

Improvement of High-Frequency Wireless Power Transfer with Capacitively Loaded Slot

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ABSTRACT: Near-field SGP (Slotted Ground Plane)-based systems, also known as DGS (Defected Ground Structure), are attractive for applications because they are easy to conceive, have low losses, and reduce circuit size to achieve a compact resonator. In this paper, we design a slim profile resonator at 13.56 MHz for HF (High Frequency) applications, such as HF RFID (High Frequency Radio-Frequency Identification) or NFC (Near-Field Communication), and couple it to a resonant loop. The PTE (Power Transfer Energy) with 30 mm between transmitting and receiving coils is enhanced from 0.88% up to 14.6% in HF with adding a compact resonator between the loops.

1. INTRODUCTION

The energy transfer in the near field at low frequency (LF and HF) classically uses capacitive transfer with the E -field, inductive transfer with the B -field, or mixed E - and H -fields to increase energy transfer volume [1]. The transfer distance can be enhanced using Magnetic Resonant Coupling: the resonators are placed between two resonating loops acting as relays or placed inside one resonating loop to catch magnetic lines and maximize the B -field intensity in an area [2]. The objective is to use the same working principle as that of magnetic resonant coupling, that is a resonating aperture in a metallic plane, for structures where the loops are close to a metallic plane. The energy transfer through a slot in a metallic plane has been studied in several papers and presents attractive characteristics: the magnetic coupling with an aperture in a ground plane enlarges frequency bandwidth and flattens the ripple of an open-loop resonator filter around 1.2 GHz [3]. By adding SMD (Surface Mount Device) capacitors on the apertures, the latter ones become resonant at 433 MHz and 900 MHz [4], and when they are coupled with a microstrip line, a dual-frequency compact resonator is realized. Two resonating loops etched in a ground plane allow to enlarge the bandwidth of a ground antenna up to 16% at 2.5 GHz [5]. In this study, a Surface Mount Device (SMD) soldered to an aperture in a metallic plane acts as a Near-Field Communication (NFC) resonator. First, the behavior of the resonating aperture in a metallic plane is clearly shown in High Frequency (HF) and improves the inductive coupling versus coaxial and lateral misalignment. The slot resonator is coupled to resonating loops to improve the Power Transfer Energy (PTE) between the loops when they are far away. Finally, we verified the transfer of energy and data of this system using an NFC reader.

2. BEHAVIOR OF SLOTTED RESONATING APERTURE

A 7 mm-radius circle is etched inside a 33 μm -thick and 88 mm-side squared metallic plane on a 1.575 mm-thick FR4 substrate with relative permittivity of 4.4 without (Fig. 1) and with (Fig. 3) SMD capacitor.

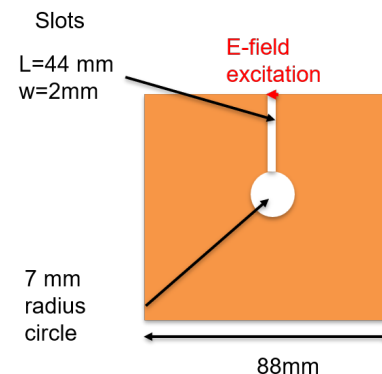


FIGURE 1. Defected Ground Structure without SMD capacitance.

All antenna simulations in this study were performed using Ansys HFSS (high-frequency structure simulator). The impedance variation of the circle etched in a metallic plane is shown with respect to the frequency without (Fig. 2) and with 7.1 nF capacitance (Fig. 4). The intrinsic quality factor, computed as the ratio between imaginary and real parts of the input impedance without capacitor on the metallic plane with a circular slot without capacitor (Fig. 2), is maximum at 70 MHz and equal to 137. The Q value was 90 at 13.56 MHz. This metallic plane with a circular slot acts as a magnetic resonant circuit by adding capacitance to decrease the 885 MHz intrinsic resonance of the metallic plane to 13.56 MHz frequency while keeping a high quality factor. Fig. 4 shows the variation of the complex impedance and resonant frequency shift to 13.56 MHz. The current on the metallic plane increased with adding the SMD capacitor, as shown in Fig. 5, which will increase the coupling

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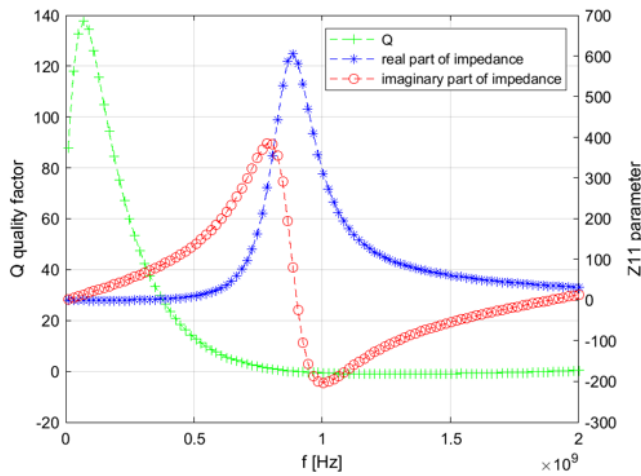


FIGURE 2. Simulated quality factor and impedance of the circle etched in a metallic plane versus the frequency without the SMD capacitor in the 10 MHz–2000 MHz bandwidth.

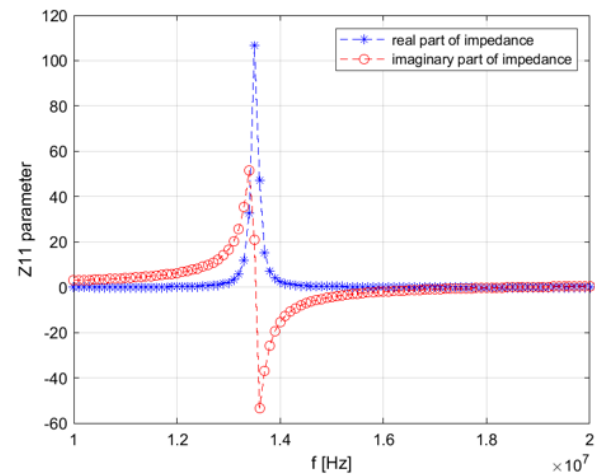


FIGURE 4. Simulated impedance of the circle etched in a metallic plane versus the frequency with the SMD 7.1 nF capacitor in the 10 MHz–20 MHz bandwidth.

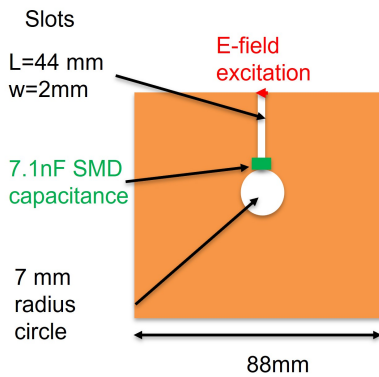


FIGURE 3. Defected Ground Structure with SMD 7.1 nF capacitance.

and PTE of the wireless power transfer (WPT) system. As H -field lines are perpendicular to the aperture plane, they could be coupled to a loop placed parallel above the aperture: it is what we want to do to increase the range distance between two loops using the resonating aperture in a metallic plane between them.

3. SIMULATED RESULTS OF INDUCTIVE COUPLING

The system without a resonating aperture is composed of two 7 mm-radius coaxial loops etched on one side of the FR4 substrate. For the system with one resonating aperture, a circular resonating aperture, coaxial to the loop, in the metallic plane is etched on the other side of the FR4 substrate for one of the loops. The input impedance is a 0.14 ohms series resistance with a 0.37 nH inductance for a loop with one resonating aperture, while it is a 0.031 ohms resistance in series with a 0.21 nH inductance for the loop without a resonating aperture. Figs. 6 and 7 present the pictures of up and down sides of the FR4 substrate for the system with and without resonating apertures, and the matching circuit (C_s , C_p) is reported.

$$k = \frac{\text{Im}(Z_{21})}{\text{Im}(Z_{11}) * \text{Im}(Z_{22})} \quad (1)$$

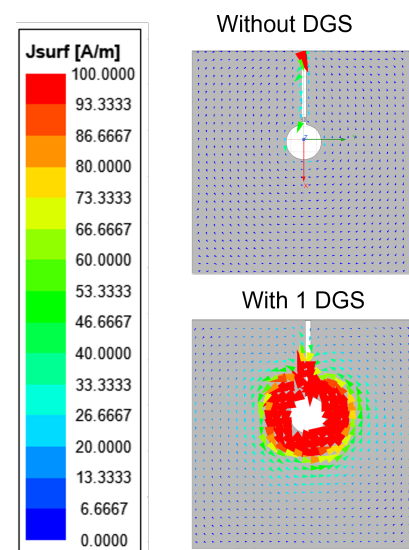


FIGURE 5. Simulated current on the defected ground structure without and with SMD 7.1 nF capacitance.

As the loop is more than 1,000 times smaller than the free-space wavelength, the primary constraint is to ensure that the system is impedance-matched via the choice of capacitors, rather than the system's dimensions. The systems' simulated coupling factor k [6–9], as seen in Equation (1), is plotted versus the lateral misalignment for different coaxial distances in Figs. 8 and 9.

d coax represents the coaxial distance between the two loops, and D_y represents the lateral displacement, in which a value of 0 corresponds to the case that the loops are one above the other. In Fig. 9, in comparison with Fig. 8, it is evident that the loop with the resonating aperture is more efficiently coupled to the loop than the loop without the resonating aperture: the coupling factor is more than two times greater for coaxial distances with the resonating aperture.

Table 1 reports the simulated relative attenuation versus the maximum value for each coaxial distance and each structure,

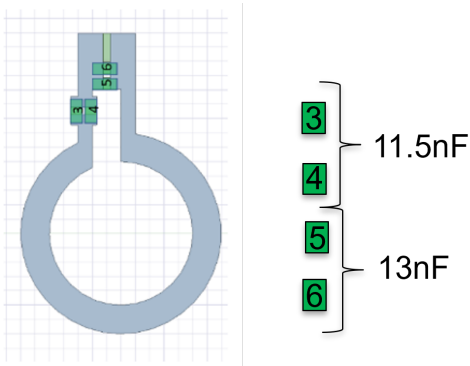


FIGURE 6. Loop with no DGS.

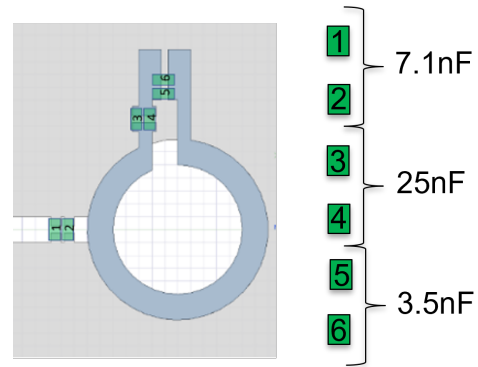
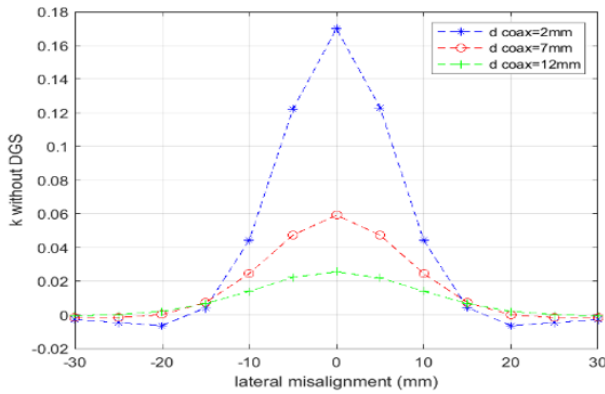
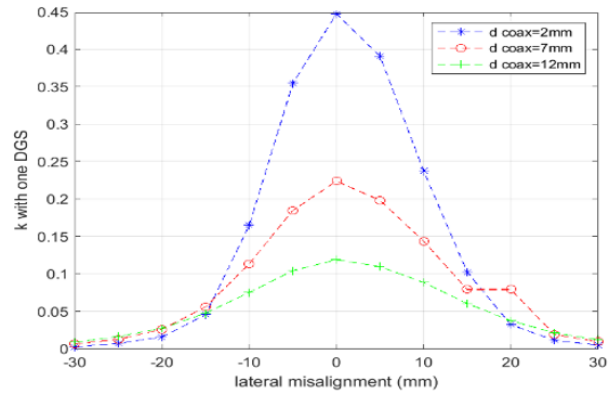


FIGURE 7. Loop with one DGS.

FIGURE 8. Simulated k coupling factor versus the lateral misalignment for several coaxial distances for a system with resonating apertures.FIGURE 9. Simulated k coupling factor versus the lateral misalignment for several coaxial distances for a system without resonating apertures.TABLE 1. Simulated relative attenuation normalized to the maximum value versus coaxial distance (d_{coax}) and lateral misalignment (D_y).

Relative attenuation (%)					
DGS	d_{coax} (mm)	$D_y = 0$ mm	$D_y = 5$ mm	$D_y = 10$ mm	$D_y = 15$ mm
1	2	0	-21.7	-46.9	-77.1
0	2	0	-29.19	-74.44	-97.45
1	7	0	-11.6	-35.7	-64.7
0	7	0	-19.7	-58.3	-88.1
1	12	0	-7.6	-25.4	-49.2
0	12	0	-13.4	-46.2	-74.2

and shows clearly that the loop with a resonating aperture is less sensitive to lateral misalignment. For measurements in the next section, loops are realized using micro-etching techniques; their input impedance is measured using a Vectorial Network Analyzer (VNA), and a matching circuit is added, as in the simulation section.

4. EXPERIMENTAL RESULTS AND DISCUSSION

S parameters were obtained using a vector network analyser, following a short-open-load-through (SOLT) calibration. The PTE is computed for a receiving loop placed at a coaxial distance from the transmitted loop.

To match the loop of 50 ohms in the HF, a series capacitor C_s and a parallel capacitor C_p were connected to the loops. The values of the matching circuit (C_s , C_p) are optimized for both structures, and the values are noted at the right of each structure (Figs. 10 and 11).

Each structure was set on a 3D-printed red socle and held by nylon screws. The results with and without the resonating aperture are compared to demonstrate the efficient role of the resonating aperture.

Figure 12 shows the system without the resonating aperture, and Fig. 13 shows the system with the resonating aperture. The PTE is computed from reflection and transmission coefficients, as follows:

$$PTE = |S_{21}|^2 \quad (2)$$

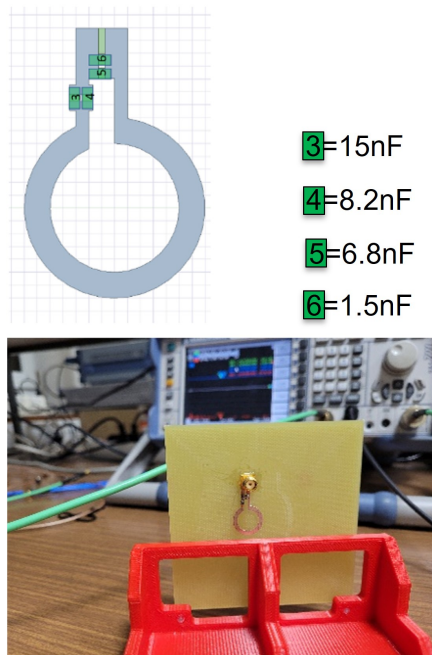


FIGURE 10. Pictures of the both faces of the FR4 substrate for the system without the resonating apertures.

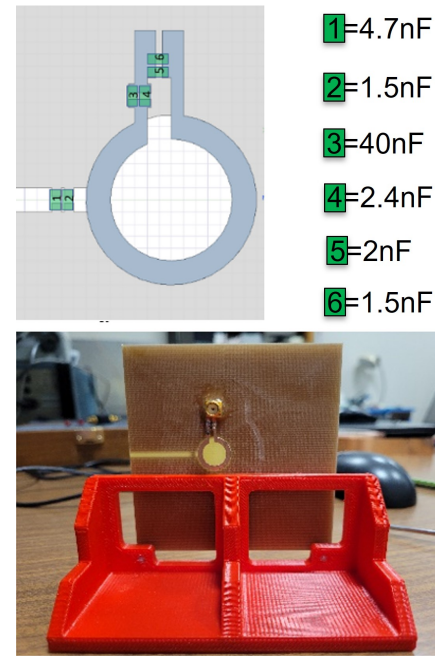


FIGURE 11. Pictures of the both faces of the FR4 substrate for the system with the resonating apertures.



FIGURE 12. System without the resonating apertures.



FIGURE 13. System with resonating apertures.

Fig. 7 shows measured reflection and transmission coefficients for loops with 30 mm between transmitting and receiving coils for structures with (Fig. 15) and without a resonating aperture (Fig. 14). Access 1 is connected to the loop without resonating aperture, while access 2 is linked respectively to the loop without resonating aperture (Fig. 14) and to the loop with a resonating aperture (Fig. 15). Input and output impedance matching in the WPT system is checked, as the reflection coefficient is less than 10 dB for each configuration.

Structures are matched (less than 10% of reflected power from the incident power) in HF, and the measured HF transmission with 30 mm between transmitting and receiving coils is increased from -20.8 dB up to -8.65 dB with adding the resonating aperture, which corresponds to a PTE increase from 0.88 up to 14.6%.

TABLE 2. PTE versus coaxial distance.

d coax (mm)	30	40	50	60	70
Structure with no DGS at 13.35 MHz					
$ S_{11} $ (dB)	−14	−14.19	−14.23	−14.14	−14.07
$ S_{21} $ (dB)	−20.8	−26.67	−34.19	−38.5	−42.37
PTE (%)	0.88	0.22	0.04	0.014	0.006
Structure with one DGS at 13.45 MHz					
$ S_{11} $ (dB)	−11.75	−14.49	−15.52	−15.74	−15.8
$ S_{21} $ (dB)	−8.65	−12.43	−16.87	−20.67	−24.43
PTE (%)	14.6	5.93	2.11	0.88	0.37

Table 2 reports reflection and transmission parameters versus the coaxial distance between the loops for each configuration at the frequency at which the transmission is maximum, with less than 1% frequency shift between the two configurations: 13.35 MHz without resonating aperture and 13.45 MHz

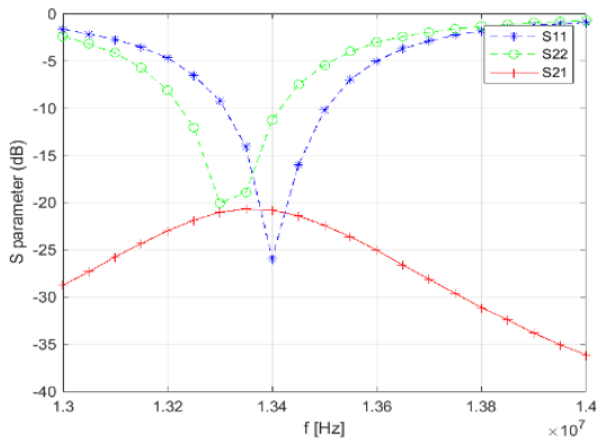


FIGURE 14. Measured S parameters for loops with 30 mm between transmitting and receiving coils without resonating aperture.

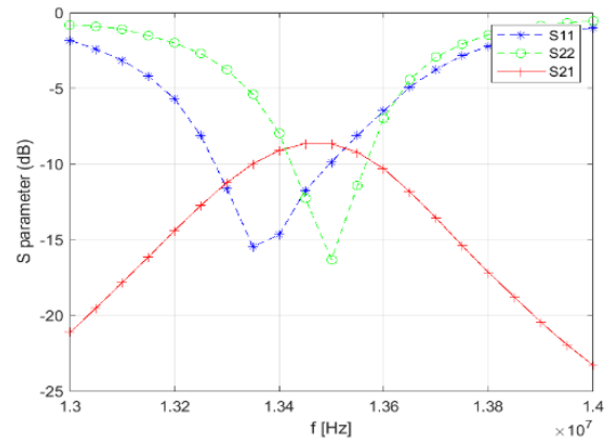


FIGURE 15. Measured S parameters for loops with 30 mm between transmitting and receiving coils with one resonating aperture.

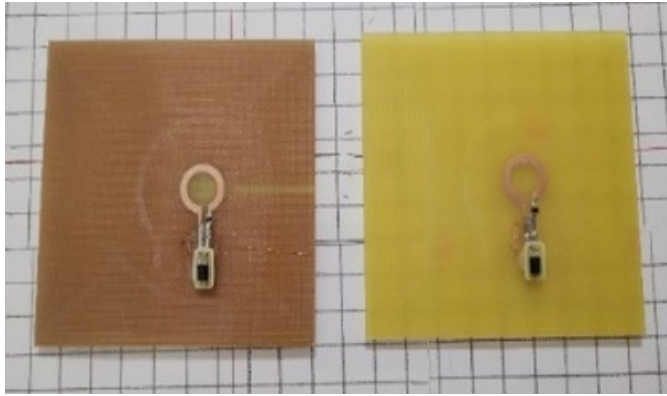


FIGURE 16. $L = 4.7 \mu\text{H}$ in series with the loop to be connected to the NFC chip at 13.56 MHz.

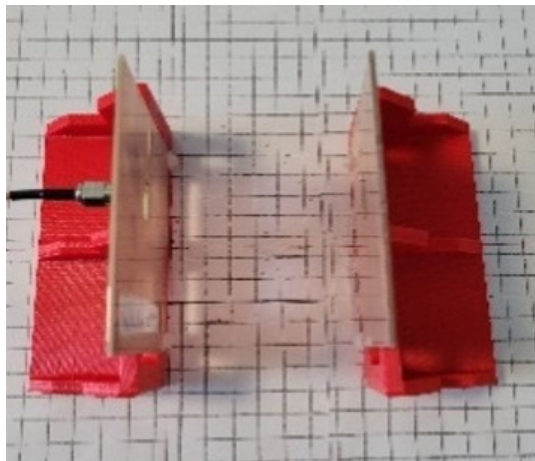


FIGURE 17. Structures on the red socles: connected to the reader (left side) and connected to the NFC chip (right side).

with resonating aperture. The PTE with a resonating aperture is efficient for all coaxial distances. The objective of the next section is to check and illustrate energy and data transfer, thanks to the structure connection with the NFC reader and NFC chip.

TABLE 3. PTE versus coaxial distance and lateral misalignment.

d coax (mm)	5	15	25	35	45	55	65	75	85
Structure with no resonating aperture									
center	×	×	×	×	×	×	×	×	×
Structure with one resonating aperture on a NFC chip									
center	✓	✓	✓	×	×	×	×	×	×
+10 mm	✓	✓	✓	×	×	×	×	×	×
+20 mm	✓	✓	×	×	×	×	×	×	×
+30 mm	×	×	×	×	×	×	×	×	×
Structure with one resonating aperture on a NFC reader									
center	✓	✓	✓	×	×	×	×	×	×
+10 mm	✓	✓	×	×	×	×	×	×	×
+20 mm	×	×	×	×	×	×	×	×	×
Structure with two resonating apertures									
center	×	×	×	✓	✓	✓	✓	✓	×
+10 mm	×	✓	✓	✓	✓	✓	✓	✓	×
+20 mm	×	✓	✓	✓	✓	✓	✓	×	×
+30 mm	×	×	✓	✓	✓	✓	×	×	×
+40 mm	×	×	✓	✓	×	×	×	×	×
+50 mm	×	×	×	×	×	×	×	×	×

5. NFC MEASURE

The prototype matched to 50Ω was connected to the NFC SIL 2225 reader. The reader power was 7.5 W. Each prototype was matched to the NFC chip (STDV64KC with Protocol ISO/IEC 15693) by adding a $4.7 \mu\text{H}$ series inductance (Fig. 16). The red socles (Fig. 17) allow both to hold the prototypes with nylon screws and to change the coaxial distance (d_{coax}) and lateral misalignment (DY) between the structures. Table 3 shows detection (green check) or null detection (red cross) of the NFC chip versus the coaxial distance and the lateral misalignment.

The resonating aperture allows the system to be more efficient with coaxial and lateral misalignment, as shown in Table 3. Detection results are the same for the structure with a

resonating aperture whether the NFC chip is on the structure with a resonating aperture or on the structure without it. If two structures with a resonating aperture are used, the detection measurements are further improved. In Table 3, for a misalignment of 10 mm, the detection range is improved from 0 mm to 15 mm by adding one resonant metal plane, whilst a transponder can be detected up to 75 mm away using two resonant metal planes.

6. CONCLUSION

By placing a capacitively loaded slot at the center of the metallic plane between resonating loops, inductive coupling between loops is improved, producing a coupling enhancement of more than 10% and less sensitivity to the relative lateral position between the loops. Detection measurements with an NFC system confirmed increased detection distance and lower sensitivity to lateral misalignment, resulting in increased volume detection. In future work, this technique will be investigated using devices with metal covers, such as smartphones, tablets, or computers, or for medical applications, for example when a loop is implanted in the body and the slotted resonator attached to the skin.

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