A novel antenna design for soil decontamination with microwaves

M. Pauli\(^1\), T. Kayser\(^1\), and W. Wiesbeck\(^1\)

\(^1\)Universität Karlsruhe, Institut für Höchstfrequenztechnik und Elektronik, Kaiserstrasse 12, 76131 Karlsruhe, Germany
Phone: +49 721 608 6259, E-Mail: mario.pauli@ihe.uka.de

Abstract—This paper deals with the investigation of different antenna types suited for high power microwave applications at a frequency of 2.45 GHz. The antennas presented here are intended to be deployed in a microwave assisted soil decontamination process. For this purpose, an antenna has to fulfill several requirements. The radiation pattern has to be omnidirectional in the azimuthal plane and the radiated power should be uniformly distributed over the complete antenna length. This is necessary to achieve a homogeneous heating of the surrounding soil. For these reasons, a coaxial antenna design was chosen. The antenna matching strongly depends on the complex permittivity of the surrounding soils. Since the dielectric properties of the soil change with moisture content and temperature the antennas must provide a sufficient matching over a wide range of permittivity. Two possible antenna designs are presented with simulated values for the matching and the field distribution in the soil and the antenna, respectively. A comparison between simulated and measured values is given for verification. Subsequently, the temperature distribution inside the soil is measured in a laboratory setup.

I. INTRODUCTION

In different situations such as traffic accidents involving tankers, or idle industrial sites, soil contaminations can occur. In most cases the soils are polluted with halogenated hydrocarbons, mineral oils, fuels, aromatic hydrocarbons or heavy metals. These contaminations are dangerous for humans, animals and the environment. In Germany, an exact determination of the contaminated areas with respect to quantity and size is impossible. According to information issued by the German Government there exist more than 10500 contaminated sites and over 230000 sites that are suspected to be contaminated [1]. To minimize the risk of exposure to humans, remediation of contaminated areas is necessary. It is also of extreme importance for the conservation of the environment and for ecological recovery. For soil remediation several technologies exist. These can be divided into two groups: in-situ and ex-situ technologies. Ex-situ methods, where the contaminated soil is excavated, are most common. They are extremely invasive and create additional possible dangers, e.g. releasing toxic gases during the excavation process.

Therefore, a new in-situ technology for remediation of soils contaminated with volatile organic compounds is being investigated and presented in this paper. In-situ means that there is no need to excavate the soil and the remediation process takes place in the contaminated area. A schematic of the decontamination system can be seen in Figure 1.

The microwaves are generated using a magnetron with an operating frequency of 2.45 GHz. The microwave energy is coupled into the soil by the use of slotted coaxial antennas. Due to the losses of the surrounding soil and the contaminants, the soil is heated and the contaminants evaporate. The so generated gases are exhausted by in-grounded suction tubes near the antennas and by a suction socket on the surface. This socket also serves as an electromagnetic shielding of the whole system.

After extraction, the gases are condensed and collected for disposal and analysis, respectively. Subsequently, the gases are filtered by active carbon filters and leave the system as clean air.

In this paper, the focus is on the design of antennas suited for this application. The operational frequency is 2.45 GHz and the antennas must handle a power of several kW. Furthermore, the antenna has to fulfill several requirements: the electromagnetic energy has to be radiated omnidirectionally in the azimuthal plane and also uniformly over the length of the antenna. To avoid soil and humidity inside the antenna either a thin radome or a dielectric filling is used.

For the use in deeper soil regions a coaxial antenna offers some advantages. Due to the design of the antenna it can easily be inserted into the ground. The microwave energy couples through slots in the outer sheath of the antenna nearly omnidirectionally into the surrounding soil and the radiation is uniform along the antenna. Since the antenna has a modular design, a good matching can be achieved over a wide range of soil types and moisture contents.
The complex permittivity of the soil plays an important role in the antenna design. For this reason, it is necessary to know the complex permittivity of the soil. However, the dielectric properties do not only depend on the type of the soil but also on the moisture content, the frequency, the temperature and the salinity [2]. Different soil samples have been investigated and the complex permittivity has been determined as a function of gravimetric moisture content and temperature. The complex permittivity \( \varepsilon_r = \varepsilon_r' - j\varepsilon_r'' \) for sand with different gravimetric moisture contents is shown in Figure 2. The solid line shows the real part of the complex permittivity while the dashed line corresponds to the imaginary part, indicating the losses of the material.

It can be seen that the real part of the permittivity increases with higher moisture content and ranges from \( \varepsilon_r' = 2.8 \) to \( \varepsilon_r' = 12.7 \). The imaginary part also increases with the moisture content and varies between \( \varepsilon_r'' = 0.01 \) and \( \varepsilon_r'' = 1.6 \). This means that loss factor lies between \( \tan \delta = 3.5 \times 10^{-3} \) and \( \tan \delta = 0.126 \). Additionally, several other soil samples have been measured and the dielectric properties showed to be approximately in the same range. A comparison of the measured data with literature [3] shows a good agreement. More measurement results can be found in [4]. A detailed description of the measurement setup and the reconstruction algorithm is given in [5].

## III. COAXIAL ANTENNA DESIGNS

For contaminations in deeper regions of the ground, it is necessary that the antenna can be inserted sufficiently deep. Via these antennas the microwave energy is symmetrically radiated around the antenna and uniformly along the slotted length. In this way, the contaminants within the soil are uniformly heated around the antenna and can be evaporated. These requirements are fulfilled by a leaky coaxial antenna. During the heating process the moisture content in the soil decreases, leading to lower values of the permittivity, as can be seen in Figure 2. By a modular construction of the antenna, a good matching can be achieved over a wide range of permittivity. The coaxial antenna is shorted at one end with a metal plate whereas the inner conductor is screwed onto the shorting plate. In this way, the inner conductor can easily be replaced by another one with a different diameter to allow for a good matching under varying soil conditions. Furthermore, the antenna can be filled with a dielectric material which can additionally improve the matching at different environmental conditions.

Position, size and design of the slots have an influence on the antenna efficiency and on the field distribution around the antenna. The maximum field around the antenna is achieved when the slots are placed in the maxima of the surface currents and in the maxima of the magnetic field inside the antenna, respectively. These slots are placed around the outer conductor in 10 periodic levels, each with 2 horizontal slots. The distance between two slot levels is \( \lambda/2 \) and each level is rotated \( 90^\circ \) with respect to each other. The dimensions of the antenna are a tradeoff between small antenna size, high power capability and the prevention of higher order modes.

Since an omnidirectional radiation pattern is desired it is necessary to have a symmetric field distribution inside the antenna. For this, the principal mode or TEM-mode (transverse electromagnetic mode) of the coaxial antenna is required. In order to suppress higher modes inside the coaxial antenna that can interact with the basic TEM-mode, the dimensions of outer \( r_o \) and inner \( r_i \) conductor are limited to [6], [7]

\[
\frac{r_o - r_i}{\lambda_0} \leq \frac{\lambda_0}{2\sqrt{\varepsilon_r}}
\]

with the free space wavelength \( \lambda_0 = c_0/f = 122.5 \text{ mm} \).

## IV. AIR-FILLED COAXIAL ANTENNA

In case of an air filled coaxial antenna the maximum power \( P_{\text{max}} \) that can be transmitted only depends on the highest allowable field strength. In the case of dry air the breakdown field strength is in the range of 3 kV/mm, depending on pressure, temperature and humidity [8].

According to

\[
P_{\text{max}} = \frac{E_{\text{max}}^2}{1200\Omega} \ln \frac{r_o}{r_i}
\]

the theoretical maximum power that can be transmitted is in this case more than \( P_{\text{max}} = 2.5 \text{ MW} \). However, it has to be taken into account, that the breakdown field strength drops rapidly with increasing humidity. For safety reasons the field strength should not be beyond 10 % of the breakdown field strength, i.e. 300 V/mm. This reduces the maximum power to 1/100. In the laboratory setup, a maximum power of 2 kW is used.

### A. Antenna Design

A schematic of the antenna including all relevant dimensions is shown in Figure 3. Assuming the same number of slots, the antenna length has no influence on the antenna characteristics. In this way the antenna can be easily adapted to different depths. On one side the antenna is shortened and

![Figure 2: Permittivity (-) and losses (-) of sand as a function of gravimetric moisture content](image-url)
the first slot is placed at a distance of $\lambda/2$ from the shorting plate. The inner and outer conductors of the antenna consist of aluminum.

The antenna is directly coupled to the output of the microwave generator. A standard rectangular S-band waveguide with cross-section dimensions of $a = 86.36 \text{ mm}$ and $b = 43.18 \text{ mm}$ forms the output of the generator. In this waveguide an $H_{10}$ mode propagates. With the feeding system this mode is transformed into the TEM-wave required for the coaxial antenna. The outer conductor of the antenna is directly tapered on the rectangular waveguide, as can be seen in Figure 4. Here, the smaller radius of the transition is $r_{\text{taper}} = 17 \text{ mm}$, the taper length is $l_{\text{taper}} = 32 \text{ mm}$, and the outer radius of the taper corresponds to the radius of the coaxial antenna. The inset depth of the inner conductor into the waveguide is $d = 22 \text{ mm}$ and the distance to the shorted end of the waveguide is $d_i = 30.5 \text{ mm}$.

In Figure 5 a picture of the antenna and the coaxial-to-waveguide transition is shown. The spike on the one side simply has a practical purpose as it allows an easier insertion of the antenna into the soil.

Fig. 3. Schematic of coaxial antenna with dimensions in mm

| length l | 1000 |
| outer radius $r_o$ | 35 |
| inner radius $r_i$ | 4 |
| slot distance a | 61 |
| slot width b | 47 |
| slot height h | 9 |

Fig. 4. Waveguide to coaxial transition

B. Antenna Matching and Field Distribution

In this section simulated results of the matching of the coaxial antenna inserted in sand are presented and compared to measured results of the reflection factor. The complex permittivity of the sand used is $\varepsilon_r = 2.8 - j0.084$. This corresponds to a dry sand. Simulations are performed with Ansoft HFSS (High Frequency Structure Simulator). In simulations the antenna is placed inside a soil cylinder, resulting in a rotationally symmetric model. The cross-section of the model can be seen in Figure 7. To save computing time, only a quarter of the model is simulated. In the case of soils with low losses it is possible that not all energy is dissipated in the soil volume. To avoid reflected energy at the soil boundary, the boundary conditions of the outer soil surface are set to radiation boundary. Thus, the soil can be treated as an infinite volume.

For the measurements the antenna is inserted into sand with a known permittivity and connected to an Agilent E8357A vector network analyzer (VNA). The reflection coefficient $S_{11}$ is measured. Simulations and measurements are performed in a frequency range from 2–3 GHz. Simulated and measured values for $S_{11}$ agree well as can be seen in Figure 6. In both cases $S_{11}$ is smaller than $-20 \text{ dB}$ at 2.45 GHz.

Additionally, the field distribution inside the antenna and the surrounding environment is investigated in simulations. The soil around the antenna has a depth of $d = 1 \text{ m}$ and an outer radius of $r_{\text{soil}} = 0.1 \text{ m}$. In the simulations the input power of the antenna is set to 1 W. Figure 7 shows the electric and magnetic field configuration in the soil as a cross-sectional plot. The fields between the inner and outer conductor are shown, and it can be seen that the slots are placed in the maxima of the magnetic field strength to obtain high radiation.
Inside the soil the power is coupled out uniformly along the antenna.

V. PTFE-FILLED COAXIAL ANTENNA

In a next step the coaxial antenna is filled with Polytetrafluoroethylene (PTFE, Teflon) as a dielectric. PTFE offers well-suited dielectric properties: The specific resistance is nearly independent of temperature and is in the range of $10^{18}$ Ωcm. The permittivity is $\varepsilon_r' = 2.1$ and is frequency independent between 50 Hz and 10 GHz. Additionally, the dielectric properties are constant in a temperature range from $-50^\circ$C to over $200^\circ$C. The loss factor is $\tan \delta = 0.001$ and the break down field strength lies between 50–80 kV/mm.

The maximum power that can be transmitted by the antenna is in this case not limited by the maximum field strength but by the losses inside the PTFE. According to (2) the maximum power is more than 690 MW, but the dielectric losses inside the material limit the maximum power to

$$P_{\text{max}} = (T_{\text{max}} - T_0) \cdot \frac{4\pi \sqrt{\varepsilon_r' \sigma_c}}{\omega \varepsilon_0 \varepsilon_r'' \ln(r_o/r_i)} \quad (3)$$

With the dielectric properties of PTFE, a thermal conductivity $\sigma_c$ of 0.3 W/Km and a maximum temperature at the inner and outer conductor of 200 $^\circ$C and 150 $^\circ$C, respectively, this results in a maximum power capability of more than 4.3 MW for a diameter of the inner conductor of $6 \text{ mm}$, and more than 11.7 MW for an inner conductor of $24 \text{ mm}$ diameter.

A. Antenna Design

The antenna design is similar to the design of the air-filled coaxial antenna. Due to the dielectric filling the wavelength is shortened by a factor of $\sqrt{\varepsilon_r'}$ and consequently the slot distance is decreased. The antenna dimensions can be found in Table I. The diameter of the inner conductor is set to $6 \text{ mm}$ if the soil permittivity is below $\varepsilon_r' = 5$ and to $24 \text{ mm}$ for higher permittivities.

B. Antenna Efficiency

Since the difference between the dielectric constant of PTFE and the surrounding soil is lower than in the case of air as dielectric the matching of the antenna improves. As can be seen in Figure 8 the reflection coefficient is better than $-10 \text{ dB}$ in a permittivity range from $\varepsilon_r' = 2$ to $\varepsilon_r' = 10$. The loss factor in this case is set to $\tan \delta = 0.01$ and has only little influence on the antenna matching.

From $\varepsilon_r' = 2$ to $\varepsilon_r' = 5$ the inner conductor has a diameter of $6 \text{ mm}$ and for higher permittivities the diameter increases to $24 \text{ mm}$. The power that is dissipated into heat in the PTFE equals approximately 34 mW. This corresponds to a reflection factor of better than $-10 \text{ dB}$, and to a minimum antenna efficiency of 90%.

VI. TEMPERATURE MEASUREMENT

Since it is difficult to measure the electric field inside the soil directly, the temperature distribution is investigated. The temperature gives an indirect measure for the electric field. Hence, as a first approximation a homogeneous temperature implies a homogeneous field distribution. This is especially true for short time periods since in this case thermal conduction can be neglected. The dissipated energy inside a lossy material can be calculated by

$$dP = 2\pi f \varepsilon_0 \varepsilon_r'' |E|^2 dV \quad (4)$$

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**TABLE I**

<table>
<thead>
<tr>
<th>Dimensions of PTFE-filled antenna</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>length in mm</td>
<td>1000</td>
</tr>
<tr>
<td>outer diameter in mm</td>
<td>60</td>
</tr>
<tr>
<td>inner diameter in mm</td>
<td>6</td>
</tr>
<tr>
<td>$\varepsilon_r' = 2-5$</td>
<td>6</td>
</tr>
<tr>
<td>inner diameter in mm</td>
<td>24</td>
</tr>
<tr>
<td>$\varepsilon_r' = 5-10$</td>
<td>24</td>
</tr>
<tr>
<td>wall thickness in mm</td>
<td>3</td>
</tr>
<tr>
<td>slot width in mm</td>
<td>40.1</td>
</tr>
<tr>
<td>slot height in mm</td>
<td>6</td>
</tr>
<tr>
<td>slot distance in mm</td>
<td>42.25</td>
</tr>
</tbody>
</table>

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Fig. 7. Electric (left) and magnetic (right) field distribution inside the soil

Fig. 8. Matching of the PTFE-filled antenna as function of soil permittivity
Equation (4) shows that the dissipated power and therefore the temperature is a function of the electrical field inside the soil. The measurement setup and results of the temperature measurements are presented in the following section.

A. Measurement Setup

Thermal measurements are performed with the laboratory measurement setup consisting of a magnetron with an output power of $P = 2 \text{ kW}$ and a tub filled with approximately $0.250 \text{ m}^3$ of sand. To avoid electromagnetic leakage the tub and its cover are shielded inside with copper foil. The laboratory setup is shown in Figure 9.

B. Measurement Results

The following results in Figure 10 show the temperature after a heating time of 60 min with a power of 2 kW. At a distance from the antenna of 5 cm and 10 cm, respectively, the temperature is nearly constant at depths from 15 cm to 45 cm. This indicates a homogeneous electric field. In the upper regions the temperatures decrease due to thermal radiation losses and in depths beyond 45 cm there are no slots in the antenna to radiate. The dash-dotted line represents a distance from the antenna of 20 cm. In this case, the temperature is homogeneous over the depth. It has to be mentioned that the moisture content in this measurement was relatively high. Therefore, the penetration depth of the microwaves is limited and the heating shown here is based primarily on heat conduction.

VII. CONCLUSION

In this work a novel antenna design for soil decontamination with microwaves was introduced. It has been shown that the antenna radiates omnidirectionally azimuthally and couples the energy uniformly over its whole length into the surrounding soil. In this way, the antenna is capable for remediation of deeper soil layers. Due to the modular design of the antenna with a replaceable inner conductor and the possibility to insert a dielectric, a good matching can be achieved over a wide range of soil conditions. A simulation result is shown with PTFE as dielectric. The matching was showed to be better than 10 dB for a soil permittivity range from $\varepsilon_r = 2$ to $\varepsilon_r = 10$. The simulation results of the air-filled antenna have been verified with measured values of the reflection coefficient. The uniform coupling along the antenna was shown by measuring the temperature at different depths in the laboratory setup. A homogeneous heating could be achieved in radial direction as well as in different depths.

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