

# Annular Slot Loaded High-Impedance Ground Plane

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**Abstract**—High impedance surfaces like electromagnetic band gap (EBG) ground planes have been used to realize low profile antennas. In this paper, an alternative ground plane design is presented for antennas with circular current distributions, which consists of an annular slot backed by a thin grounded substrate. The slot ring generates a high impedance condition at a resonant frequency in the vicinity of the slot. This annular slot loaded ground plane results in efficient radiation of the low profile antenna in the broadside direction. Since the slot loaded ground plane consists of a single slot ring rather than periodic structures, it is much simpler to construct than the standard EBG ground plane. Numerical simulations and experimental measurements are shown to validate the design concept and are compared with a mushroom-type EBG ground plane. A parametric analysis was also conducted by varying the slot ring's dimensions and tuning varactors are shown to vary the ground plane's resonant frequency.

**Index Terms**— High impedance ground plane, low-profile antenna

## I. INTRODUCTION

LOW profile antennas with hemispheric radiation typically employ a cavity backing filled with absorber or a high impedance surface like an electromagnetic band gap (EBG) structure [1]. The former method wastes energy in the absorbing material while the latter enforces efficient radiation at a resonant frequency. EBG ground planes take advantage of the high surface impedance condition that occurs when the frequency dependent reflection phase passes through zero degrees. These structures are typically made of periodic patches on a grounded substrate and may have vias extending from the patches down to the bottom ground plane to suppress surface waves within a frequency band.

The ground plane presented in this paper operates in a

Manuscript received Month XX, 2012; accepted Month XX, 2012. Date of publication Month XX, 2012.

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Distribution Statement A: Approved for public release; distribution unlimited.

similar manner as a frequency dependent EBG, where the high impedance of the ground plane loads the antenna and results in efficient radiation near the resonant frequency. The main difference between the proposed ground plane and the conventional high impedance surface is the lack of periodicity in the structure, which greatly simplifies the manufacturing process. Section I explains the operation of the annular slot loaded high-impedance ground plane and its application to a low profile loop antenna. Section II presents numerical simulations used to validate the ground plane concept and compares results to an EBG ground plane. Measurements of a loop antenna over an annular slot loaded ground plane are shown in Section III. Section IV presents a parametric analysis of the ground plane's effect using a numerically simulated broadband spiral antenna, including parametric analysis of the slot ring radius, slot width, substrate height, and substrate material. A method of dynamically tuning the annular slot loaded ground plane using varactors is also presented.

## II. ANNULAR SLOT LOADED HIGH-IMPEDANCE GROUND PLANE

When an antenna is placed close to a high impedance surface, like an EBG, the surface is in the near field of the antenna. Under certain conditions, the frequency dependent impedance of the surface loads the antenna, resulting in a good impedance match between the antenna and the feeding transmission line at some resonant frequency, which results in efficient radiation. An alternative way to think about the operation of a high impedance ground plane is that it reflects the incident wave with a zero degree reflection phase at a resonant frequency. The reflected wave constructively interferes with the wave radiating directly from the antenna, which enforces efficient radiation.

The alternative high impedance ground plane proposed in this paper, which operates on a similar principle to the EBG described above, is composed of a slot ring backed by a thin grounded dielectric. The height of the grounded dielectric is much less than a quarter wavelength at the resonant frequency. A conventional slot ring without a grounded dielectric will radiate at a frequency determined by the guided wavelength of the slot. That is, an annular slot antenna will radiate its fundamental mode at a slot radius of [2]

$$r = \frac{\lambda_0}{\pi \sqrt{\epsilon_{reff}}}, \quad (1)$$

where  $\lambda_0$  is the wavelength in free space and  $\epsilon_{reff}$  is the effective permittivity of the surrounding medium.

Adding a ground plane close to the slot presents an inductive impedance to the slot and prevents efficient radiation. However, at a resonant frequency the impedance in the slot ring becomes very high. This high impedance condition loads the low profile antenna in a similar manner to an EBG ground plane. The main difference between an EBG and the proposed annular slot loaded ground plane is that the high impedance condition is only present in the vicinity of the slot and is not an averaged impedance taken over the entire surface. Therefore, if an antenna shaped similarly to the slot is placed nearby, its near fields will be affected by the high impedance boundary condition of the slot ring and will radiate efficiently. For example, a loop antenna of similar radius to the slot ring will generate its near fields in the region of the ground plane that presents a high impedance boundary condition. The effect of the annular slot loaded ground plane will be efficient radiation in a single broadside direction, similar to that of an antenna over an EBG. Fig. 1 shows a diagram of the annular slot loaded ground plane with pertinent dimensions.

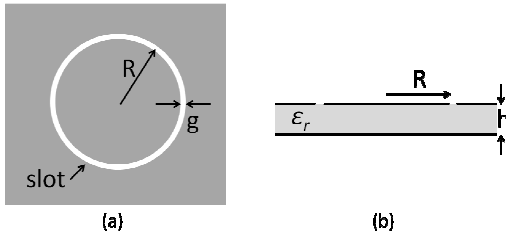


Fig. 1. (a) Top view of the high impedance slot ring ground plane with slot radius  $R$  and slot width  $g$  (b) Side view of the ground plane with substrate permittivity  $\epsilon_r$  and height  $h \ll \lambda/4$ .

The resonant frequency of the annular slot loaded ground plane can be observed by numerically modeling the slot and observing the impedance inside the slot itself. Using the HFSS finite element software package, the slot ring impedance can be observed by driving the slot with an ideal lumped port. The fields generated in the slot can then be used to determine the slot impedance. In this way, an annular slot loaded ground plane can be designed quickly without using an incident plane wave or antenna structure in the model. Fig. 2(a) shows the impedance in a slot ring ground plane with a radius of 21.5 mm, slot width 1 mm, substrate permittivity 4.4, and substrate height 3.175 mm. It can be seen that the impedance in the slot is high at a resonant frequency of 1.85 GHz. The resonant high impedance condition leads to a reflection phase that passes through zero degrees, which is shown in Fig. 2 (b). This frequency dependent reflection phase can be used to create a low profile antenna, similar to an antenna over an EBG. Notice that when the imaginary component of the impedance in Fig. 2(a) approaches zero, the real part is also very low, indicating that the slot itself is not the primary radiating structure.

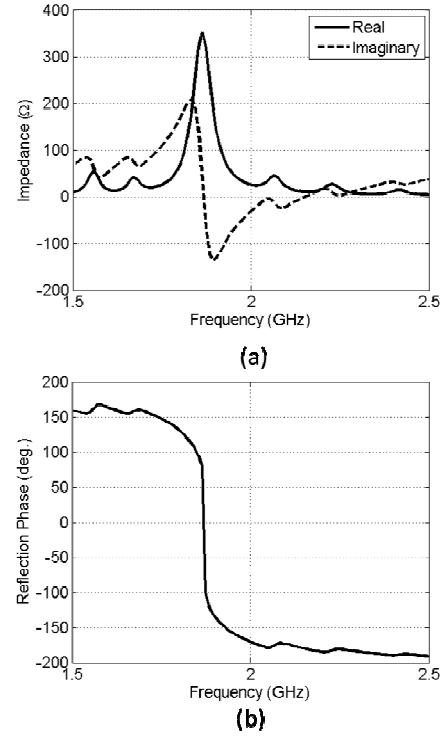


Fig. 2. (a) Input impedance and (b) corresponding reflection phase of an annular slot over a thin grounded substrate. The impedance becomes very high and the reflection phase goes through  $0^\circ$  at resonant frequencies.

It has been shown that the input impedance of a slot ring can be calculated analytically [3]-[5], although numerical simulations are relatively trivial for the simple geometry. The grounded substrate underneath the slot ring introduces a parallel connection of the slot impedance and the input impedance of a TEM line section of length  $h$  [6]. Given a slot impedance of  $Z_s$ , the impedance of the slot ring over a grounded substrate is given by

$$Z = \frac{Z_s j\eta \tan(kh)}{Z_s + j\eta \tan(kh)}, \quad (2)$$

where  $\eta$  is the wave impedance of the substrate material and  $k$  is the propagation constant in the substrate material. For small values of  $h$ , (2) can be approximated by

$$Z = \frac{Z_s j\alpha\mu h}{Z_s + j\alpha\mu h}, \quad (3)$$

where  $\mu$  is the permeability of the substrate material.

### III. NUMERICAL ANALYSIS WITH A LOOP ANTENNA

A numerical simulation of a loop antenna with a tapered microstrip balun was created using HFSS. The loop antenna had a radius of 21 mm in order to resonate at 2 GHz in free space when supported on a 0.79 mm thick sheet of FR4 with a relative permittivity of 4.4. The loop was then modeled 6 mm above the top of the ground plane, which is  $0.04\lambda$  at 2 GHz.

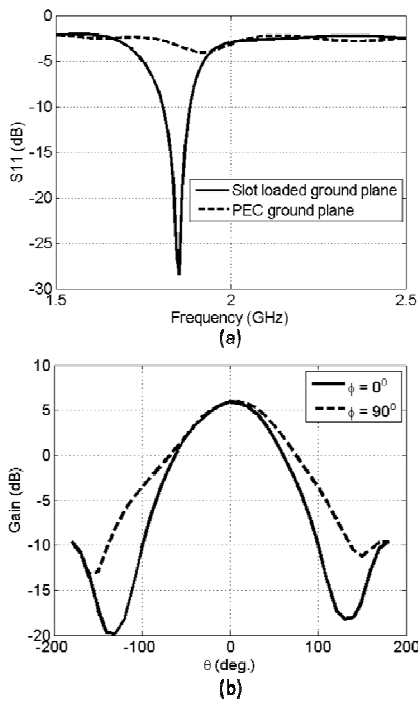


Fig. 3. (a) S11 of a simulated loop antenna over an annular slot loaded ground plane and (b) the realized gain pattern at the resonant frequency of 1.85 GHz.

To simulate the slot loaded ground plane, the geometry shown in Fig. 1 was created with  $R = 21.5$  mm,  $g = 1$  mm,  $h = 3.175$  mm, and  $\epsilon_r = 4.4$ . The planar size of the ground plane was 135 mm by 135 mm. The slot ring ground plane was modeled without the antenna in a separate simulation with an ideal lumped port to determine that its first order resonant frequency occurs at 1.85 GHz. When the loop antenna was simulated over the annular slot loaded ground plane, a resonance was generated at 1.85 GHz where the return loss reached -28 dB. The -10 dB bandwidth of the antenna over the slot loaded ground plane was approximately 100 MHz centered around 1.85 GHz. The peak realized gain was 5.8 dB at broadside and the back lobe was -15.3 dB down from the main lobe. The peak gain was 3.2 dB higher than the loop antenna modeled in free space without the ground plane. Fig. 3 shows the simulated S11 of the loop antenna over the annular slot loaded ground plane and its gain pattern at the resonant frequency of 1.85 GHz.

Since the slot loaded ground plane is acting as a high impedance surface, similar to an EBG ground plane, the reflection phase will not be  $180^\circ$  like a PEC ground plane. This can be seen in the simulated current distribution on the loop, shown in Fig. 4(a), and on the slot loaded ground plane at the resonant frequency, shown in Fig. 4 (b). The vector current distribution on the slot loaded ground plane inside the loop radius is in the same direction as the current on the loop, which indicates that the reflection phase is closer to  $0^\circ$  than  $180^\circ$ . Fig. 4 (c) shows the current distribution on a ground plane with no slot for comparison, where the currents inside the loop radius are in the opposite direction of the antenna

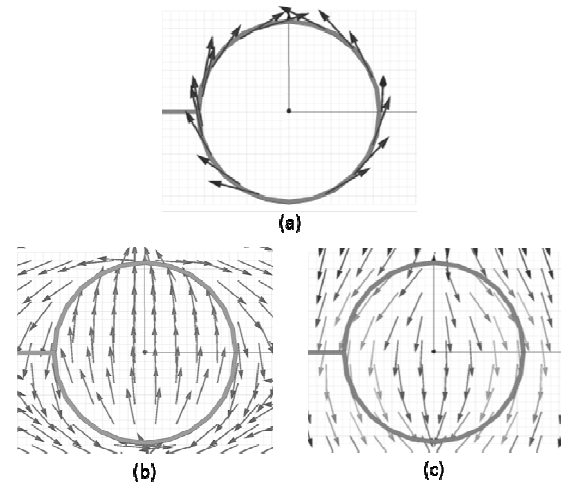


Fig. 4. (a) Vector current distribution on the simulated loop antenna (b) current distribution on the slot loaded ground plane underneath the loop antenna and (c) current distribution on a ground plane with no slot.

currents, indicating a  $180^\circ$  reflection phase.

The slot loaded ground plane can only act as a high impedance surface when the field from the antenna is in the vicinity of the slot. Otherwise, the field would only encounter the continuous PEC area on the ground plane. In order to examine the effect of the antenna's field being misaligned with the slot, the radius of the simulated slot was varied and the loop antenna's radius was kept constant. The resulting S11 curves are shown in Fig. 5 as the slot radius is varied from 19 mm to 23 mm. It can be seen that the S11 is best when the radius of the slot equals the radius of the loop antenna. The S11 of the loop antenna in free space is also shown for comparison. Similar to the case of an antenna over an EBG ground plane, the resonance over the slot loaded ground plane is lower in frequency compared to free space since the ground plane is effectively loading the input impedance of the antenna. Fig. 6 shows the gain of the loop antenna over the slot loaded ground plane as the slot radius is varied. The gain was taken at the frequency where the minimum S11 occurred from Fig. 5. The gain is maximized when the slot radius is close to the loop antenna radius.

Since much of the ground plane is simply two sheets of metal separated by a dielectric, it can act as a TEM waveguide for any energy that gets coupled into it through the slot ring. Periodic vias between the top and bottom metal sheets were inserted into the numerical model to act as a filter and suppress any propagating waves within the ground plane. Vias were only placed in the region outside of the slot ring radius. Placing vias inside the slot ring radius disturbs the slot ring fields and degrades the high impedance resonance. The vias were spaced 15 mm apart with equal spacing in the x and y directions, which acts as a high pass filter with a 2.7 GHz cut-off frequency. The loop antenna still resonated at 1.85 GHz with approximately the same S11 of -28 dB. The peak realized gain improved from 5.8 dB to 6.9 dB and the back lobe was 19 dB down from the front lobe, which showed that adding vias does improve the overall performance.

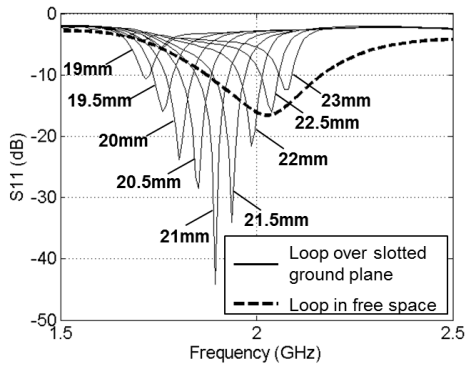


Fig. 5. Simulated S11 of the loop antenna with 21 mm radius over a slot loaded ground plane where the slot radius was varied from 19 mm to 23 mm (solid) compared to the S11 of the loop in free space (dashed).

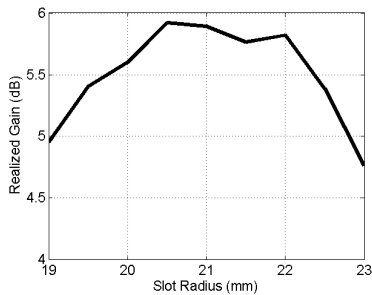


Fig. 6. Simulated gain of the loop antenna over the slot loaded ground plane with varying slot radius. The gain was taken at the frequency where the minimum S11 occurred shown in Fig. 5.

A numerical model of the same loop antenna was created over a “mushroom-type” EBG with vias for comparison. The patch width and gap width were varied over a range of values to determine an optimal design with the constraint that the overall ground plane size be restricted to 135 mm x 135 mm, which was the size of the annular slot loaded ground plane. The EBG was composed of a 4 by 4 grid of mushroom type unit cells. The substrate permittivity was 4.4 and the substrate height was 3.175 mm. A patch width of 32.25 mm and gap width of 1.5 mm generated an optimal return loss in the loop antenna of -32 dB at 1.72 GHz. The peak realized gain was 8.4 dB at broadside and the back lobe was -23 dB down from the main lobe. Fig. 7 shows the S11 of the loop antenna over the EBG with vias compared to the antenna over the slot loaded ground plane with vias. Fig. 7 also shows the gain pattern of the antenna over each ground plane at their respective resonant frequencies. The -10 dB bandwidth of the loop antenna over the EBG was much greater than the annular slot loaded ground plane. However, much of this bandwidth is outside of the surface wave band gap where the beam pattern and peak gain are significantly degraded. The gain of the antenna with the EBG is slightly greater than the antenna over the annular slot loaded ground plane with vias. It is theorized that the gain with the slot loaded ground plane is lower because the near fields from the antenna that extend beyond the annular slot do not encounter the same high impedance condition that occurs

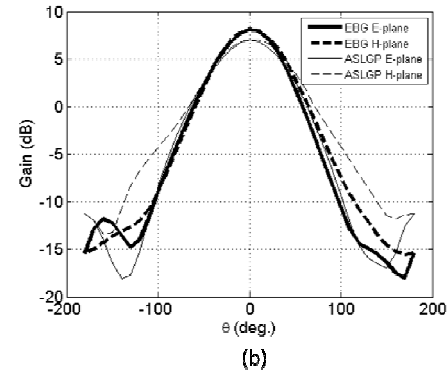
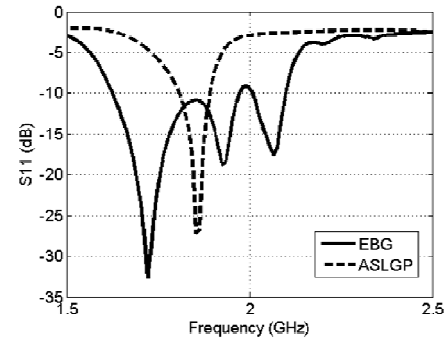


Fig. 7. (a) S11 of a simulated loop antenna over a mushroom type EBG with vias and an annular slot loaded ground plane (ASLGP) with vias (b) the realized gain pattern at 1.72 GHz for the EBG and 1.85 GHz for the ASLGP.

directly in the slot. This is compared to the EBG surface where the high impedance condition exists over the entire plane, so all of the incident near fields are reflected with the same reflection phase.

#### IV. ANTENNA MEASUREMENTS

A loop antenna with a balun and an annular slot loaded ground plane without vias were constructed and measured to validate the design concept and simulations. The slot ring ground plane was constructed using a 3.175 mm thick sheet of FR4 and the slot ring had the same dimensions as the numerical model. Fig. 8(a) shows the slot ring ground plane, where the slot was simply cut from a thin sheet of copper on top of the FR4 substrate. The bottom of the substrate was covered with a continuous sheet of copper. The loop antenna had a radius of 21 mm and a trace thickness of 1 mm, which is the same as the simulated antenna. A tapered balun was constructed on the same sheet of FR4 as the antenna and was fed using a standard 50  $\Omega$  SMA connector. The size of the ground plane was 135 mm by 135 mm. A 6 mm thick spacer of Rohacell material with a permittivity near 1 was placed between the loop antenna and the ground plane to provide structural support. Fig. 8(b) shows the loop antenna on top of the slot ring ground plane with the Rohacell spacer.

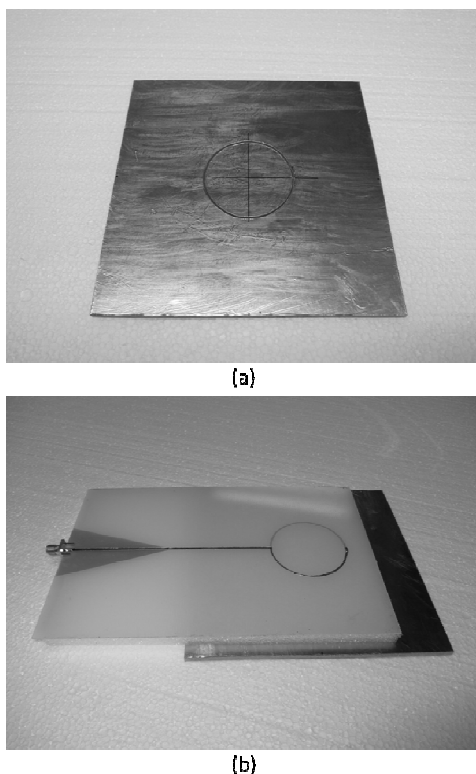


Fig. 8. (a) Annular slot loaded ground plane and (b) a loop antenna with a balun on top of the ground plane with a thin Rohacell spacer.

The measured response of the loop antenna in free space was very similar to the numerical model. The measured S11 of the loop antenna over the annular slot loaded ground plane reached -27 dB at 1.75 GHz, which is close to the simulated antenna and ground plane. The bandwidth of the measured antenna over the ground plane was 78 MHz centered around 1.75 GHz. Fig. 9 shows the measured S11 of the antenna over the annular slot loaded ground plane as compared to the simulated response. The 0.1 GHz difference in resonant frequency is likely due to manufacturing tolerances for the antenna, balun, and ground plane. The S11 is also compared to the measured loop at the same height over a continuous ground plane. The peak gain of the measured antenna was 5.2 dB at broadside as compared to the simulated peak gain of 5.8 dB.

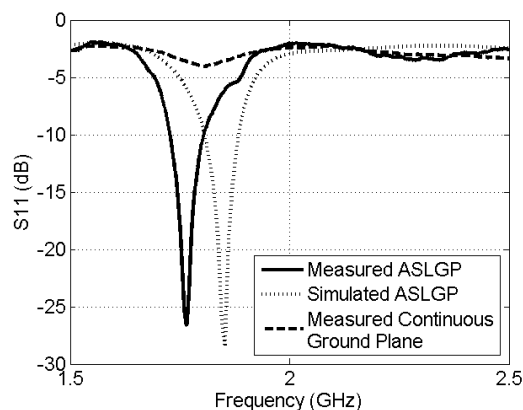


Fig. 9. Measured S11 of a loop antenna over an annular slot loaded ground plane (ASLGP) without vias compared to the simulation and to a loop at the same height over a continuous ground plane.

## V. PARAMETRIC ANALYSIS

In order to determine the effects of varying the slot ring's parameters, an antenna must be chosen that radiates over a broad frequency range with near constant input impedance and that has a current distribution that follows the shape of the slot ring at all radii. An Archimedean spiral antenna fits these criteria. For this analysis, the spiral antenna is not intended to radiate over a broad band when placed over the slotted ground plane. It is merely used as a tool to demonstrate the effects of changing the annular slot loaded ground plane's parameters.

An Archimedean spiral antenna with a diameter of approximately 100 mm was numerically modeled using an ideal lumped port with a port impedance of 188  $\Omega$ . The spiral antenna was modeled 6 mm above an annular slot loaded ground plane. The dimensions of the ground plane were varied and the effects on the simulated return loss and realized gain were observed. The parameters that were varied include the slot radius, the slot gap width, the substrate height, and the substrate permittivity. Figure 10 shows the model of the spiral antenna and the annular slot loaded ground plane developed in HFSS.

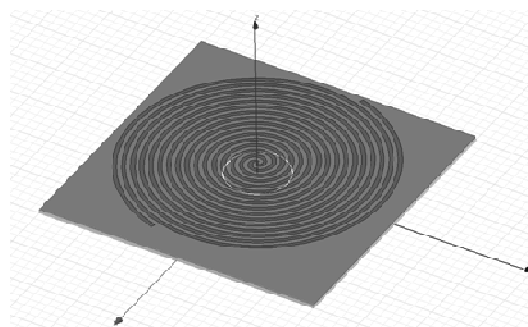


Fig. 10. HFSS model of a spiral antenna over an annular slot loaded ground plane used for a parametric analysis.

Since the guided wavelength of the annular slot is related to the slot radius by (1), it is evident that increasing the slot radius will cause the resonant frequency of the annular slot loaded ground plane to decrease. A spiral antenna was simulated with a slot ring ground plane where the slot radius was varied from 18 mm to 24 mm. The slot gap width was 1 mm, the substrate permittivity was 4.4, and the substrate height was 3.175 mm. Fig. 11(a) shows the simulated S11 of the spiral antenna for each slot radius, which verifies the expected trend of decreasing resonance with increasing slot radius. The simulated realized gain at broadside is shown in Fig. 11(b) for each slot radius. Each gain value is calculated at the resonant frequency for its respective slot radius. The realized gain for the spiral antenna in free space without a ground plane is also shown for comparison.

The width of the slot gap was then varied to analyze the effect on the spiral antenna's performance. The center of the slot, i.e. the average slot radius, was kept constant at 16 mm. The substrate permittivity was 4.4 and the substrate height was 3.175 mm. As the gap width was varied, the resonant frequency of the ground plane did not change significantly.

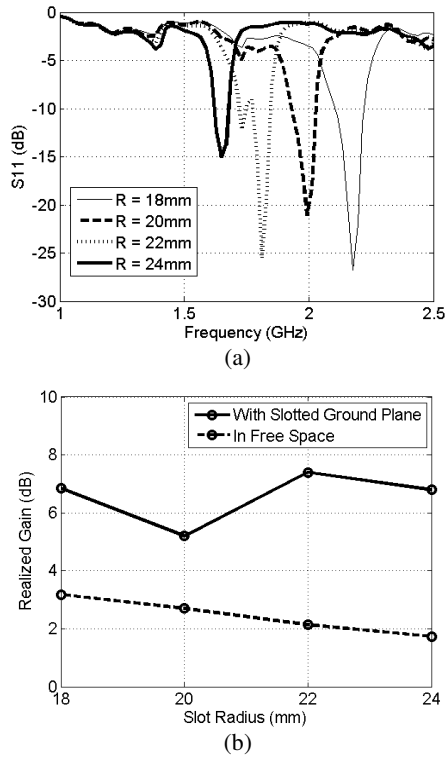


Fig. 11. (a) Simulated S11 of an Archimedean spiral antenna over an annular slot loaded ground plane for varying slot radii and (b) simulated realized gain at broadside at the resonant frequency of each slot radius.

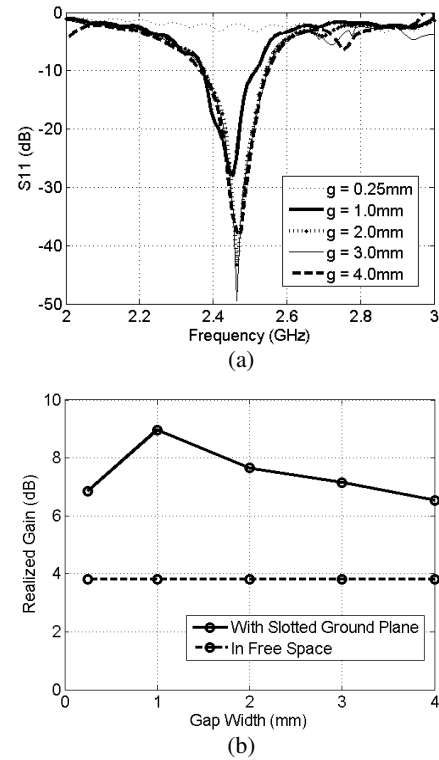


Fig. 12. (a) Simulated S11 of a spiral antenna over an annular slot loaded ground plane for varying slot gap width and (b) simulated realized gain at broadside at the resonant frequency.

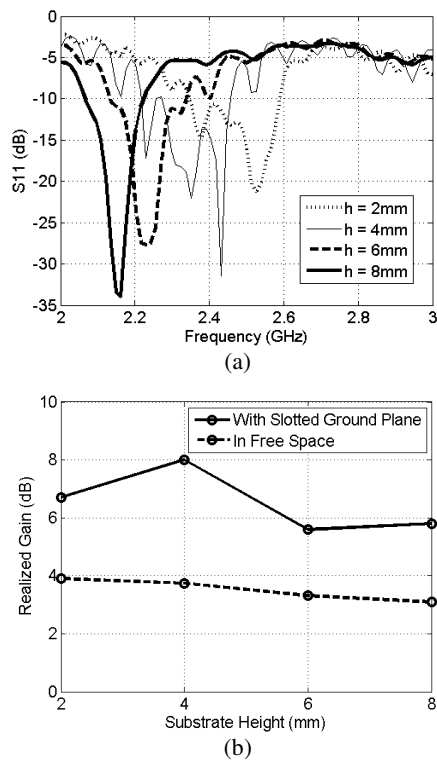


Fig. 13. (a) Simulated S11 of a spiral antenna over an annular slot loaded ground plane for varying substrate heights and (b) simulated realized gain at broadside at the resonant frequency for each substrate height.

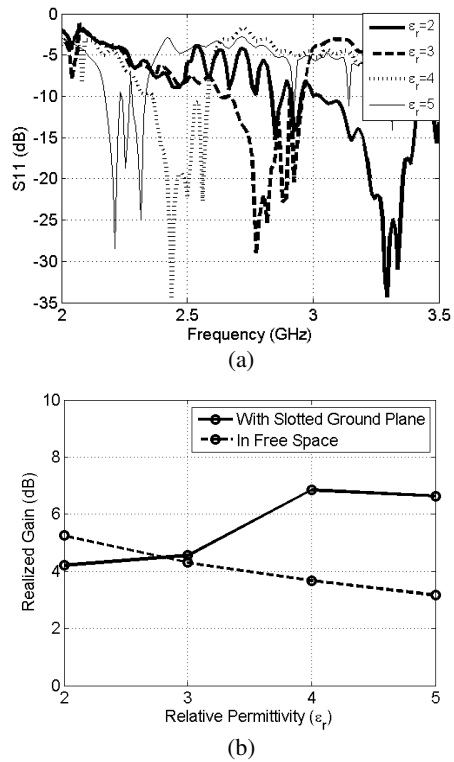


Fig. 14. (a) Simulated S11 of a spiral antenna over a high impedance annular slot ground plane for varying substrate permittivity and (b) simulated realized gain at broadside at the resonant frequency for each permittivity value.

However, the S11 magnitude at the resonant frequency did change as can be seen in Fig. 12(a). At the resonant frequency of 2.45 GHz, the S11 curve shows an optimal impedance match when the gap width is 3 mm. This shows that, while the gap width is not a frequency tuning parameter, it is an impedance matching parameter that can be used to optimize the performance for a particular antenna. The simulated realized gain at broadside is shown for each gap width at the resonant frequency in Fig. 12(b).

Next, the height of the ground plane's substrate was varied while the other parameters were held constant. The slot radius was 16.5 mm, the slot gap was 1 mm, and the substrate permittivity was 4.4. The height of the substrate affects the inductive impedance as shown in (2). Similar to the case of a mushroom-type EBG [1], increasing the height of the substrate lowers the resonant frequency of the ground plane as can be seen in Fig. 13(a). The simulated realized gain at broadside is shown for each substrate height at its resonant frequency in Fig. 13(b).

The relative permittivity of the substrate material affects the guided wavelength of the annular slot. The result is a lowering of the ground plane's resonant frequency with increasing substrate permittivity. A spiral antenna was simulated over an annular slot loaded ground plane and the permittivity of the substrate was varied. The slot ring radius was 17 mm, the gap width was 2 mm, and the substrate height was 3.175 mm. Figure 14(a) shows the simulated S11 for the various permittivity values and Fig. 14(b) shows the simulated realized gain at broadside for each permittivity value at its resonant frequency. The gain for the antenna over the slotted ground plane with a substrate relative permittivity of 2 and 3 is especially low because the beam width becomes very broad, resulting in a lower gain value at broadside.

It was shown that certain parameters of the annular slot loaded ground plane can be varied to tune the resonant frequency. An alternate method of tuning the annular slot involves placing varactors across the slot ring's gap [7]. Introducing the tunable capacitance of a varactor across the slot ring allows the resonance to be tuned dynamically with a DC bias voltage.

A spiral antenna was simulated over an annular slot loaded ground plane with lumped capacitors placed across the slot. Varactors were placed in four equally spaced positions around the slot ring as shown in the diagram in Fig. 15. The slot radius was 16 mm, the substrate height was 3.175 mm, and the substrate permittivity was 4.4. The value of the capacitance across the slot was varied to simulate the variable capacitance of a varactor and the resulting S11 is shown in Fig. 16(a). It can be seen that the resonant frequency of the ground plane decreases as the capacitance across the slot is increased. The simulated realized gain at broadside is shown in Fig. 16(b) for each capacitance value at the corresponding resonant frequency.

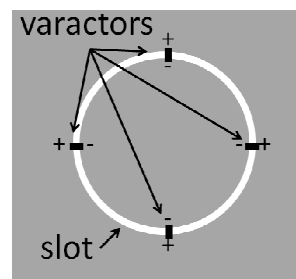


Fig. 15. Diagram of an annular slot loaded ground plane with varactors placed across the gap to enable dynamic tuning of the ground plane's resonant frequency. The direction of the DC voltage bias across the varactors is indicated by the plus and minus signs.

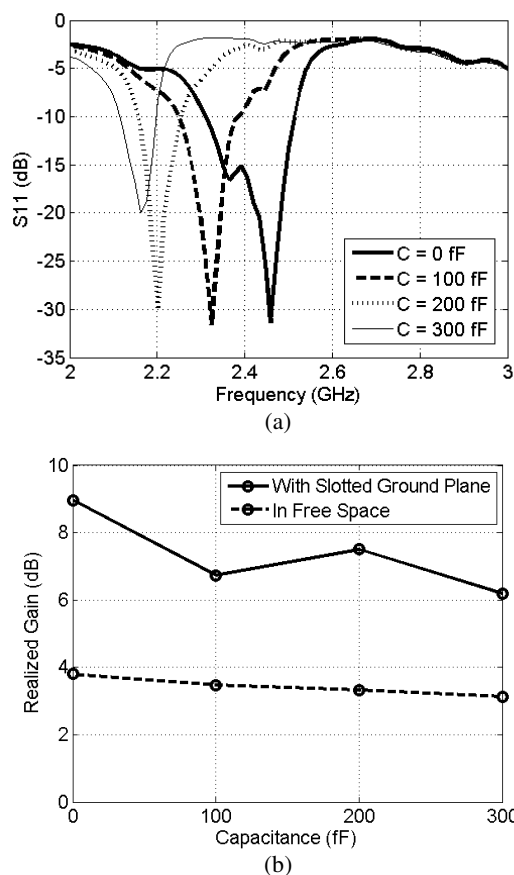


Fig. 16. (a) Simulated S11 of a spiral antenna over an annular slot loaded ground plan with varactors across the slot. The capacitance of the varactors was varied to show the affect on the ground plane's resonant frequency. (b) Simulated realized gain at broadside for each capacitance value at its resonant frequency.

## VI. CONCLUSION

A high impedance ground plane composed of an annular slot backed by a grounded dielectric was proposed for low profile antennas where the antenna's current distribution approximately follows the shape of the slot ring. Numerical simulations and measurements of a loop antenna over an annular slot loaded ground plane were shown to validate the concept. A parametric analysis was shown with numerical simulations to demonstrate the effect of the slotted ground plane's dimensions. Furthermore, it was shown that tuning varactors can be placed across the slot to dynamically tune the ground plane's resonance. It was shown that the gain of the loop antenna over the annular slot loaded ground plane is similar to a mushroom-type EBG. The slot loaded ground plane is much simpler to construct compared to a mushroom-type EBG because of the lack of periodicity in the structure. The authors are currently investigating the design of an annular slot loaded ground plane with multiple concentric slots, which produces multiple resonances.

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