Optimal Size of Uniform Aperture for Near-field Penetration through Lossy Medium

OPTIMAL SIZE OF UNIFORM APERTURE FOR NEAR-FIELD PENETRATION THROUGH LOSSY MEDIUM

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Abstract—We present our investigations on the optimal size of uniform antenna aperture for the maximum near-field penetration of microwave signals through lossy materials. Penetration ability of an antenna through a certain depth in a lossy material depends on how much the radiated power from the antenna is focused at that depth. A figure of merit, the near-field 3dB beam radius, is used to define this focusing. Empirical formulaa to calculate the minimum 3dB radius and its location are provided in the paper. Verification of the results has been carried out by simulations using a commercial electromagnetic solver.

Keyword— near-field antenna, penetration ability, optimal aperture distribution

I. Introduction

The near-field microwave systems for detection and sensing have found more and more applications in recent years [1], such as in the areas of biomedical imaging and diagnosis systems [2], [3], production process control and monitoring [4], quality classification and defect detection [5], etc.

One challenge which has stayed for years in such applications is that the objects to be detected or imaged are often located inside lossy materials, such as human bodies, foods, tree timbers, pharmaceutical particles, etc. As it is known, microwave signals may have large attenuation through the aforementioned materials. One way to increase the penetration ability [6] of a microwave system through a lossy material with a certain depth is to make the radiated power concentrated at that depth. Then, a fundamental question arises: what is the optimal aperture, in terms of both the size and the source current distribution, for the maximum penetration (most concentrated radiation field) through lossy materials in the near-field?

The purpose of this paper is to find an optimal size of a circular uniform aperture for antennas in order to maximize the penetration for microwave signals through lossy materials. The reasons for doing so are the followings: i) we can have a better insight of the phenomenon of how the radiated power is focused; ii) the uniform aperture is the simplest and a very practical one; iii) a uniform aperture has low sidelobe level in both near-field and far-field regions; iv) uniform apertures focus at a kind of "long tube", instead of a point in near-field region, which is needed in near-field sensing systems.

II. Problem Formulation

Assume a foreign object, located inside a homogeneous lossy medium. In order to detect it best, we would like to have such an antenna (or antenna array) which results in maximum strength of total scattered field from the foreign object when the antenna illuminates the medium. By a common sense, if the antenna can focus the radiation power on the area along the object, the scattered-field strength would be maximized. For a near-field problem, if the size of a uniform aperture is very large, it would be very hard to focus the radiation power on an area just a short distance away from the aperture. On the other hand, if the aperture size is very small, the radiation field may be already diverged when the radiated wave reaches the foreign object. Thus, it is interesting and important for sensing systems to determine the optimal size of the aperture.

A model for analyzing this problem is set-up as shown in Fig.1: a circular aperture of currents (electric, magnetic or Huygen's), is located in *x*-*y* plane ($z = 0$). For simplicity without losing generality, we assume that the current is y-polarized, which can be expressed as

$$\boldsymbol{J}(\rho') = C\hat{\boldsymbol{y}}, \rho' \leq a \tag{1}$$

for electric current,

$$\boldsymbol{M}(\rho') = C\hat{\boldsymbol{x}}, \rho' \leq a \tag{2}$$

for magnetic current, and

$$\boldsymbol{J}(\rho') = C\hat{\boldsymbol{y}}, \rho' \leq a;\ \boldsymbol{M}(\rho') = -C\eta\hat{\boldsymbol{x}}, \rho' \leq a \tag{3}$$

for Huygen's source, where C is a constant, $\eta = \sqrt{\mu/\varepsilon}$ the homogenous space impedance and a the radius of the aperture. Then, the electric field can be expressed by (valid for both the near-field and the far-field) [7]:

$$\boldsymbol{E}_{tot} = C_k \int_0^{2\pi} \int_0^{a} \boldsymbol{V} \frac{e^{-jkR}}{R} \rho' d\rho' d\varphi' \tag{4}$$

where

$$\boldsymbol{V} = \boldsymbol{V}_E = \eta C\left[\hat{\boldsymbol{y}}C_{N1} - \left(\hat{\boldsymbol{y}} \cdot \hat{\boldsymbol{R}}\right)\hat{\boldsymbol{R}}C_{N2}\right] \tag{5}$$

for electric current,

$$\boldsymbol{V} = \boldsymbol{V}_M = C\left(\hat{\boldsymbol{x}} \times \hat{\boldsymbol{R}}\right)C_N \tag{6}$$

for magnetic current,

$$\boldsymbol{V} = \boldsymbol{V}_H = \eta C\left[\hat{\boldsymbol{y}}C_{N1} - \left(\hat{\boldsymbol{y}} \cdot \hat{\boldsymbol{R}}\right)\hat{\boldsymbol{R}}C_{N2} - \left(\hat{\boldsymbol{x}} \times \hat{\boldsymbol{R}}\right)C_N\right] \tag{7}$$

for Huygen's source, where $k = 2\pi/\lambda$ is the wave number, and

$$\boldsymbol{R} = \boldsymbol{r} - \boldsymbol{r}',\ \hat{\boldsymbol{R}} = \frac{\boldsymbol{R}}{R},\ C_k = \frac{-jk}{4\pi}, C_N{=}1{+}\frac{1}{jkR},$$
$$C_{N1} = 1 + \frac{1}{jkR} - \frac{1}{(kR)^2},\ \ C_{N2}{=}1{+}\frac{3}{jkR} - \frac{3}{(kR)^2}.$$

III. 3dB Near-Field Beam Radius

In order to have a measure of how the radiation power from an antenna is focused along the propagation direction, say on z-axis as in Fig. 1, we define a so-called 3dB near-field beam radius $r_{3dB}(z_1)$ (Abbreviated as 3dB radius in this paper) for the plane at $z = z_1$ as the radius of the smallest circle which contains all field points where the Poynting vector strength is higher than -3 dB of the strongest value in that plane. In other words, all field points outside this 3dB-beam circle have a Poynting strength below -3dB of the maximum in that plane. The center of the 3dB-beam circle is always on the symmetry axis of the aperture, which is z-axis in our case. Note that although the word "beam" is used in the definition, a beam may not be really formed in the near-field of an antenna.

$r_{3dB}(z_1)$ is measured in terms of millimeters or wavelengths, which is different from 3dB beam width for far-field radiation characterization, which is an angle.

Fig. 2 shows an example of simulated field distribution over different z planes for a uniform Huygen's aperture with a radius $a = 5\lambda$ located at $z = 0$. Fig. 3 illustrates the definition of 3dB near-field beam radius.

IV. Optimal Aperture Size

Field produced by a uniform aperture with a certain size can be calculated by (4) at different *z* planes. Then, by applying the definition described in previous section, the 3dB beam radius can be calculated for each plane.

We observed that the 3dB beam radius is independent of the type of the current sources. Fig. 4 shows an example of the 3dB radius along the propagation direction (*z*-axis) for a uniform aperture ($a = 5\lambda$) with the electric, magnetic or Hyugen's currents through two materials (free space and a medium with $\varepsilon_r = 10,\ \mu_r = 1,\ \tan\delta = 0.2$). It can be seen that the 3dB radius has the same values for these three types of current apertures. This is because the 3dB beam radius is a relative value (compared to the maximum) and the electromagnetic waves have the property of superposition (Maxwell equations are linear ones). Therefore, we need to take into account only one type current, say Hyugen's source, for the following discussion.

Fig. 5 shows the 3dB radius along the propagation direction (*z*-axis) in the near-field radiating zone ($z \leq 2\,(2a)^2/\lambda$) for apertures with different sizes through free space and brain tissue [8]. From the figure, we can see that the beam is formed at different distances from the apertures with different sizes, and when the beam is formed, the beam radius has its minimum (we refer this to as the near-field focus). We express this minimum 3dB radius as r_{3dBmin} and its location as z_{3dBmin}. The scattering and disturbance from a foreign object will be the strongest if the foreign object is located at a "long tube" after z_{3dBmin} about

$5{\sim}10\lambda$ compared to other locations. From Fig. 5, we can see also that at a certain distance in a media, there is an optimal size of uniform aperture which has r_{3dBmin} at this depth. For example, in brain tissue at $z = 10\lambda$, the aperture with $a = 3\lambda$ has the minimum r_{3dB} of 1.2λ.

The effect of different media on the 3dB radius has been investigated in this work. Figs. 6 and 7 show r_{3dBmin} and z_{3dBmin} as a function of aperture size for five media whose electric properties are listed in Table I. From the figures, we can conclude: i) Loss in medium increases the values of r_{3dBmin} and z_{3dBmin}, and the medium loss has larger effect on larger apertures than smaller ones; ii) The changes of medium's permittivity do not change the ratio of r_{3dBmin}/λ and z_{3dBmin}/λ, where λ is the wavelength in the medium. This can be clearly observed by the curves of Hypothetical media 1 and 2 in Figs. 6 and 7.

We have further investigated 20 media. From them, by using a least square error polynomial curve-fitting scheme, we conclude an empirical formula of r_{3dBmin}/λ and z_{3dBmin}/λ as a function of the aperture size a/λ and the medium loss tangent (tan δ) as

$$\begin{aligned}\frac{r_{3dBmin}}{\lambda} &= (0.2067 - 0.1985\tan\delta) \\ &+(0.2060 + 0.3650\tan\delta)\left(\frac{a}{\lambda}\right)\end{aligned} \tag{8}$$

$$\begin{aligned}\frac{z_{3dBmin}}{\lambda} &= (0.3101 - 1.6993\tan\delta + 3.2400\tan^2\delta) \\ &-(0.0102 - 0.2552\tan\delta + 0.6960\tan^2\delta)\left(\frac{a}{\lambda}\right) \\ &+(0.7632 - 0.8137\tan\delta - 0.2149\tan^2\delta)\left(\frac{a}{\lambda}\right)^2\end{aligned} \tag{9}$$

Using the above formulae, when a detection depth in a sensing system is decided, an optimal aperture size can be determined. In an array antenna, if we excite part of the array elements by using the above formulae to have a changeable size of the aperture, we can scan the lossy medium under test, along the depth and improve the sensing system's performance.

Table I Electric properties of five investigated media.

Medium	ϵ_r	$tan\delta$
Free Space	1	0
Fat	10	0.04
Hypothetical 1	10	0.2
Hypothetical 2	5	0.2
Brain tissue	57.5	0.38

V. Verification

In presence of an object in a lossy medium, if an aperture has a smaller 3dB radius near the object, the scattered power from the object should be higher. In order to verify this hypothesis a model with a PEC sphere with a radius of 1.2λ in front of a Huygen's source aperture in free space is created in CST MS [9]. Three uniform apertures with radius of 2λ, 5λ and 8λ are chosen in this case. From Fig. 5, the aperture with a radius of 5λ will have a "focus" along $z = 20\sim30\lambda$, and other two do not. Fig. 8 shows the relative scattered field level when the metal sphere is located at $z = 25\sim30\lambda$. It can be seen that the scattered field by the aperture of 5λ radius illuminating is about 3dB and 6 dB higher than that by the apertures of 2λ radius and 8λ radius, respectively. Note that in order to have a scattering field from the metal sphere in CST, the medium should be lossless. Nevertheless, this verification case indicates that an optimal size of the uniform aperture will have the strongest scattering from a foreign object in lossy medium.

VI. Conclusions

We have presented the optimal size of uniform aperture for different depth of detection in lossy materials. An empirical formula for determining the relation between the aperture size and the location of the minimum bean radius is provided.

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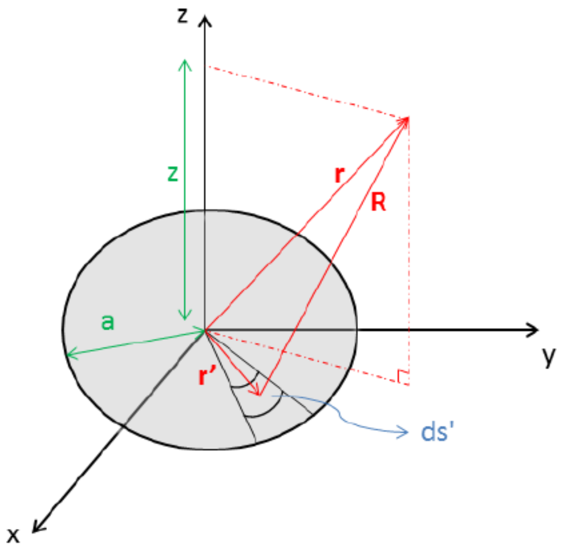

Figure 1 Geometry of a circular aperture.

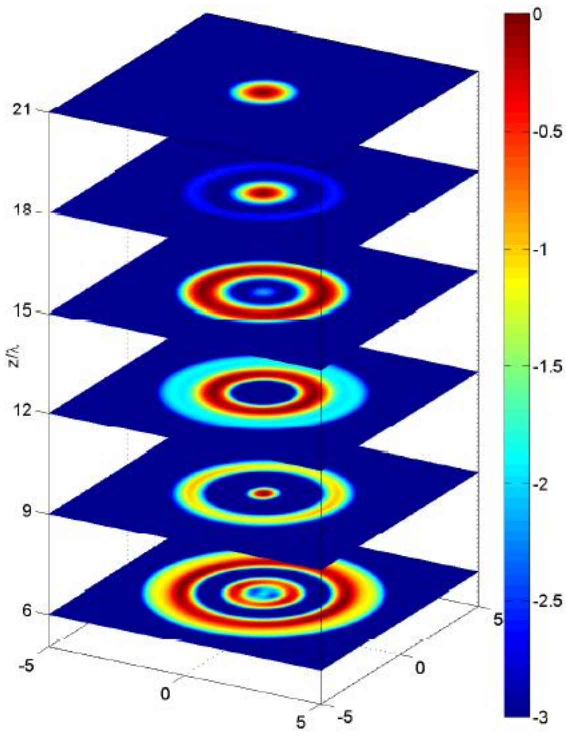

Figure 2 Example of field distribution in different *z* planes.

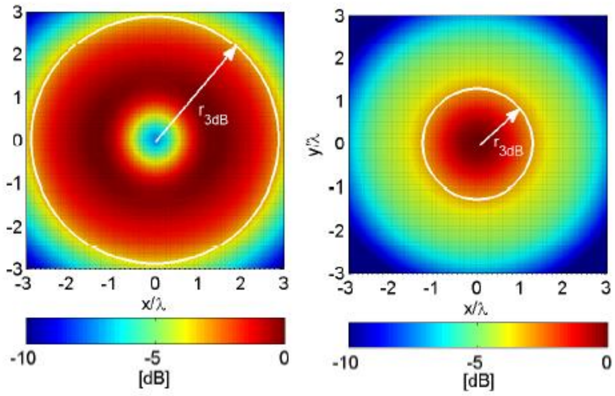

Figure 3 Illustration of the definition of 3dB near-field beam radius, shown by the white circle.

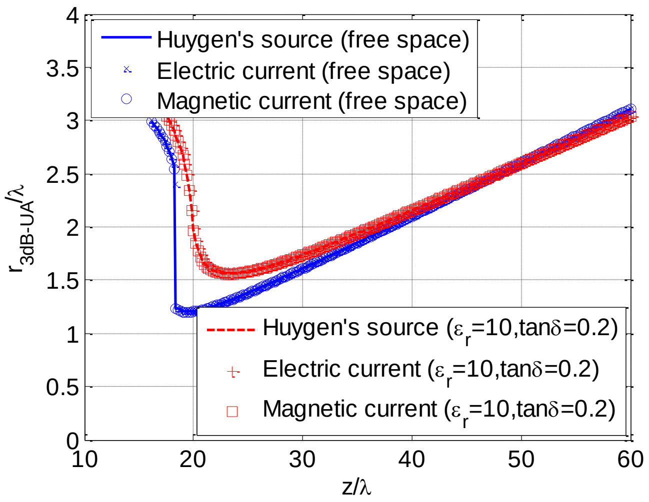

Figure 4 Comparison of beam radius profile produced by different current source types on an aperture of radius $a = 5\lambda$. Blue curves show the free-space case and red curves show a medium with $\varepsilon_r = 10$ and $\tan\delta = 0.2$.

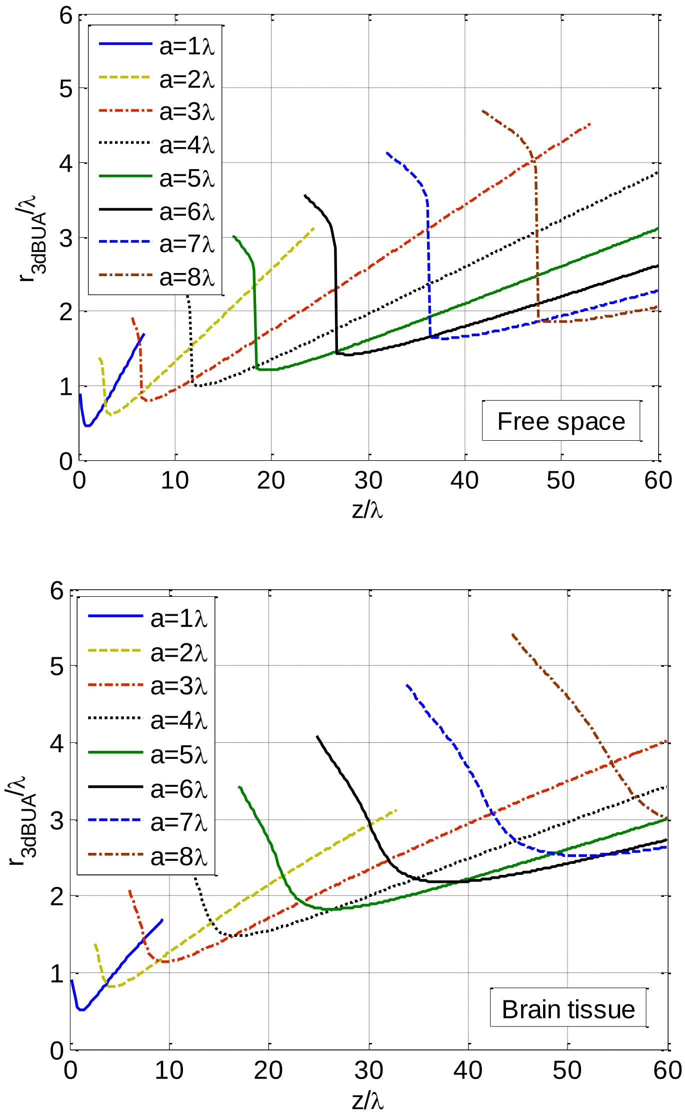

Figure 5 Values of 3dB beam radius along the propagation direction (*z*-axis) for uniform apertures with different sizes (*a* is the radius of the aperture) in free space (top) and brain tissue (bottom).

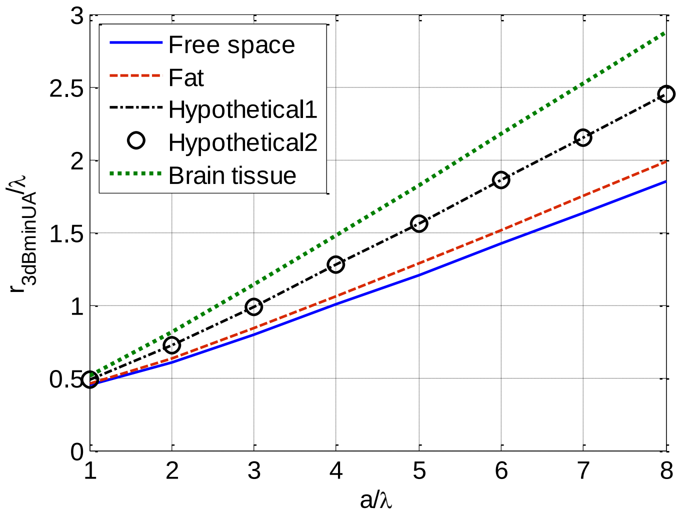

Figure 6 Minimum 3dB near-field beam radius vs. aperture size in different lossy media, where λ is the wavelength in the medium.

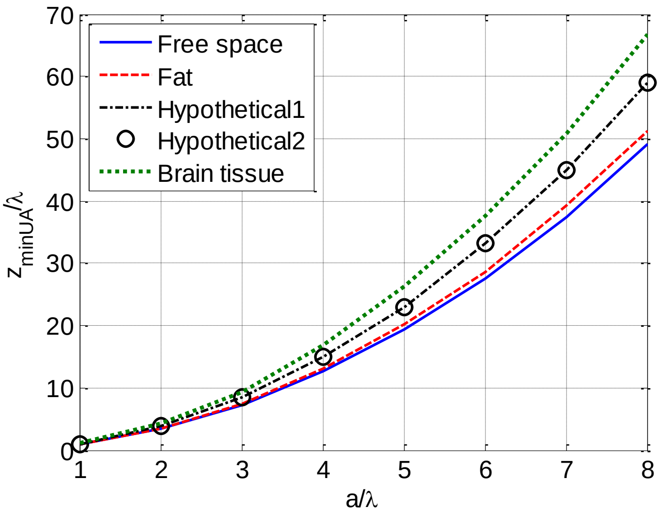

Figure 7 Distance of the minimum 3dB near-field beam radius from aperture vs. aperture size in different lossy mediua, where λ is the wavelength in the medium.

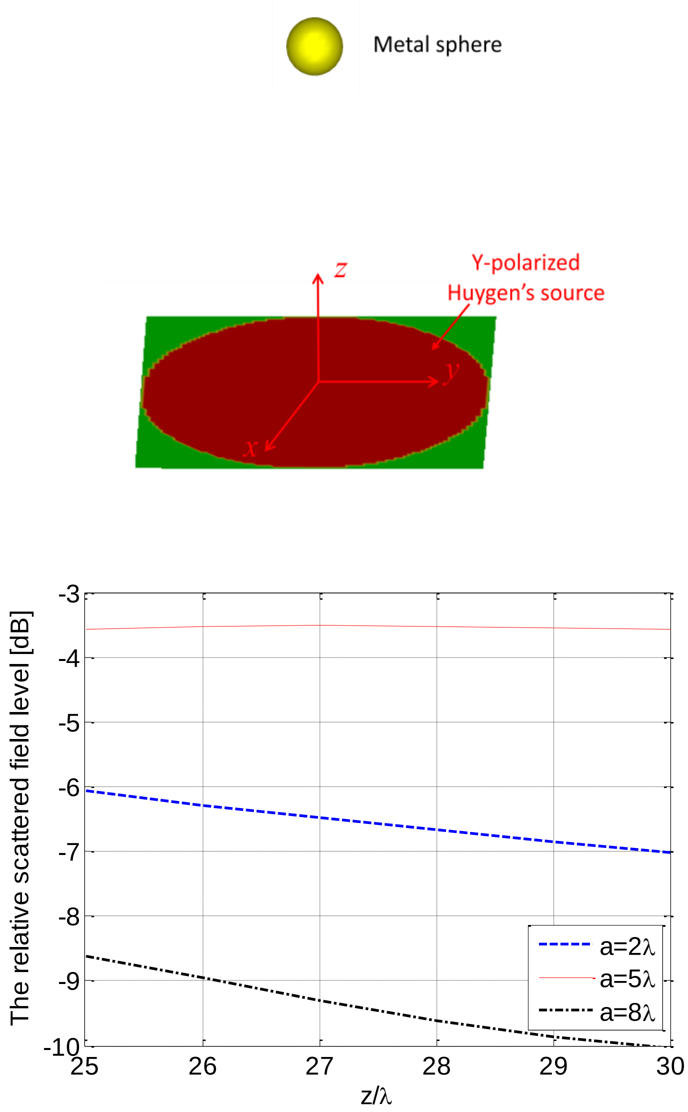

Figure 8 A verification model in CST: the set-up in CST (top); the relative scattering field level from a metal sphere with a radius of 1.2λ located at $z = 25{\sim}30\lambda$ (bottom).