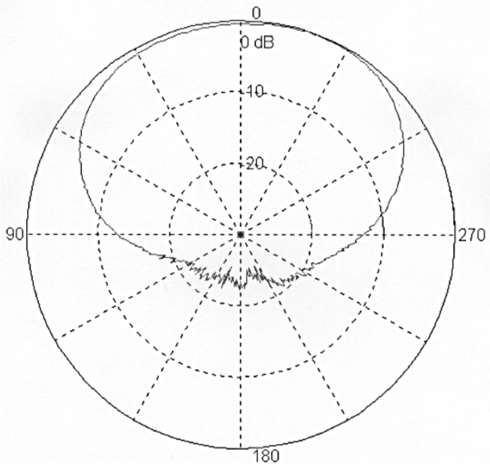

Figure 13. Radiation pattern of the High Precision GPS antenna.

5. APPLICATION TO DATA AND VOICE TRANSMISSION

As the world goes wireless, the data and voice transmission are going to be implemented in many applications. At lot of attention is concentrated toward Bluetooth and wireless local area network, the first implementations of such systems in everyday life. Moreover, for older applications like cell-phones, the specific absorption rate, SAR, is particularly important. The shielding offered by the antenna is essential.

5.1. Shielding of the User Head

The interaction between an antenna and the user head is a popular subject as it concerns public health. On the other point of view, the energy lost in the user head does not participate to the transmission. This loss can even be larger as the interaction may have an influence on the matching of the antenna and reduce the radiated power. Therefore it is very important to reduce the backward radiated field.

The suppression of the surface waves is one way to reduce this kind of interactions. Some experiments have been made comparing a dipole to the antenna presented in Section 3. The dipole has been measured in free space and then near an absorber, in this case a jar of water. Then, the same measurements have been performed using the antenna described in Section 3.

Figure 14 shows the different measurements performed. It shows that when the dipole is placed near the absorber, not only the head absorbs half of the energy but also the mismatch due to the interaction between the absorber and the antenna reduces by 2 dB the gain in the main direction. In the case of the High Z antenna near the absorber, the gain on the main axis is 3 dB higher than the dipole in free space (no field radiated backward). This gain remains the same when the antenna is placed near the absorber. This shows the advantage of an antenna, which has a limited interaction with its backward environment.

5.2. Interaction with the Case

The shielding is not only important in the case of applications where the user head is involved. It is also important when a piece of equipment is involved. For example, an antenna placed on the side of a laptop interacts with the screen and the case. This interaction may detune the antenna, therefore reduce the overall efficiency and may create some ripples on the radiation pattern. Figure 15 shows the radiation pattern obtained with a commercialized antenna and a High Z antenna. The commercialized antenna is a stub printed on a piece of dielectric material. The high impedance ground plane antenna radiation pattern is smoother and the overall efficiency is 3 to 4 dB higher than the commercialized one. The efficiency is ideally calculated by integrating the power radiated over the 4π ste- radiant. In the present case,

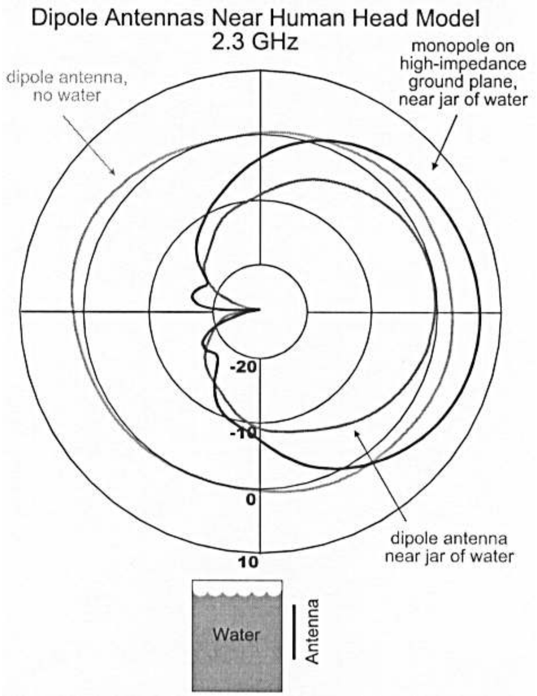

Figure 14. Dipole radiation pattern away and near a jar of water and High Z antenna radiation pattern near a jar of water.

E-plane and H-plane radiation patterns, co-polarization and cross-polarization, have been measured and integrated. The experience shows that those results give a fair result, within 1 dB of the full 3D measurement.

5.3. Bit Rate Measurements

This difference of efficiency clearly appears in the bit rate measurement. To make such a measurement, a file is selected and transferred from one computer to another. The transfer is timed in order to obtain the active or effective bit rate. The configuration can be changed in order to obtain another measurement point, for example the distance between the two laptops can be increased. Such measurements have been performed using the commercialized Home RF system associated with the antenna previously tested. Figure 16 shows the bit rate obtained and the configuration used. For a short range, the bit rate is the same in both cases. But then, as the distance increases, the bit

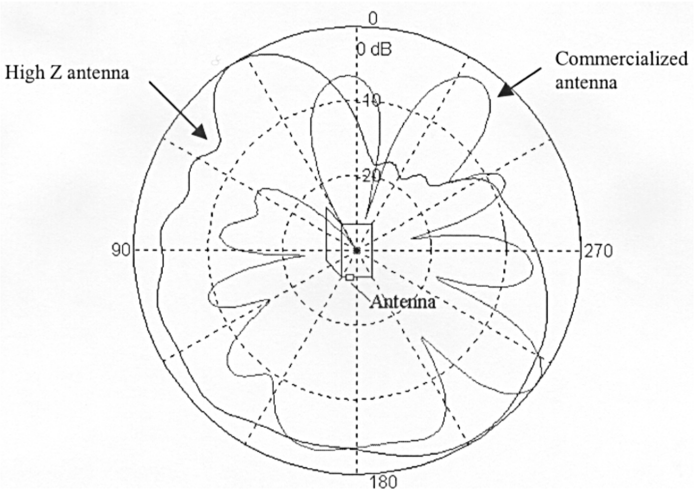

Figure 15. Radiation pattern of the commercialized and the High Z antenna mounted on the side of the laptop.

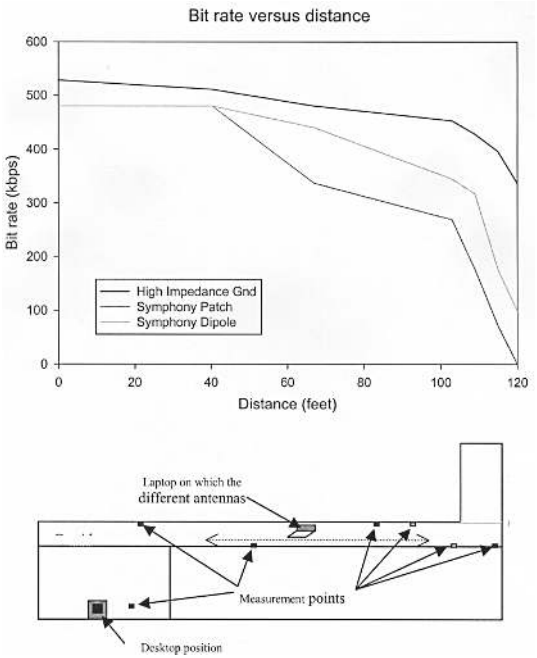

Figure 16. Bit rate measurement versus distance between the two laptops and measurement configuration.

rate of the commercialized antenna drops. The bit rate obtained with the high Z antenna remains constant and then drops slowly until the corner of the corridor where it finally completely vanishes. This figure also shows the results obtained with a dipole on the top of the screen of the laptop. These results are already enough to show the advantage of a more isolated antenna. The improvement appears not only in the bit rate but also in the distance range. For some applications like Bluetooth, the range may be an issue, therefore highly efficient and highly isolated antennas are required.

6. CONCLUSION

Photonic band-gap materials and more recently high impedance ground planes have found most of their radio-frequency applications in the antenna field. High impedance ground planes are particularly interesting as they offer planar solutions. Their electromagnetic characteristics allow reducing the interactions between the antenna and its backward environment. Measurements in an anechoic chamber show that by improving the isolation of the antenna it is possible to improve the overall efficiency by a few decibels when the antenna is placed in its real world environment, for example inside a cell-phone or on the side of a laptop. These results have also been validated in a bit rate measurement. The improvement of the efficiency allows obtaining a better bit rate and/or a better distance range.

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