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Developing of A Ground Penetrating Radar Antenna for Detecting Water Pollution in Underground Pipelines

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ABSTRACT

Full wave analysis of a prototype laboratory model of a pipe buried in sandy soil is used to examine the feasibility of using ground penetrating radar in detecting water pollution in underground water distribution systems. A wideband microstrip patch antenna with half and defected ground plane is designed for detection of pollution in buried plastic water pipes. The contrast in the dielectric constant between pure and polluted water is one of the most important parameters to be considered for detecting the presence of pollutants. The complex dielectric permittivity of water is measured and analytically represented by Cole-Cole fit model. The experimental set up is described and the procedure followed to obtain an effective permittivity data is outlined. Microwave technique developed in this manuscript is proved as a successful non-destructive technique in detecting water pollution in buried pipes.

Key words: water pollution, ground penetrating radar, reflection coefficient, microstrip antenna design.

1. INTRODUCTION

Recently, many parts of the world are suffering because of a lack of pure water. Contaminants present above a certain level in water are extremely harmful to human beings' health. The pollution of water in underground pipelines may be caused by the interaction of water with pipe material causing some types of bacteria. Water in underground pipelines may be also contaminated by leaks or explosions that may occur in the pipeline [1]. The detection and control of pollutants in water have great importance. Water pollution is detected in laboratories, where small samples of water are analyzed for different contaminants. However, testing for all known water contaminants is a complicated and expensive process.

Microwave propagation through obscuring layers is recently of tremendous interests with practical applications in security, inspection, and mine detection [2]–[4]. In the current study, simulations of the reflection coefficient of the water pollution detection model are conducted to determine the validity and effectiveness of Ground Penetrating Radar (GPR) technology in detecting water pollution in underground pipes. The scenario includes a plastic tube embedded in the soil and filled with water, which is represented as a multi-layer dielectric medium. The frequency of the radar signal used for this scenario is a trade-off. Low frequencies give better penetration but low resolution so that pipes may not be seen. Pipes may be seen using higher frequencies but the depth of penetration may be limited to only a few centimeters especially in the wet soil. The GPR frequency is dependent upon the antenna. In the current study, the design of a wideband antenna that offers a wide bandwidth from 0.5 GHz up to 3 GHz is presented. Results of this research indicate that microwave sensing is able to accurately discriminate between pure and polluted water.

2. MULTILAYER PROTOTYPE MODEL

The main goal of this research is to investigate the effectiveness of GPR as a tool for detecting water pollution in underground pipelines. To accomplish this goal, a prototype laboratory model is carefully designed. This model simply consisted of a wooden box filled with sand, in which a plastic PVC pipe is placed in soil for simulation. The geometry of the prototype model is shown in Figure 1 and the optimized dimensions, used for modelling, are tabulated in Table 1.

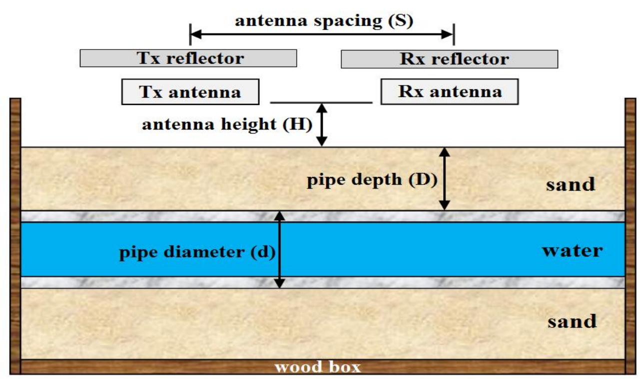

Figure 1: Multi-layer prototype water pollution detection model.

Table 1: Modelling dimensions of model

Parameter	Unit (cm)
soil box length	100
soil box width	50
soil box height	70
antenna height (H)	5
antenna spacing (S)	30
pipe burial depth (D)	20
diameter of pipe (d)	20
pipe material thickness	0.4

3. DIELELCTRIC MODELLING OF MATERIALS

The electromagnetic model for the scenario presented in Fig. 1 needs a dielectric modelling of materials of interest. Propagation of electromagnetic waves in materials such as dielectrics and conductors is determined by their electrical parameters. Permittivity describes the interaction of a material with an electric field and is a complex quantity:

$$\varepsilon = \varepsilon' - j\varepsilon'' \quad (1)$$

where $\varepsilon' = \varepsilon_0\, \varepsilon_r'$ is the dielectric constant, ε_0 the free space permittivity, ε_r' the relative dielectric constant, $\varepsilon'' = \varepsilon_0\, \varepsilon_r''$ is the dielectric loss factor and ε_r'' the relative dielectric loss factor of the dielectric. Cole-Cole relaxation model have been used to extrapolate the measured permittivity of a material to higher frequencies. The dielectric spectrum can be described by Cole-Cole function [5]:

$$\varepsilon(\nu) = \varepsilon_\infty + \frac{\varepsilon_S - \varepsilon_\infty}{1 + (i\omega\tau)^{1-\alpha}} - j\frac{\sigma}{\omega\varepsilon_0} \quad (2)$$

where ε_∞ is static permittivity, ε_S is the extrapolated high frequency permittivity, τ is the discrete relaxation time, and $\omega = 2\pi\nu$, where ν denotes the frequency, σ is the conductivity and α is an exponent factor.

At microwave frequencies, different measurement techniques can be used for the measurement of the dielectric permittivity [6]. In the current study, the complex dielectric permittivity of the materials of interest is measured using Dielectric Assessment Kit (DAK). DAK system is based on the open-ended coaxial probe technique. The dielectric probes are designed for fast, precise, non-destructive and easy to use measurements of liquids, solids and semi-solids in the 10 MHz to 67 GHz frequency range. The DAK user interface is intuitive to use and provides a wide range of graphical and numerical analyses. DAK interfaces with a vector network analyzer (VNA) to measure the impedance seen at the end of the open-ended coaxial probe, while DAK software on an external computer calculates the dielectric constant from the measurement. The sample volume should be large enough to ensure that reflections at the sample boundaries do not significantly influence the measurements. The minimum sample volume depends on the frequency, probe size and dielectric parameters. DAK measurement system setup is shown in Figure 2.

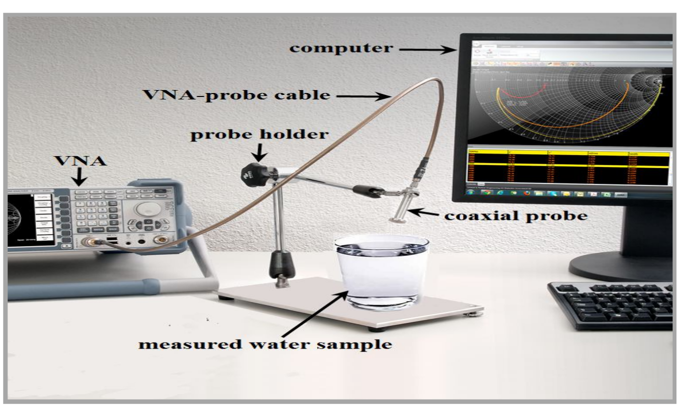

Figure 2: DAK measurement system setup.

The dielectric permittivity of pure and polluted water is measured at $25\,°C$ using DAK system. The polluted water sample is collected from Lake Qarun in the Fayoum of Egypt. Permittivity measurements using the DAK system can be fitted nicely by Cole–Cole function. A curve fitting routine is implemented based on the least square method to search for the most appropriate values of Cole-Cole fitting model parameters. The best fit sets of parameters of a Cole-Cole model for both measurements are tabulated in Table 2.

Table 2: Cole-Cole model parameters for measured water

Parameter	ε_∞	ε_s	$\tau\,(ps)$	α	$\sigma\,(s)$
Pure water	**5.43**	**78.52**	**9.45**	**0.0**	**0.0**
Polluted water	**1.14**	**73.38**	**10.21**	**0.0**	**3.95**

The dielectric constant and the dielectric loss factor of pure and polluted water at $25\,°C$ are compared in Figure 3.

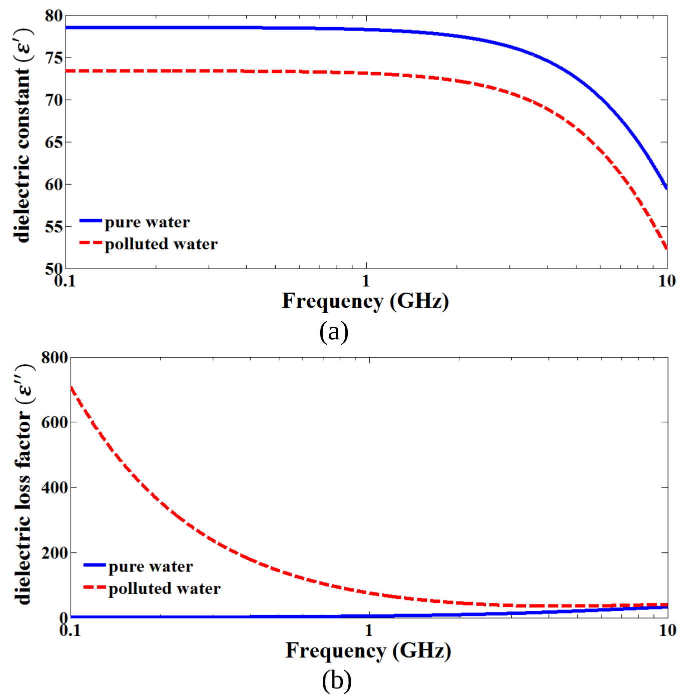

Figure 3: Measured permittivity of pure and polluted water at room temperature versus frequency [log scale] (a) dielectric constant (b) dielectric loss factor.

Microwave emission and backscattering of soil depend on its dielectric constant which affected by the moisture content. A dry sandy soil with dielectric constant of 2.53 and dielectric loss tangent of 0.0036 is used for modelling the soil [7]. Plastic PVC is one of commonly used materials in water service pipelines. PVC has dielectric constant of 2.25 and dielectric loss tangent of 0.01 [7].

4. ANTENNA DESIGN

The need to obtain a fine resolution and reasonable penetration depth for a portable GPR requires the antenna to have a certain features such as high gain, wide operational bandwidth, good impedance matching, compact in size and directional radiation pattern [8]. A circular patch antenna with half defected ground plane operating from 500 MHz to 3 GHz is proposed. This operational frequency range is suitable for the application of water pollution detection in underground pipelines. The antenna is designed using Computer Simulation Technology (CST) and Rogers RT5880 is used as a substrate with permittivity 2.2 and thickness 1.57 mm. Figure 4 shows the proposed structure of the antenna. In this design, the size of the substrate is 220mm x 220mm. The antenna is excited with 50 Ohm waveguide port. The length of the ground plane is the same as the length of transmission line of the circular patch antenna. A modification on the ground plane is done to obtain a wideband antenna where a staircase structure with the width, *g* is introduced. This modification is located exactly below the contact point between the transmission line and the circular patch. The circular radius, *r* is 75 mm, is calculated using the circular patch formula [9].

$$r = \frac{F}{\{1+\frac{2h}{\pi\varepsilon_r}[\ln\left(\frac{\pi F}{2h}\right)+1.7726]\}^{0.5}} \tag{3}$$

$$F = \frac{8.791 * 10^9}{f_r\sqrt{\varepsilon_r}} \tag{4}$$

Here, f_r is the operating frequency, ε_r is the dielectric constant of the substrate and h is the thickness of the substrate in cm.

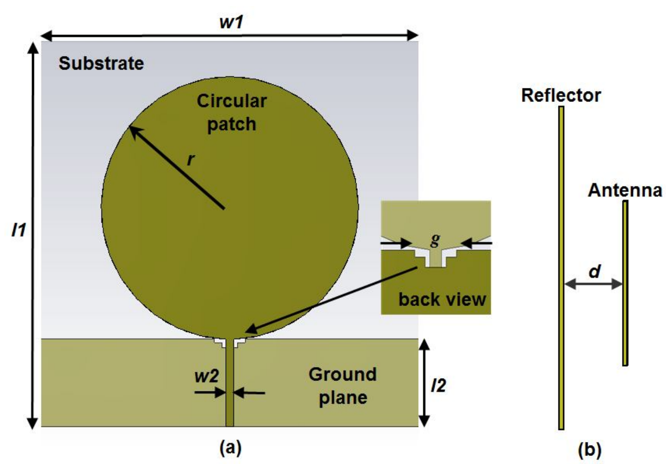

Figure 4: Geometry of proposed monopole antenna: a) top view, b) side view.

In order to obtain a unidirectional radiation pattern, the rectangular reflector is located at the back of the antenna with spacing, *d*. The overall optimized dimensions of the proposed antenna are shown in Table 3.

Table 3: Optimized dimensions of antenna

Antenna parameters	Unit (mm)
length substrate, *l1*	220
width substrate, *w1*	220
length ground plane, *l2*	50
radius patch, *r*	75
width trline, *w2*	5

Figure 5 shows the simulated return loss, S_{11} for the proposed antenna. As shown in Fig. 5, the -10 dB bandwidth of the antenna extend from 0.5 GHz to 3.0 GHz. The simulated 2D radiation pattern of the antenna with a reflector at 1GHz is shown in Figure 6. Interestingly, introducing the reflector at the back of the antenna makes the radiation pattern becomes more directional. Moreover, the gain of the antenna has increased up to 10 dB at 1GHz. With these improvements, the antenna with a reflector has better performances. These characteristics give advantages to the antenna as a GPR antenna because the signal can propagate deeper under the ground surface.

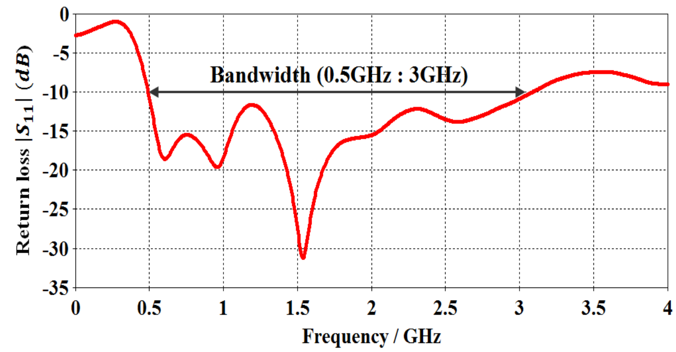

Figure 5: Return loss of designed antenna.

5. RESULTS AND DISCUSSION

The backscattered reflected signal coefficient from the transmitting antenna (antenna #1) to the receiving antenna (antenna #2), S_{21}, from the multi-layer media is simulated using Computer Simulation Technology (CST) in the range from 0.5GHz to 3GHz. Two configurations are performed; the first one is where pure water is placed inside the pipe as illustrated in Figure 1 while the second one is where polluted water is placed inside the pipe. The designed wideband GPR antenna presented in the previous section is used to collect GPR data. Different cases are studied such as the increase of moisture content of soil, change of the height of the antenna from the surface of the ground, change of the spacing between the transmitting and receiving antennas, the depth at which the pipe is buried, the change of the pipe diameter and the change of the thickness of pipe material.

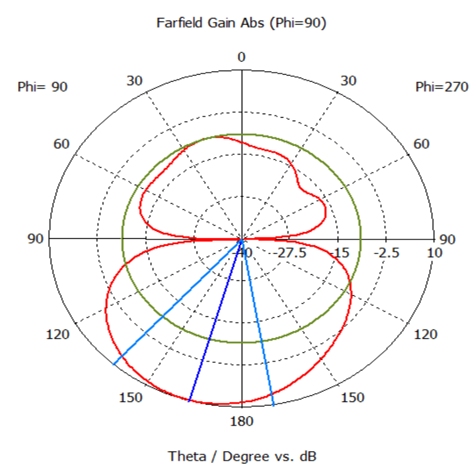

Figure 6: Radiation pattern of designed antenna with a reflector at 1 GHz.

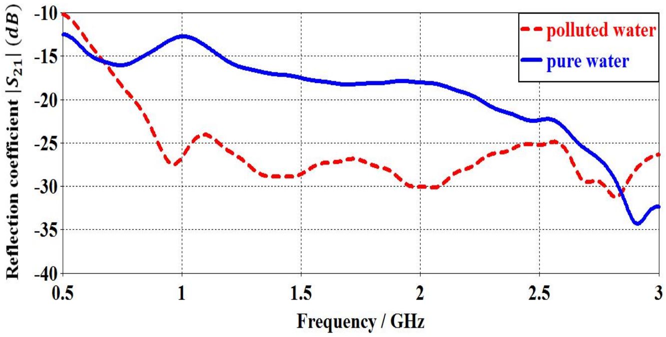

Figure 7: Frequency response of the backscattered reflected signal coefficient S_{21} for pure and polluted water models for dry sandy soil.

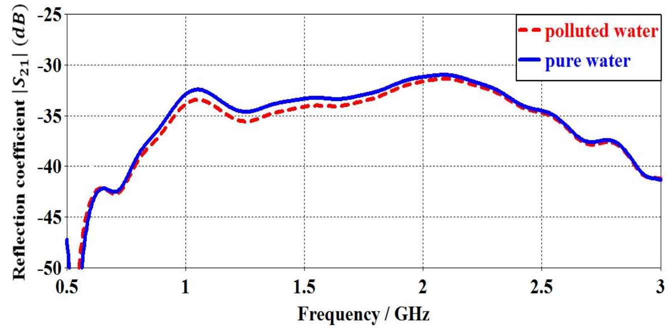

Figure 8: Frequency response of the backscattered reflected signal coefficient S_{21} for pure and polluted water models for moist sandy soil.

The frequency response of the backscattered reflected signal coefficient S_{21} for pure and polluted water models are compared in Figure 7 for dry sandy soil with the dimensions presented in Table 1. The results indicate significant decrease in the reflection coefficient of polluted water model compared to pure water model due to the contrast of the dielectric constant and the high conductivity of polluted water which increase the absorption of the signal. It is also observed that for pure and polluted water models, the backscattered reflected signal coefficient decrease with the increase of frequency this is due to the increase of attenuation of soil with the increase of frequency.

5.1 Effect of Moisture in Soil

The dry sandy soil model indicates significant differences in the backscattered reflected signal coefficient S_{21} of pure water vs. polluted water. By changing the dry sandy soil with moist sandy soil with dielectric constant of 13 and dielectric loss tangent of 0.29 [7] these differences becomes insignificant at the simulated range of frequency due to the high attenuation of moist soil which reduces the backscattered reflected signal from water inside the pipe as shown in Figure 8. It is observed also that the backscattered reflected signal coefficient decreased compared to dry soil also due to the high attenuation of moist soil.

5.2 Effect of Change of Antenna Height (H)

Figure 9 illustrate the effect of increase of the height of the antenna from the surface of the ground (H) from 5cm to 10cm and all other dimensions are the same as in Table1. The results indicate that while the antenna height increases, the backscattered reflection coefficient S_{21} slightly decreases for pure and polluted water model because of the decrease of signal reflected from soil and from water, so in many GPR applications the antennas are recommended to be close to the surface of the ground to obtain higher reflected signals from object detected.

5.3 Effect of Change of Antenna Spacing (S)

The choice of spacing between the transmitting and receiving antenna (S) is critical as it controls the direct coupling between the transmitting and receiving antennas. In order to have better water pollution detection, this direct coupling should be minimized. With the increase of the spacing between the two antennas the direct coupling decreases but the received reflected signal from the underground water pipe becomes weaker while with the decrease of the spacing between the two antennas the direct coupling increases. The optimized spacing between the transmitting and receiving antennas is 30cm at which the direct coupling is minimized and at the same time the received reflected signal from underground water pipe is notable. Figure 10 illustrate the effect of increase of antenna spacing (S) from 30cm to 40cm and all other dimensions are the same as in Table 1. The results indicate that while the antenna spacing increases, the backscattered reflection coefficient S_{21} decreases for pure and polluted water model because of the decrease of the direct coupling between the two antennas and the reflected signal from the soil and water pipe.

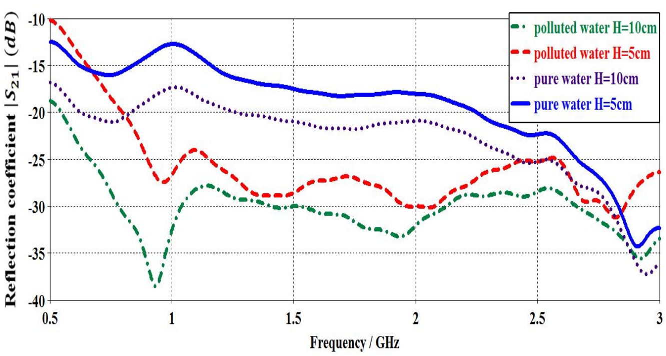

Figure 9: Frequency response of the backscattered reflected signal coefficient S_{21} for pure and polluted water models at two different antenna heights (H) [5cm and 10cm].

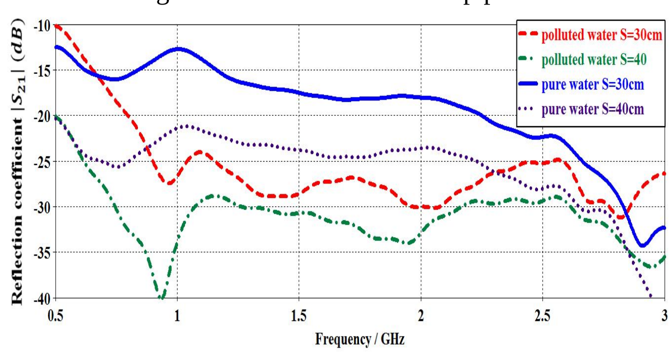

Figure 10: Frequency response of the backscattered reflected signal coefficient S_{21} for pure and polluted water models at two different antenna spacing (S) [30cm and 40cm].

5.4 Effect of Change of Pipe Burial Depth (D)

Figure 11 illustrate the effect of increase of the depth at which the pipe is buried (D) from 20cm to 30cm and all other dimensions are the same as in Table 1. The results indicate that while the pipe burial depth increases, the backscattered reflection coefficient S_{21} decreases for pure and polluted water models and the contrast between the two models decreases due to the increase of attenuation of signal in the soil while it travel from the transmitting antenna to the buried water pipe and while it returns back to the receiving antenna.

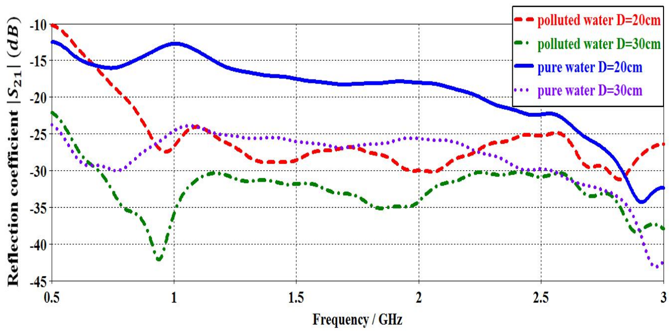

Figure 11: Frequency response of the backscattered reflected signal coefficient S_{21} for pure and polluted water models at two different pipe burial depth (D) [20cm and 30cm].

5.5 Effect of Change of Pipe Diameter (d)

Figure 12 illustrate the effect of increase of the pipe diameter (d) from 20cm to 30cm and all other dimensions are the same as in Table 1. The results indicate that while the pipe diameter increases, the contrast of the backscattered reflection coefficient S_{21} for pure water model vs. polluted water model increases because of the increase of the cross sectional area of water which expose to GPR signal.

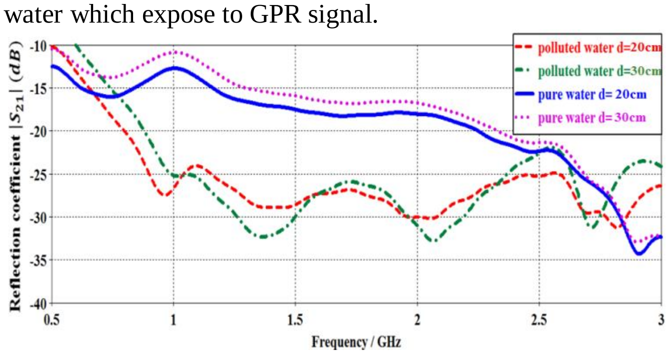

Figure 12: Frequency response of the backscattered reflected signal coefficient S_{21} for pure and polluted water models at two different pipe diameters (d) [20cm and 30cm]

5.6 Effect of Change of Pipe Material Thickness

The effect of the change of the thickness of the pipe material on the reflected signal is studied and the results indicate that the change in the thickness of the pipe material have an insignificant effect on the backscattered reflection coefficient.

6. CONCLUSIONS

The GPR geophysical method is a high-resolution, rapid tool for non-invasive subsurface investigation. In this study, the feasibility of using GPR as a tool for detecting water pollution in underground pipes is examined. Simulations of prototype laboratory water pollution detection models are presented for two different configurations, the first one is done for pure water while the second is done for polluted water. A monopole circular patch antenna with defected ground plane for GPR application has been proposed and discussed. The obtained results show that there are notable differences in the reflection coefficients for both types of water. Different conditions are studied such as the effect of moisture content in soil, the change of the antenna configurations and the change of pipe burial depth or diameter. The main conclusion of this research is that GPR may easily be adapted to detect water pollution in underground water distribution systems.

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