

Modeling and Analysis of Electromagnetic Field Distribution in Vicinity of Patch Antennas at Millimeter-wave Frequencies

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Abstract

In this work, the spatial electric and magnetic field distributions in the vicinity of a rectangular patch antenna, excited with the fundamental transverse magnetic (TM) resonance mode, are analyzed. The results yield physical insight into the lateral decay of the dominant field components with distance from the antenna. Furthermore, the effects of the dielectric substrate, dielectric losses and the antenna feed on the field and power decay are individually quantified. Based on the results obtained, design guidelines for compact component placement with the aim of reducing undesired electromagnetic coupling can be derived.

Keywords: Planar antenna integration, millimeter-wave, electrical design and modeling.

1. Introduction

The increasing demand on RF/wireless systems for higher data-rates is pushing for the usage of frequencies in the millimeter-wave range with large spectrum availability. Applications include WLAN/WPAN, video streaming and data synchronization.

Planar antennas such as patch, dipole and slot configurations are popular candidates for lower millimeter-wave applications [1]-[3]. These antennas can be integrated on the same substrate with other electronic components, potentially allowing a high degree of system miniaturization.

The ideal integrated antenna is electromagnetically isolated from the package and board i.e., the signal fed to the antenna is radiated into a space wave with an efficiency of 100 %. Also, the antenna parameters, such as impedance and radiation patterns, are independent of the antenna's environment. However, in reality, the electromagnetic interactions between the antenna, the package/board, as well as other system components cannot be neglected. Undesired electromagnetic coupling may occur in the near- and far-field regions of an excited antenna.

Achieving high integration densities entails compact placement of package/board components together with the antenna, potentially giving rise to high amount of coupling. Undesired coupling potentially jeopardizes electromagnetic reliability (EMR) if not dealt with in the design phase.

Surface waves, excited by planar antennas in the substrate, are considered a primary cause for undesired coupling at millimeter-wave frequencies [4]. Consequently, configurations for surface wave suppression (e.g., EBG structures) have been proposed [5]-[6]. However, shielding configurations are space consuming. In order to utilize the available package/board space efficiently, it is important to determine whether additional shielding is required and where in the vicinity of the antenna components can be safely placed. On the other hand, coupling at the near-field of the antenna is predominantly capacitive or inductive in nature, also potentially taking influence on the antenna parameters, such as the impedance and radiation characteristics. Also, since the antenna is operated at resonance, the electric and magnetic fields are particularly high compared to

the fields excited by other non-resonant components in the vicinity (e.g., transmission lines). As a result, an integrated and excited antenna needs to be considered as one of the main aggressors with a high potential coupling to victims. For these reasons, an in-depth study of the field and power decay in the vicinity of an integrated antennas is necessary with the aim of deriving design guidelines.

To date, much research effort have focused on methods to calculate the electromagnetic field distribution in the vicinity of planar antennas. A general model of a microstrip-type antenna is to consider an elementary horizontal electric dipole (HED) on top of a grounded substrate. Green's functions for HED source have been derived forming the basis for Method of Moments (MoM) formulations [7]. Although accurate, Green's functions comprise Sommerfeld integrals and their integration requires numerical effort or asymptotic approximation. Alexopolous *et al.* have derived closed-form analytical expressions for the far-fields of a HED using transmission line analogy [8]. The near-fields are, however, not included in this approximation. Concerning patch antennas, a simple yet practical analytical model is the magnetic line current model, which delivers accurate results for far-field radiation patterns of patch antennas [9]. Ojha *et al.* have reported that the near-field of rectangular patch antennas can also be determined from magnetic line currents if an incremental length is added to account for the fringing fields [10]. Hammer *et al.* proposed a radiation model based on the equivalence principle and an aperture model for microstrip patch antennas [11]. This model also includes higher order modes and substrate effects. Dubost *et al.* used the volume equivalence principle and an analytical expression for the voltage distribution on the rectangular patch antenna to determine the total electric field in the substrate [12]. Although all these techniques yield accurate and efficient models, a quantification of the field and power decay near the antenna and an analysis of the contributions of the dielectric substrate, dielectric losses and the antenna feed has not been conducted.

Therefore, in this contribution, the spatial decay of electric and magnetic fields as well as the power density in the lateral plane next to patch antenna (regions where other package/board components are potentially placed) is studied with the aid of numerical full-wave simulations. Furthermore, the effects of the dielectric substrate, dielectric losses and the antenna feed on the field and power distributions are quantified.

2. Analysis of Excited Antenna Fields and Power

Figure 1 shows a geometry of the patch antenna on a grounded substrate which is used in the analysis throughout his paper. The patch length l and patch width w are $0.246 \lambda_0$ (4.1 mm) and $0.24 \lambda_0$ (4 mm), respectively. The substrate has a height of $h=0.021 \lambda_0$ (350 μm) and a relative dielectric constant $\epsilon_r=3.66$. λ_0 is the free-space wavelength at antenna resonance. The patch antenna is excited with its fundamental TM_{001} resonance mode.

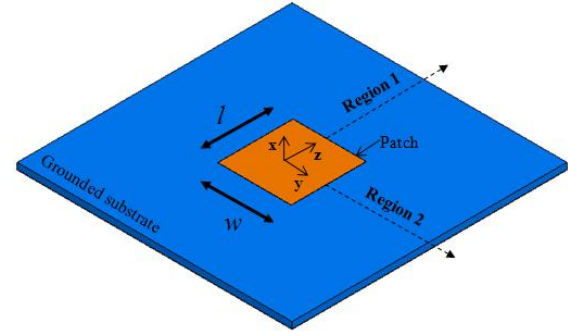


Figure 1: Model of patch antenna on a grounded dielectric substrate used in the analysis. Note that the origin of the coordinate system is at the center of the patch.

Additionally, two regions are defined which are oriented in the two principle planes of the patch antenna.

- Region 1 (in E-plane): $x=0, y=0, z>0$
- Region 2 (in H-plane): $x=0, y>0, z=0$

Since the antenna is symmetrical in both principle planes, it is sufficient to define these regions from the center of the patch since the field decay on the other side would be same.

The simulations were conducted with Ansoft HFSS v11, a 3D full-wave electromagnetic field solver in the frequency domain based on the Finite Element Method (FEM). The adaptive mesh refinement process was used to ensure stability of the computed solution. At this stage the influence of the feeding line is neglected. Therefore, the antenna is excited with a horizontal current excitation at the center of the patch i.e., a z -directed current. In Section 2.3 the influence of the antenna feed is quantified.

The simulation predicts a resonance frequency of 18 GHz ($\lambda_0=16.67$ mm) for this configuration with the above given physical dimensions. This matches well with the analytical design expressions found in [13] for the physical geometry of the patch.

The simulated electric and magnetic field distribution are evaluated in the vicinity of the patch antenna. Figures 2 and 3 show the distributions of the electric and magnetic fields on the ground plane underneath the substrate. Since the

absolute values of the field strengths are not of concern here, the results are normalized.

Based on the cavity model, the electric and magnetic field distributions underneath the patch antenna can be approximated for the TM_{001} resonance mode. The cavity model neglects the fringing

The electric field of this mode is x -directed and sinusoidal along the non-radiating apertures and constant along the radiating apertures [13].

$$E_x = E_0 \sin\left(\frac{\pi}{l} z\right)$$

At the antenna resonance frequency a standing wave is excited on the patch, the magnetic field underneath the patch antenna is 90° out of phase with the electric field.

$$H_y = H_0 \cos\left(\frac{\pi}{l} z\right)$$

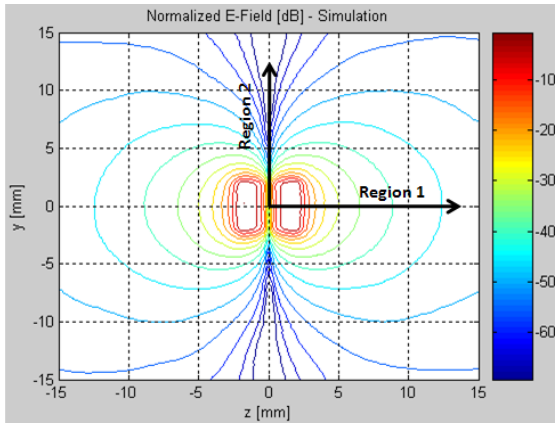


Figure 2: Distribution of electric field excited by patch antenna on the ground plane.

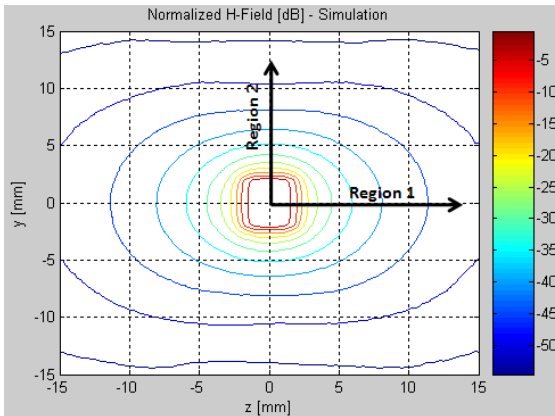


Figure 3: Distribution of magnetic field excited by patch antenna on the ground plane.

On the ground plane only normal electric and tangential magnetic field components exist i.e., the normal E-field component E_x and the two tangential field components H_y and H_z . Furthermore, as a

result of the electric current orientation on the patch, ideally the z -component of the magnetic field H_z is zero or small compared to H_y . The electric field is zero in the plane at $z=0$ because of symmetry. The equipotential lines of the magnetic field decay are quasi elliptically around the antenna. It is observed that the decay of the H-field is slower in region 1 than in region 2. This effect, resulting from surface wave excitation and propagation, is studied in more detail in the following section.

2.1. Quantification of Substrate Influences

The influence of the dielectric substrate plays a crucial role with regards to the field and power distribution in the vicinity of the antenna. A grounded dielectric substrate is capable of guiding electromagnetic waves in the form of surface wave modes. The fundamental surface wave mode is a TM_0 mode and propagates down to DC [14]. With increasing frequency more power is guided along the air/dielectric interface potentially causing increased coupling to other components sensitive to the reception of surface waves. The next higher-order surface wave mode is the TE_1 mode. Its cut-off frequency f_c for typical substrate configurations is generally high enough so that it can be neglected.

$$f_c = n \frac{c_0}{4h \epsilon_r - 1}$$

The mode number is n , h is the substrate height, c_0 is the speed of light and ϵ_r is the relative dielectric constant of the substrate. Considering a typical RF substrate with $h=350 \mu m$ and $\epsilon_r=3.66$, the cut-off frequency for the TE_1 mode is ~ 161 GHz.

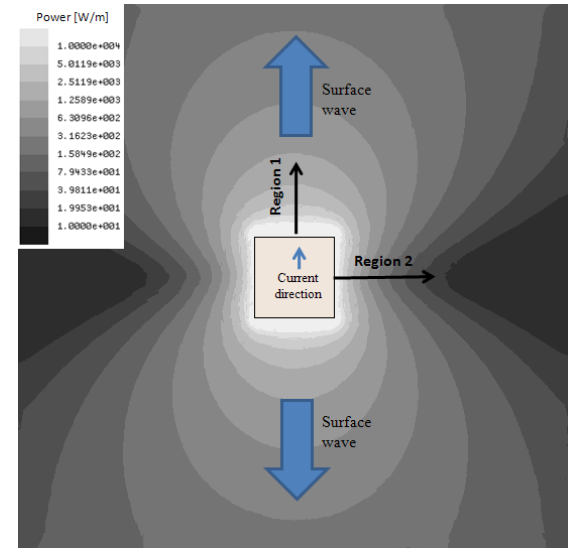


Figure 4: Simulation of the distribution of real power density excited by patch antenna on top of substrate with 1 A current excitation.

In Figure 4, a plot of the simulated real power density is shown. The real power density is given by the real part of the Poynting vector. It is simulated and evaluated on top of the substrate of the antenna configuration in Figure 1. The region on top of the substrate is of interest, since other package/board components can potentially be placed there.

Most of the power density on the substrate is launched in the region 1 (see Figure 1) i.e., in the direction of the electric current on the patch (normal to the radiating apertures). The power propagation is primarily in the form of a surface wave mode. The ripples seen in the plot are the result of substrate edge reflections and spurious reflections caused by non-ideal PML boundary conditions.

In order to demonstrate the increase in power density in region 1, as a result of the surface wave propagation, a comparison between the power density for the cases with and without the influence of the dielectric substrate is conducted. For reasons of better comparison, the same patch geometry was used in the simulations. The only difference is that the relative dielectric constant is set to one for the second case. The resonance frequency of the patch configuration in Figure 1 in the case that $\epsilon_r = 1$ is 32 GHz, as predicted by simulation. Again, a current at the center of the patch is used as an excitation. Figure 5 shows the results of the comparison of the real power density in region 1.

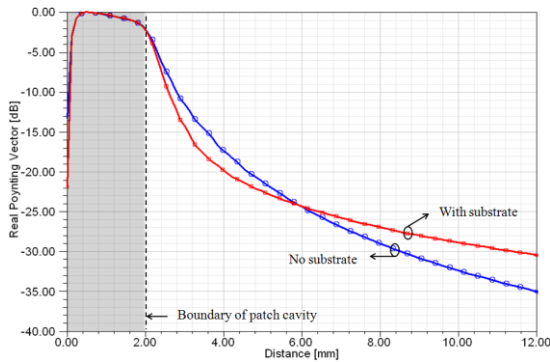


Figure 5: Comparison of power density (magnitude of the real Poynting vector) in region 1 of the patch antenna with and without a substrate. The distance is taken from the patch center.

It is observed in Figure 5 that at close distance to the antenna, the laterally radiated power is less confined to the substrate. Beyond a distance of approximately 4 mm from the patch edge the surface wave power increases the lateral radiation. This distance corresponds to approximately $\sim 0.24 \lambda_0$. Beyond this distance, the reactive power density has decayed and the surface wave can be said to be launched.

Beyond the distance where the surface wave is launched it is observed that the power density decay is roughly ~ 10 dB/decade. This corresponds to $1/r$ (r is the distance from the antenna). In the case that no substrate is present and, hence, no surface wave is excited, the power density decays faster with ~ 20 dB/decade. This corresponds to $1/r^2$. To illustrate this, Figure 6 shows a logarithmically scaled distance axis (x axis) of the plot in Figure 5 for the values between 5 mm and 10 mm.

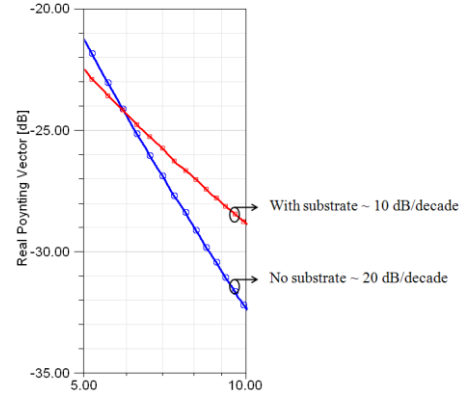


Figure 6: Illustration of power density decay with and without a substrate. Note that the x axis is scaled logarithmically.

The slower decay of the surface wave can be intuitively explained as follows: Since the surface wave is a guided wave, the power is distributed on a cylindrical surface ($\sim r$) around the antenna. The space wave power, however, is distributed on a spherical surface ($\sim r^2$) around the antenna. As a result, the presence of the substrate causes the power density to decay slower with distance from the antenna.

As shown in [15], the TM_0 surface wave mode shows inductive behavior. Its impedance at the air/dielectric interface depends on the propagation constant k_z .

$$Z_{TM} = \frac{k_z}{\omega \epsilon_0 \epsilon_r}$$

Therefore, the quotient of magnetic field and electric field of the surface wave mode is higher than that of a free-space wave mode. As a result, it can be concluded, that TM surface waves mode on grounded substrates will couple energy to components primarily through the magnetic field.

To illustrate the inductive behavior of the TM surface wave mode the decay of the magnetic field is studied in region 1 at the radiating apertures and compared to the case without the substrate. The results are depicted in Figure 7.

For close distance from the patch edge, the magnetic field of the antenna with the dielectric substrate is less confined to the substrate. Only

beyond a distance of 6 mm ($\sim 0.36 \lambda_0$) from the patch edge is the magnetic field strength larger as a result of the excited surface wave. E.g., at a distance of 10 mm from the patch edge the magnetic field strength is already ~ 4 dB higher as a result of the presence of the substrate.

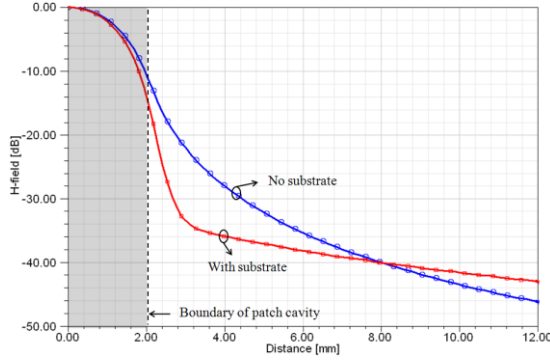


Figure 7: Comparison of magnetic field on the ground plane in region 1 of the patch antenna with and without a substrate. The distance is taken from the patch center.

It is also observed in Figure 7 that the magnetic field underneath the patch resonator i.e., for distances < 2 mm from the patch center, varies roughly as predicted by the cavity model i.e., sinusoidal.

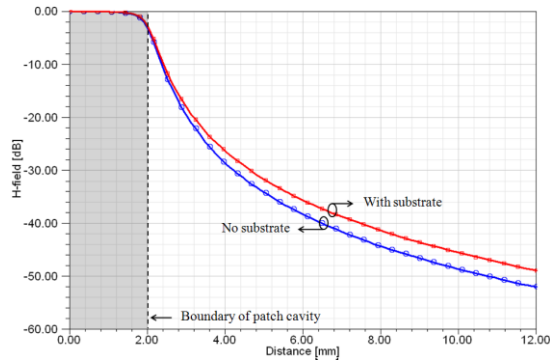


Figure 8: Comparison of magnetic field on the ground plane in region 2 of the patch antenna with and without a substrate. The distance is taken from the patch center.

Next, the spatial magnetic field decay in region 2 is analyzed and the results are depicted in Figure 8. Again a comparison with and without the dielectric substrate is done. It is observed that field strength is only ~ 4 dB slightly larger for the antenna with the dielectric substrate. Also, the field decays are similar. As a result, it can be concluded that no surface wave is excited in this region.

As predicted by the cavity model, the magnetic field underneath the patch (< 2 mm) is constant with varying y .

Figure 9 shows the simulation results of the electric field decay in region 1. As was observed in

Figure 2, the electric field on the ground plane in region 2 is ideal zero (asymmetries caused by the excitation or antenna feed are neglected). The interesting effect observed in Figure 9 is that the magnitude of the electric field strength is smaller in the case of that the dielectric substrate is present.

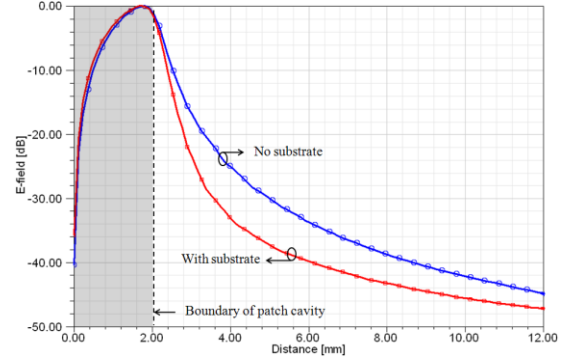


Figure 9: Comparison of electric field on the ground plane in region 1 of the patch antenna with and without a substrate. The distance is taken from the patch center.

In summary, the effects of the dielectric substrate cause an increase in power density as a result of the excited TM_0 surface wave mode. This causes the magnetic field strength to increase near the ground plane, particularly in region 1.

2.2. Quantification of Dielectric Losses

Dielectric losses contribute significantly to the reduction of the efficiency of planar antennas. Dielectric losses increase roughly proportional with the frequency f whereas conductor losses increase only roughly with the square root of f , as a result of the skin effect [13].

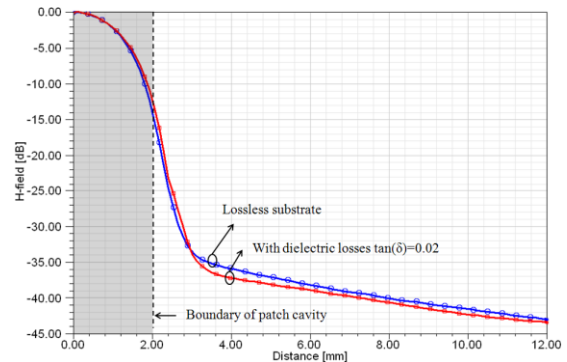


Figure 11: Comparison of magnetic field on the ground plane in region 1 of the patch antenna with and without dielectric losses in the substrate. The distance is taken from the patch center.

To study the influence of dielectric losses on the excited antenna fields the same patch antenna configuration as in Figure 1 was simulated and analyzed. This time, a dielectric loss tangent $\tan(\delta)$ is considered and the results are compared to the

case with no dielectric losses. It was found that a dielectric loss tangent e.g., $\tan(\delta)=0.02$ which is typical for a lossy organic substrate, negligibly effects the resonance frequency. To illustrate this, Figure 11 shows the simulation results and a comparison of the magnetic field decay in region 1 of the patch antenna.

The decrease in magnetic field strength caused by the additional dielectric losses is ~ 1 dB for distances >1 mm from the patch edge in the case of $\tan(\delta)=0.02$. Therefore, assuming that the same power is fed to the antenna, the dielectric losses do not significantly cause a decreased magnetic field strength.

2.3. Quantification of Antenna Feed

In this section the influence of the antenna feed on the field and power distribution is studied. For this purpose, a probe feed is designed to feed the antenna. Figure 10 shows the configuration of the probe feed.

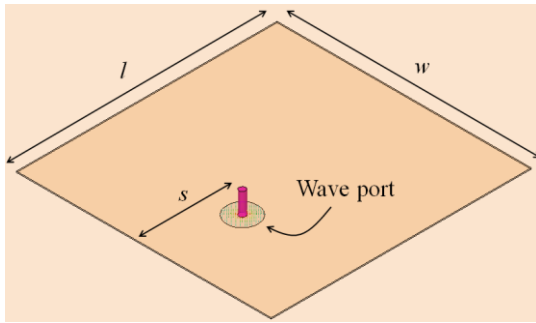


Figure 10: Configuration of the coaxial probe feed and the inset length s to match the antenna to 50Ω .

The probe feed comprises a via connected to the patch antenna and isolated from the ground plane. A good impedance ($Z_{in}=Z_0=50 \Omega$) match for the excitation of the TM_{100} mode is obtained by placing the feeding point between the center and the edge of the patch, roughly according to the following approximation for the input impedance of patch antennas [13].

$$Z_{in} \approx Z_{edge} \cos^2\left(\frac{\pi}{l} z\right)$$

The probe feed offset s was determined as 0.5 mm by simulations. The probe feed causes the resonance frequency of the antenna to drop down from 18 GHz by $\sim 1.5\%$ as a result of the additional inductance.

Figure 12 shows the simulation results to quantify the influence of the antenna feed on the decay of the magnetic field with distance. It should be noted that the presence of the antenna feed causes a current discontinuity at the feeding point

underneath the patch antenna. Concerning the magnetic field strength, it is observed that the field strength is ~ 3 dB higher in region 1 after a distance of about 1 mm from the patch edge. Therefore, the feed does not influence the near-field significantly, but rather the surface wave power which is launched into the substrate. The probe feed itself can intuitively understood as a vertical electric dipole underneath the patch. The current on the feed itself is particularly large, resulting from the resonance condition on the patch and the impedance matching to the 50Ω feed.

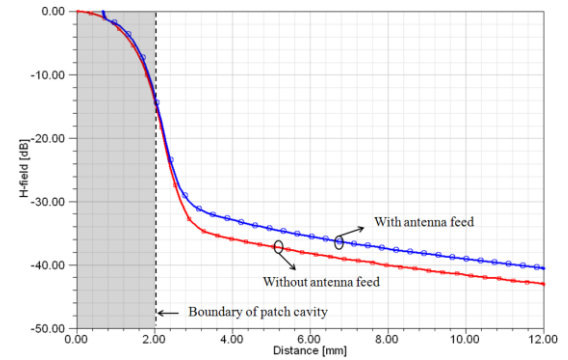


Figure 12: Comparison of magnetic field on the ground plane in region 1 of the patch antenna with and without the antenna feed. The distance is taken from the patch center.

It can be concluded that the feed has a significant effect on the excited fields of the patch antennas.

3. Conclusion

In this contribution, the electric and magnetic field distributions as well the power density in the vicinity of an excited rectangular patch antenna were analyzed. The effects of the dielectric substrate, dielectric losses and the antenna feed were quantified individually. Some of the results obtained include the following:

- The dielectric substrate guides a surface wave excited by the patch antenna in region 1. The surface wave does not only cause an increase in power density with slower spatial field decay, but also an increase in magnetic field strength of ~ 4 dB at a distance of 10 mm from the patch edges. However, since the surface wave impedance is inductive, a decrease in the electric field strength was also observed.
- The influence of dielectric losses of the antenna substrate cause a decreased magnetic field strength of ~ 1 dB in the case of $\tan(\delta)=0.02$ i.e., primarily more surface wave power is dissipated.
- The antenna probe feed causes an increase of the magnetic field strength of ~ 3 dB primarily as a result of additional surface wave power launched into the substrate.

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