A Tunable Antenna with the Combination of Two Kinds of Liquid Materials

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Abstract **─** A tunable antenna consists of two kinds of liquid materials is designed and investigated for the first time. Compared with single liquid antenna, the antenna with two kinds of liquids offers more flexibility for the designing. Insoluble liquid such as oil can be used together with the distilled water, the sea water or saline water. A thin pole is added to make use of the fluidity of liquid and bring adjustment to the antenna according to the principle of communicating vessels. The comparison of pure liquid and the combination of different materials are carried out first. Furthermore, the influence of the distribution of the liquid materials, the feeding locations and the length of the feeding probe are analyzed. The simulation results indicate the radiation potential and the reconfigurability of the antenna. To drag out or push in the adjustment pole as well as to change the parameters of the structure can bring the variations of the antenna performance effectively, including the matching and the radiation features.

Index Terms **─** Hybrid antenna, liquid antenna, monopole antenna, tunable antenna, water antenna.

I. INTRODUCTION

Liquid antennas have drawn more and more attentions during recent years. The popular types of liquid antennas include Dielectric Resonator Antenna (DRA) and monopole antenna. Since the investigations on the two types of antennas remain a hot topic, it is convenient for drawing on the experiences of the conventional ones [1-4]. A liquid-based DRA was introduced [5]. The miniaturization of the antenna due to the high relative permittivity of water was demonstrated. Furthermore, a DRA-based technique was proposed for measuring liquid permittivity. A low-profile broadband antenna was designed [6]. It was a hybrid structure combined the resonance of a dielectric resonator and a monopole together. A hybrid antenna with solid and liquid materials was discussed [7], with the focus of the influence of the feeding locations and the distribution of the liquid. A water dielectric patch antenna array for Wi-Fi communication application was presented [8]. The new idea was that the conventional metal patches were replaced by water. A shunt-excited seawater monopole antenna was studied in the paper [9]. Dynamic-type seawater monopole antenna of high efficiency was realized by using a shunt-excited feeding structure, which was formed by a conducting tube and a Gamma-shape feeding arm. A pump was applied to provide seawater for the antenna. It offered a potential for designing high-efficiency dynamic-type sea-water monopole antennas. A seawater half-loop antenna of VHF band was developed for maritime wireless communications [10]. The antenna was made of a capacitive coupling feeding structure and a stream of seawater produced by a water pump. This antenna could be turned off in real time, which made it suitable for maritime wireless communications. A mechanically reconfigurable microstrip antenna which applied a liquid actuator as the dielectric layer to reduce the size was designed in the paper [11]. By using direct polymer vacuum deposition on a liquid, the dielectric liquid could be encapsulated inside the polymer to form an actuator, which changed the liquid thickness. When the actuator was mounted within the antenna, its resonant frequency could be changed by changing the liquid thickness. A transparent water dielectric patch antenna fed by an L-shaped probe was designed in the paper [12]. The presented design had an operation style similar with the conventional metallic microstrip antenna [13]. A broad bandwidth could be obtained by applying a thick supporting substrate between the ground and the water patch.

The liquid antennas published till now have achieved fairly good performance and have shown potentials abilities in the applications of various areas. But there was only one kind of liquid in all of them, and there were limited styles for the realization of the liquid antennas. We attempt in this paper to make use of two kinds of

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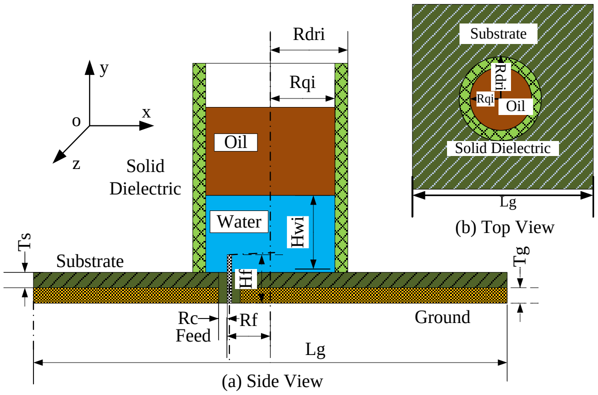
liquid to provide more design flexibility for the antenna. At the same time, an additional structure will benefit the adjustment of the antenna.

II. DESIGN AND SIMULATIONS

A. Structure and performance of the untunable liquid antennas

As shown in Fig. 1, a tube made of a solid dielectric material is fabricated on the substrate and the ground layer to hold the liquid. At the beginning, a liquid material such as sea water, distilled water, oil or saline water can be injected into the tube to produce liquid antennas with fairly good radiation and matching performance. Furthermore, the combination of oil and water can be carried out to obtain hybrid antennas with more flexibility.



(a) Side View

(b) Top View

Fig. 1. Structure of the untunable liquid antennas: (a) side view and (b) top view.

The commercial software of CST Microwave Studio is used to carry out the model building and the simulations. In the simulations, the solid material is chosen to be glass with the relative permittivity of 4.82 and the thickness of 1.0 mm. The relative permittivity of the sea water and the distilled water are 74.0 and 78.4, respectively, while the relative permittivity of oil is 2.33. The thickness of the substrate is 3.0 mm and that of the ground is 0.8 mm. Rogers TMM10 with the permittivity of 9.2 is used as the substrate.

There are several types of interfaces referring to the scenarios in this manuscript. The saline water and the sea water tend to act as conductive objects, so do the surfaces of them. While the distilled water and the oil remain dielectric materials and act as non-conductive objects. The discipline of general electromagnetic radiation and reflection characteristics also has an effect on the liquid interfaces.

Four curves of the reflection coefficients are shown in Fig. 2, each of which is corresponding to a specific configuration of the liquid inside of the tube, namely, a single liquid of distilled water, oil, sea water and the combination of oil and seawater. The total height of the liquid is 36 mm for both single pure liquid and the combined materials. The height of the oil is 20 mm and that of the sea water is 16 mm when they operate together, and the water (with a density of 1.0 g/cm^3) lies in the bottom layer as the higher density compared to the oil (with a density of 0.8 g/cm^3).

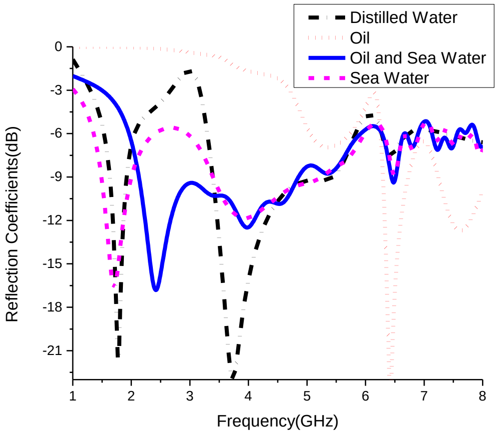


Fig. 2. Reflection coefficient curves of several untunable liquid antennas.

It could be seen from the curves that all the four configurations can operate at one or two certain frequency bands among 1.0-8.0 GHz. The distilled water has the best matching performance with the reflection coefficient S11<-10 dB in the frequency ranges of 1.65-1.90 GHz and 3.41-4.66 GHz, whose relative bandwidth are 14.08% and 30.98%, respectively, with the valley of reflection points of -21.74 dB and -23.13 dB. The pure oil and the sea water achieve the highest and the lowest frequency, respectively, with a rather large gap of 4.73 GHz (1.70 GHz and 6.43 GHz).

For the validation verification of the simulations, a result of the S11 curve obtained from another software ANSYS HFSS (High Frequency Structure Simulator) is presented in Fig. 3, with the liquid materials of distilled water and oil. The result from CST is shown for a comparison. Similar matching performance could be seen from the two calculations, especially for the positions of the resonant frequency points.

Figure 4 presents the curves of the radiation patterns of different liquid materials and their combination at 4.0 GHz, namely pure oil, distilled water and oil, sea water and oil, pure sea water. The gain values of them are 2.63 dBi, 5.88 dBi, 3.51 dBi and 3.63 dBi, respectively. The combination of distilled water and oil get the highest gain, while that of the pure oil is the lowest. To be mentioned, the gain and radiation pattern of the distilled water and the sea water is nearly the same under this configuration, so we only offer one of them here in Fig. 4. The direction of the main lobe varies a lot according to the changes of material, as it could be observed from the figure.

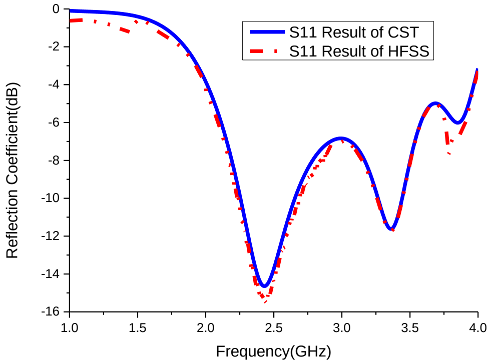


Fig. 3. The comparison of S11 from CST and HFSS.

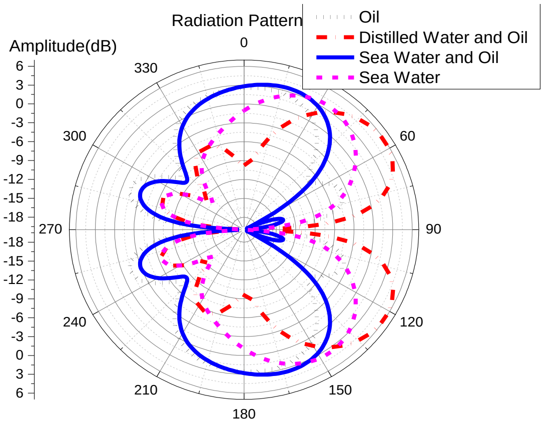


Fig. 4. Radiation patterns of different materials (Pure Oil, Distilled Water and Oil, Sea Water and Oil, Pure Sea Water).

Similarly, we compared the radiation pattern results from HFSS and CST, as shown in Fig. 5. Both curves refer to the combination of distilled water and oil.

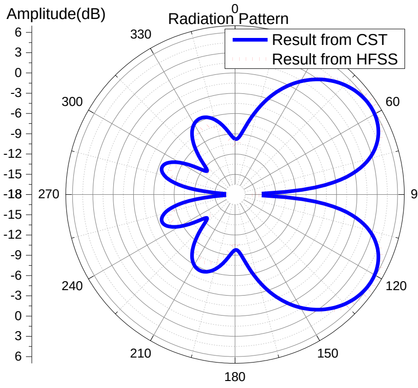


Fig. 5. Comparison of the radiation patterns from HFSS and CST.

It could be seen from Fig. 5 and Fig. 3 that the gaps between the absolute values of the two curves have little impact for the discussion about the antenna performance.

B. Structure of tunable liquid antennas

To make the antenna tunable, we make use of the principle of the communicating vessel, as shown in Fig. 6. The liquid of the same kind of material will have the same height of surface in the tube, no matter what the shape of it or how thick or thin the diameter is. As for a different kind of liquid, the height will increase when the density decreases, and the variation of the height is linear. For example, if the height of the water in the tube is 80 mm, that of the oil will be 100 mm according to their difference of density.

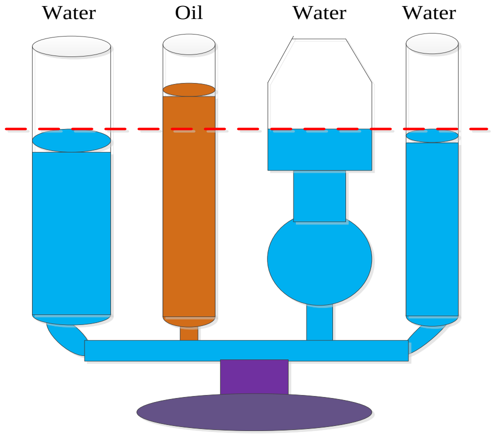
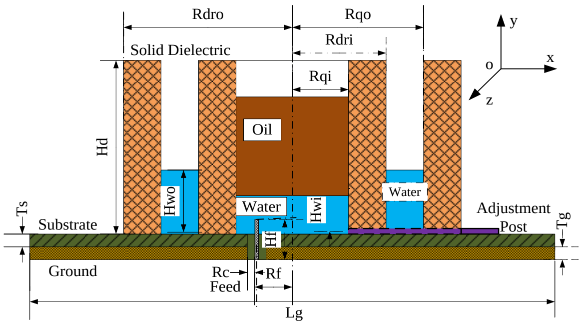


Fig. 6. The diagram of a communicating vessel.

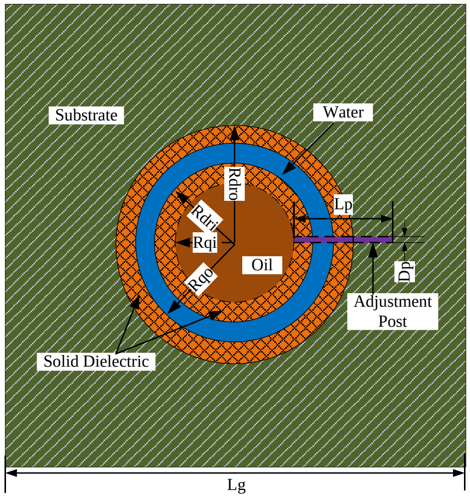
Further flexibilities would be obtained when the structure is changed to the scenario as shown in Fig. 7. Where, Lg= 80 mm, Hd=36 mm, Rqi=3 mm, Rdo=5 mm, Rdri=4 mm, Rdro=6 mm, and Rqo=5 mm. An outside cavity is formed by adding a shell with a bigger diameter. The liquid materials now acquire a new space to stay. The fluidity of them could then achieve a better usage. Oil and seawater are used to form the main part of the radiation, and they are arranged inside of the inner cavity.

There is a thin pole mounted in the right outer part of the structure that can be dragged out or be pushed in, thus the water can flow into the exterior shell or be blocked in a certain cavity as we want. Furthermore, a kind of solid dielectric material (DRT (Dielectric Response Technology) from the company of IMCC (Intelligent Material of Ceramic Company in Nanjing, China)) is used to substitute glass to make the shell, whose dielectric permittivity is 30.0 (1.0-12.0 GHz). The user-defined parameters for the specific materials are supported in CST.

Actually, there is a series of formulas to calculate the dimensions of the antenna corresponding to certain performance requirements, mainly according to the design theory of dielectric resonant antennas. However, for the demonstration of the feasibility of the tunable cavity antenna with two kinds of liquid materials, the operation frequency together with the dimensions of the antenna could be chosen to be a set of values of common size.



(a) Side view



(b) Top view

Fig. 7. Structure of the tunable liquid antenna (the oil is injected into the inner cavity of the structure): (a) side view and (b) top view.

C. Influence of the distribution of the liquid

The different performance will be achieved when the distribution of the liquid is changed. The calculated results of S11 in four typical statements are shown in Fig. 8. The heights of the sea water in the inner cavity are 16 mm, 11 mm, 5 mm and 0 mm, respectively. So the heights of the outer part are in the reverse order of the above numbers. The oil remains 20 mm and will vary its position as the changing of the seawater.

The highest operating frequency occurs when the whole sea water flows out of the inner cavity. The configuration of 11 mm of seawater remains inside of the cavity obtains the best performance with the minimal S11 of -35 dB and the broadest bandwidth of 22.99%. Detailed data are shown in Table 1, where the phrase of “In 5” means the height of the liquid in the inner cavity is 5 mm, while the “Out 11” means the height of the liquid in the outer cavity is 11 mm.

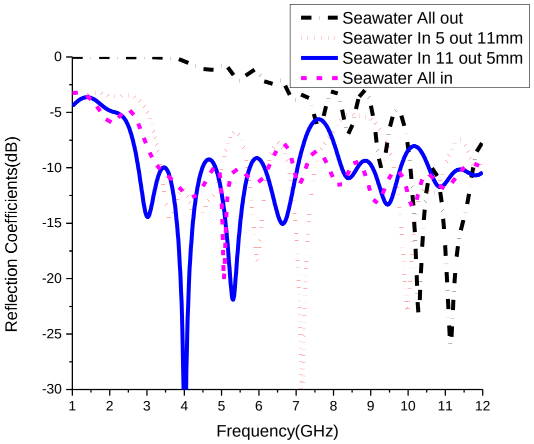


Fig. 8. S11 corresponding to the variation of the liquid distribution.

Table 1: Frequency features of the four distribution statements of the liquid materials

Liquid Distribution (mm)	Resonant Freq. (GHz)	Freq. Range of Center (GHz)	Relative Bandwidth @ Central Freq.
In 16, Out 0	4.21, 5.07, 9.15	4.83-5.43	11.70%
In 11, Out 5	4.02, 5.30, 6.65	3.45-4.48	22.99%
In 5, Out 11	5.97, 7.16, 9.99	6.78-7.53	10.48%
In 0, Out 16	9.28, 10.29, 11.15	10.66-11.76	9.81%

The radiation patterns of the four configurations at their resonant frequencies are shown in Fig. 9. There are not much different in shape, but the values of side lobes, back lobes and gains are not the same. The highest gain is obtained when the height of the seawater outside of the cavity 16 mm, and the widest main lobe is achieved when the height is 5 mm. The minimal back lobe occurs when the water is totally constrained inside of the cavity.

Figure 10 provides a 3 D radiation pattern of the hybrid antenna at the frequency of 10.29 GHz, with the height of the exterior sea water to be 16 mm and the oil is constrained totally inside of the tube. The gain of the antenna is 8.22 dBi, and the side lobe is 7.7 dB lower than the main lobe. The highest gain in the back lobe is only -18.6 dBi.

If the liquid is injected into the exterior ring of the structure at the beginning, as shown in Fig. 11, the radiation performance would be different from the above, as shown in Fig. 12.

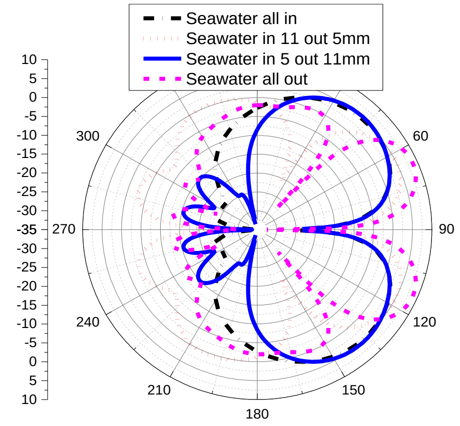


Fig. 9. Radiation patterns of different liquid distributions (the oil located inside of the inner cavity).

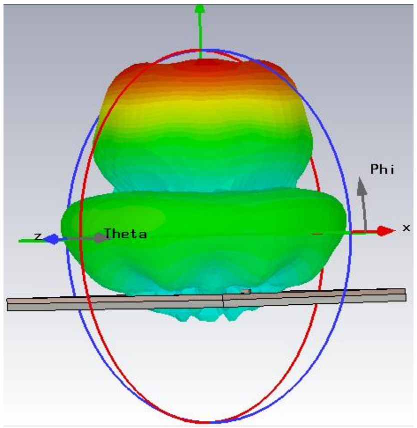


Fig. 10. The 3 D radiation pattern of the tunable antenna with the sea water stay outside at 10.29 GHz.

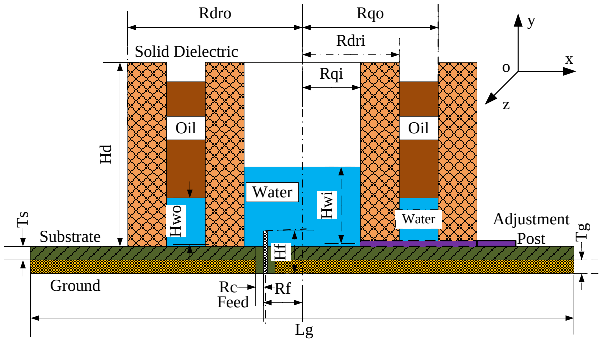


Fig. 11. Structure of the tunable liquid antenna (the oil is injected into the outer cavity of the structure).

Moreover, the heights of the solid dielectric material are expected to be changed to hold the liquid effectively. It can be seen that neither the gain values nor the heights of the side lobes remain the same with those in Fig. 9. The highest gain occurs when the inner height of the water is 5 mm, as shown in Fig. 12.

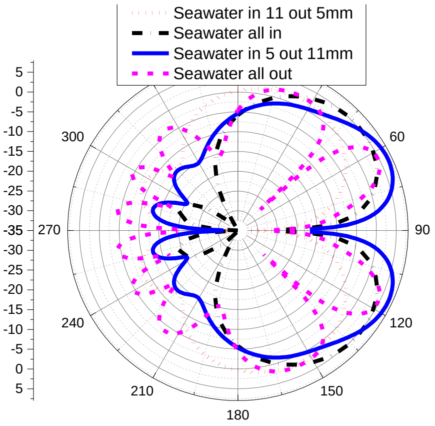


Fig. 12. Radiation patterns of liquid distributions at another original state (the oil located outside of the inner cavity).

D. Influence of the length of the feeding probe

Figure 13 indicates the influence of the length of the feeding probe. Here, the feeding locations are at the center of the bottom of the inner liquid. All the lengths from 1.5 mm, 2.0 mm, 2.8 mm to 4.0 mm can generate valid excitations and the longer one operates better in a lower band with a longer wavelength.

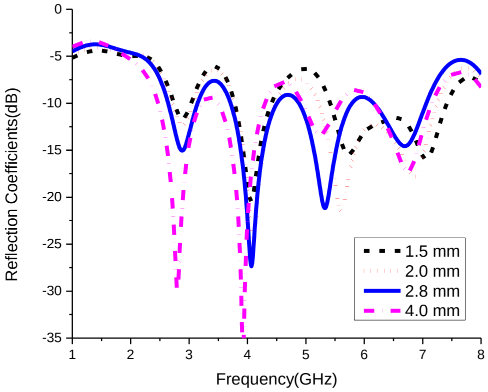


Fig. 13. Influence of the length of the feeding probe on S11.

If we change the excitation by reducing or increasing the length of the probe, the radiation would get variations too, as shown in Fig. 14. The gains of the antenna with a probe length of 1.5 mm, 2.0 mm, 2.8 mm and 4.0 mm are 2.25 dBi, 2.19 dBi, 1.82 dBi and 3.90 dBi, respectively. And as it can be seen from the figure, the shape of that of 1.5 mm and 2.0 mm are very similar, while that of the other two has distinguished features.

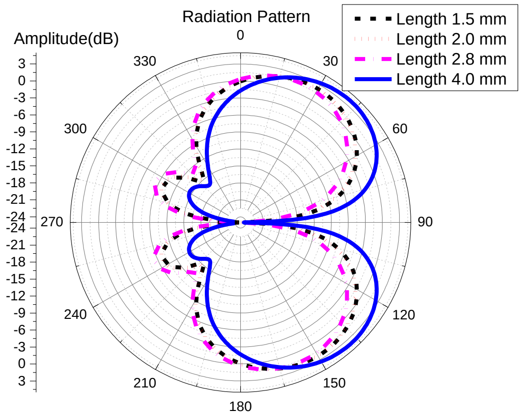


Fig. 14. Radiation pattern vs. the length of the probe.

E. Influence of the feeding locations of the probe

As we choose solid dielectric materials to build the shell and the cavity of the antenna, there is a special freedom for the designing of the antenna. That is, the feeding location of the probe can be moved from the inner liquid to the outer liquid as well as to the dielectric shell.

Figure 15 shows the reflection coefficients of several probe locations, including the center of the inner liquid and a distance of 3 mm, 7 mm and 8 mm to the center. The latter three distances stand for that of the probe put in the inner liquid, in the inner shell and at the interface of the inner shell and the outer liquid. It is very close for the resonance frequency of the location of 7 mm and 8 mm, which is 5.56 GHz and 5.61 GHz, respectively. It is very high for the central feeding of the antenna (7.16 GHz) and much lower for that inside of the liquid but with a bias from the center (4.05 GHz).

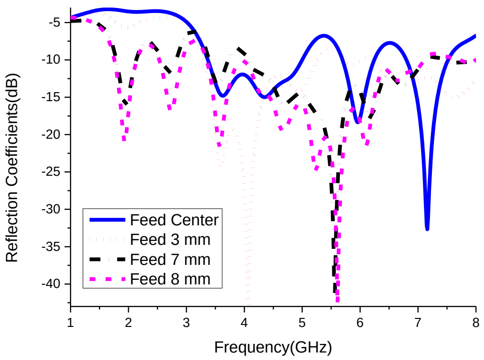


Fig. 15. Reflection coefficients vs. feeding locations of the probe (oil inside).

At the same time, the variation of the feeding positions will influence the radiation pattern, as shown in Fig. 16. It could be found from the figure that the pattern changes a lot when the excitation probe is put in the center of the antenna or be moved to the outer area. The gains of the four locations are 8.2 dBi, 0.7 dBi, 8.3 dBi and 7.1 dBi, respectively, from center to the outside. And there is much difference for the largest radiation directions of them.

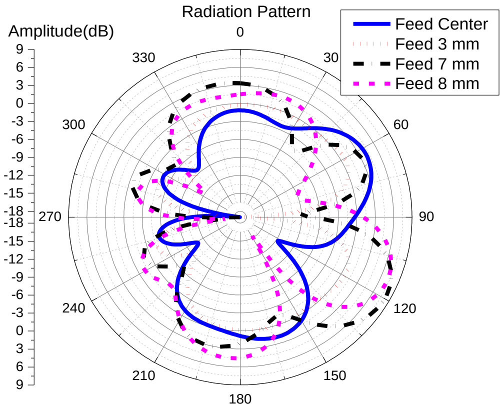


Fig. 16. Radiation pattern vs. the feeding location.

There are some tips for CST simulation for liquid antennas. Although the waveguide ports are the most accurate way to excite a field, discrete edge ports are sometimes more convenient to use. They have two pins to be connected to the structure. This kind of port is often used as feeding point source for antennas. At higher frequencies (e.g., the length of the discrete port is longer than a tenth of a wavelength) the S-parameters may differ from those when using waveguide ports because of the improper match between the port and the structure.

For the liquid antenna model consisting of several parts needs to be meshed. The solution methods require consistent meshes at the interfaces of different parts in order to set up the matrix equations correctly. If the meshes were created independently for all the blocks, the meshes might become inconsistent at the interfaces. The typical solution to this problem is to create a "non-manifold" simulation model first. This intermediate operation converts coincident faces from two solids to a single common double-sided face. Once it is done, the edges and faces can be meshed first, and the volume mesh can then be created.

The transient solver based on the Finite Integration Technique (FIT) is recommended, due to the memory efficient computation together with a robust hexahedral meshing to successfully simulate the complex structures.

III. CONCLUSION

This paper is the first to investigate the liquid antenna with two different liquids. The simulation results have revealed that this new type of antenna can offer a lot of flexibility and reconfigurability of the radiation and the matching performance of the antenna, which offers a new design freedom for the liquid antennas. However, this paper is just an initial study, thus, it could be further investigated to improve the antenna performance. To enable the adjustment characteristic of the liquid antenna is another important problem and the method mention in this paper is only an elementary one that needs further optimizations.

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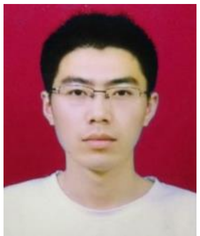

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