ENERGY ABSORPTION FROM SMALL RADIATING PROBES IN LOSSY MEDIA

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Theoretical calculations of energy deposition around small antenna probes in lossy media have been made and are reported here. Such small probes have been used or proposed for use in dielectric constant measurements, hyperthermia threatment of small tumors, and microwave spectroscopic investigations of liquids. The results of this investigation are instructive in all of the above cases, but are particularly helpful for those interested in hyperthermia.

The design of probes has varied depending upon the desired use. Basically, these probes are open-ended coaxial lines with the center conductor extending beyond the outer conductor by an amount which is always a small fraction of a wavelength in the medium. The authors' interest in these evaluations stems from the use of this type of probe for coupling microwave energy into dielectric media and the subsequent observation of absorption as a function of frequency with an optical heterodyne technique (Davis and Swicord, companion paper, this conference).

Two theoretical models were used and compared, a short dipole antenna and an open-ended coaxial cable replaced with its equivalent magnetic current. The dipole model yields exact results for the fields. The calculated fields, however, become infinite as one approaches the origin, yielding an infinite value for the total power absorbed in a small sphere or radius R. This method can be used for calculating isopower contours in the far field.

The second theoretical approach follows the far field, free space calculation made by Jordan and Balmain in which the surface separating the inner and outer conductor of the coaxial cable is replaced by an equivalent magnetic sheet. The results must be integrated numerically. An examination of the results by either method indicates that extraction of exact values of the absorption coefficient in the near field of this particular antenna design is at best very difficult if not impossible due to the complexity of the equations. Any attempt to use the results in the far field is also difficult because of the poor microwave induced heating of the liquid in this region. Thus an alternative method is suggested. The fields calculated from the open coax method remain finite in value as one approaches the origin allowing for the calculation of the relative total power absorbed in a sphere of radius R. Such calculations and their implications for hyperthermia will be presented. Isocontour plots of absorbed power for various values of frequency, dielectric constant, loss tangent and antenna dimensions will also be presented.

Theoretical calculations of energy deposition around small antenna probes in lossy media have been made and are reported here. Such small probes have been used or proposed for use in dielectric constant measurements (1); hyperthermia treatment of small tumors (2), and microwave spectroscopic investigations of liquids (3). The results of this investigation are instructive in all of the above cases but are particularly helpful for those interested in hyperthermia.

The design of probes has varied depending upon the desired use. Basically these probes are open-ended coaxial lines with the center conductor extending beyond the outer conductor by an amount which is always a small fraction of a wavelength in the medium. The outer conductor at the point of termination may be extended radially outward to form a ground plane. It has been previously shown that the (impedance) response of this type of probe in a lossy medium is approximately the same with or without the extended ground plane.(4).

The authors' interest in these evaluations stems from the use of this type of probe for coupling microwave energy into dielectric media and the subsequent observation of absorption as a function of frequency with an optical heterodyne technique (5). The probe used was an open-ended coaxial line with an inner diameter of 0.8 mm and an outer diameter of 4 mm. No ground extension was used and the center conductor extended less than 0.1 mm beyond the outer conductor. The principal question of interest was whether or not the exact value of the attenuation constant could be determined from measurements of absorption as a function of distance from the probe (5).

Two theoretical models were used and compared, a short dipole antenna and an open-ended coaxial cable replaced with its equivalent magnetic current. The dipole yields exact results for the fields. In this case, the absorbed power in cylindrical coordinates is

$$\sigma |E|^2 = \frac{\sigma e^{-2\alpha r}}{(\sigma^2+\omega^2\epsilon^2)}\left[\frac{I\,dl}{4\pi}\right]\frac{1}{r^2}\left\{\left(1-\left(\frac{z}{r}\right)^2\right)\left(|\gamma^2|^2+\frac{2\,\mathrm{Re}(\gamma\gamma^{2*})}{r}+\frac{2\,\mathrm{Re}(\gamma^2)}{r^2}\right)+\left(1+3\left(\frac{z}{r}\right)^2\right)\left(\frac{|\gamma^2|^2}{r^2}+\frac{2\,\mathrm{Re}\,\gamma}{r^3}+\frac{1}{r^4}\right)\right\}$$

where $r = \sqrt{z^2+\rho^2}$, $\gamma = \alpha + i\beta$

$$\begin{pmatrix}\alpha \\ \beta\end{pmatrix} = \omega\sqrt{\frac{\epsilon\mu}{2}\left(\sqrt{1+\frac{\sigma^2}{\epsilon^2\omega^2}} \mp 1\right)}$$

$\sigma E^2$ becomes infinite as one approaches the origin. This is the result one would expect from a point source.

The integral of $\sigma E^2$ over a sphere of radius R is also infinite, unless small values of R are neglected. This apparent break down in the model does not stem from antenna construction(presence or absense of insulation)as suggested by some authors (6), since no assumptions concerning antenna construction were made. The explanation lies, rather, in considerations of the amount of power needed to drive an infinitesimial dipole. This method can, however, be used for calculating isopower contours in the far field.

The second theoretical approach follows the far-field, free-space calculation made by Jordan and Balmain (7), in which the surface separating the inner and outer conductor of the coaxial cable is replaced by an equivalent magnetic sheet. The resulting electric fields in the lossy medium in cylindrical coordinates are:

$$E_{\rho'} = \frac{k}{4\pi}\int_0^{2\pi}\int_A^B \frac{z'\cos\varphi\, e^{-\gamma r}}{r^2}\left(\gamma+\frac{1}{r}\right)d\rho\, d\varphi$$

$$E_{z'} = \frac{k}{4\pi}\int_0^{2\pi}\int_A^B \frac{\cos\varphi\, e^{-\gamma r}}{r}\left\{\frac{1}{\rho'}+\frac{1}{r}\left(\gamma+\frac{1}{r}\right)(\rho\cos\varphi-\rho')\right\}d\rho\, d\varphi$$

where $r = \sqrt{\rho^2+\rho'^2+z'^2+z^2-2\rho\rho'\cos\varphi}$

A and B are the inner and outer radii of the coax.

The above integrals were evaluated numerically and $\sigma E^2$ calculated. An examination of these results or the results obtained with the dipole approximation, indicate that extraction of exact values of the absorption coefficient in the near field of this particular antenna design is at best very difficult if not impossible due to the complexity of $\alpha$ in the equation. Any attempt to use the results in the far field is also difficult because of the smallness of the microwave induced heating of the liquid in this region. Thus, an alternative method is proposed (5).

Figure 1 demonstrates the difference in the results obtained from the two models. The antenna is located along the $z$-axis with the open-end of the coax lying in the x,y plane $z=$ zero). The upper solid curve is obtained from the dipole approximation. As discussed previously the field values blow up as one approaches the origin. The open-ended coax is not small compared to the dimension presented in figure 1. Due to its large size compared to the observation distance, one would expect slow variation of the field values with distance as predicted by the open coax approximation and shown by the lower solid curve of figure 1. The fields for this method of calculation remain finite in value as one approaches the origin allowing for the calculation of the relative total power absorbed in a sphere of radius R. Such calculations and their implications for hyperthermia will be presented at the conference.

A typical isocontour plot for $\sigma E^2$ using the open-ended coax approximation is shown in figure 2. The contours indicate a large degree of spherical symmetry in absorption close to the antenna. This symmetry decrease rapidly for large distances due to the lack of radiated power ($1/r^2$ terms) in the $z$ direction. The effects of various parameters and possible scaling methods will be further discussed at the conference.

## REFERENCES


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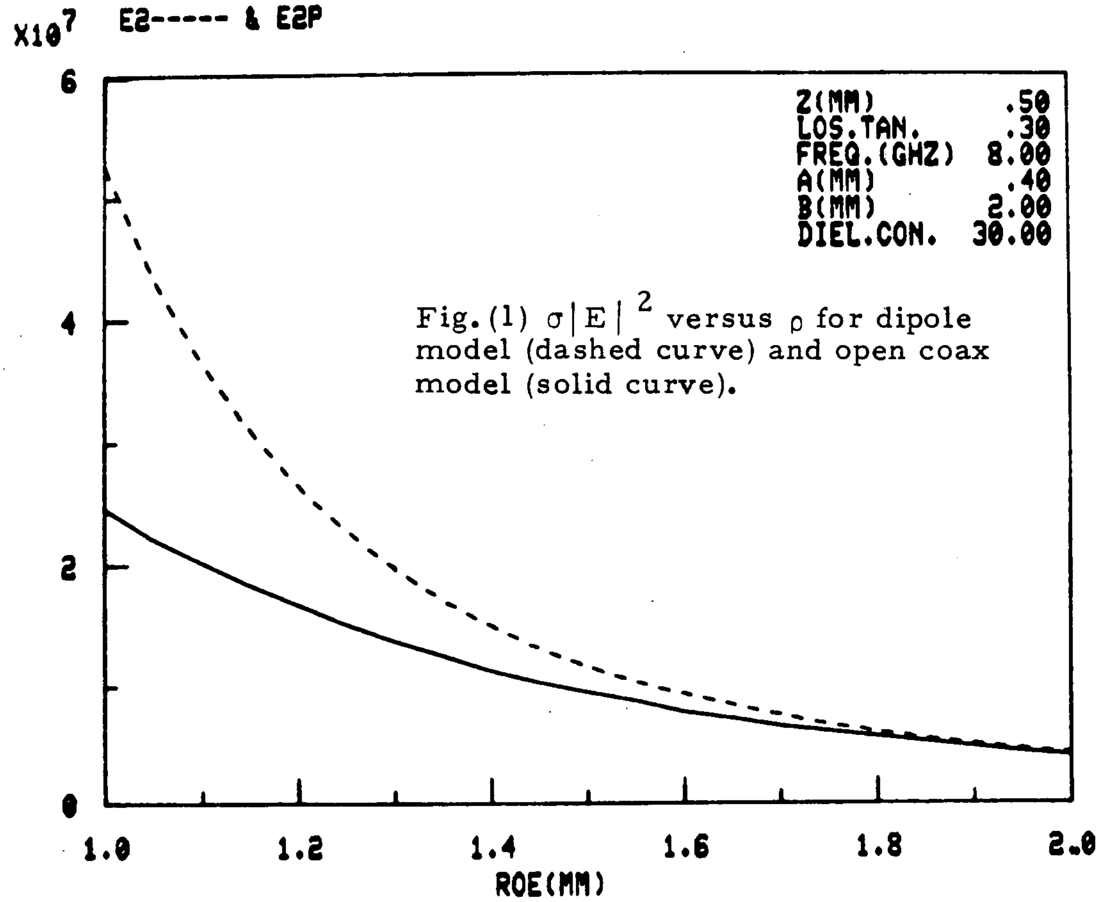


Fig. (1) $\sigma|E|^2$ versus $\rho$ for dipole model (dashed curve) and open coax model (solid curve).

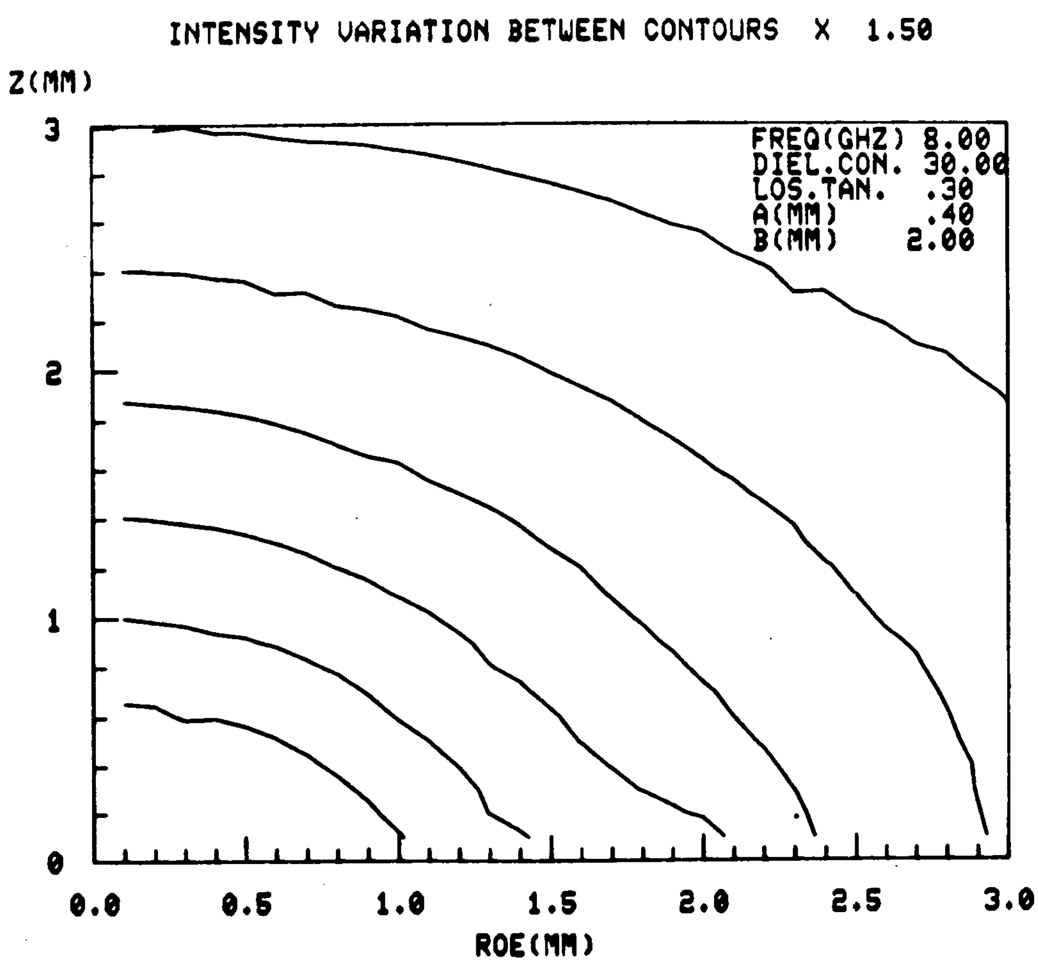


Fig. (2) Contours of $\sigma|E|^2$ calculated using open coax model.