Dielectric properties of soils at X-band microwave frequency

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Measurements of real ($\varepsilon'$) and imaginary ($\varepsilon''$) parts of the complex dielectric constant ($\varepsilon^*$) of soil with varied moisture content have been made at 9.44 GHz using infinite sample method. The electrical properties of dry soil samples are found to be in good agreement with the earlier work. The values of $\varepsilon'$ and $\varepsilon''$ first increase slowly and then increase rapidly with moisture content. From this data, the ac conductivity and relaxation time are also reported in the present paper. The result shows the change in electrical properties of soils before and after the addition of water. These results provide a basis for using ground-penetrating radar or other high-frequency electromagnetic sensors in the detection of soil moisture content.

Keywords: Microwave X-band, Dielectric constant, Dielectric loss, Conductivity, Relaxation time

1 Introduction

Over the last decade, microwave remote sensing is the emerging field to study the natural resources of planet earth. It emphasizes the interaction of microwaves with the material under study. The study of dielectric properties of different earth constituents at microwave frequencies plays a vital role as it gives interpretation of various remote sensing data. Many researchers working on this aspect, have studied dielectric parameters of different materials with various methods1-7. The dielectric constant of soil is a function of its moisture content1. Microwave emission depends upon the dielectric constant of the soil2,3. The dielectric constant of red soil in frequency range 12-18 GHz has been measured4. Microwave transmission and reflection of moisture-laden brown and black soil using Ku-band are also reported5. The dielectric constant and conductivity of soil samples contaminated by diesel oil in the frequency range 2-250 MHz have been measured6. The soil water content in coaxial transmission line has been determined7. The Q-meter was used to measure the dielectric constant and tangent loss of some Indian clay minerals8 in frequency range 0-11 MHz. The different methods have been used to study the various electrical properties at X-band microwave frequency2,3. The dielectric properties of different soils collected from Bidar region of Karnataka State, at X-band microwave frequency using infinite sample method13 have been studied. In the present paper, the experimentally determined values of the real and imaginary parts of the complex dielectric constant have been shown for soils under study at different water content. From this, the values of conductivity and relaxation time have been determined.

2 Experimental Details

The technique used in this measurement is the infinite sample method9. An X-band microwave bench operating at 9.44 GHz in the TE10 mode with slotted section and a crystal detector are used for measurement of VSWR and the shift of minima is needed in this technique. The complex dielectric constant is calculated using the relation:

$$\varepsilon^* = \varepsilon' - j\varepsilon'' = \frac{1}{1 + \frac{\lambda_c^2}{\lambda_g^2}} + \frac{1}{1 + \frac{\lambda_g^2}{\lambda_c^2}} \left[ \frac{r - j\tan[k(D - D_R)]}{1 - jr\tan[k(D - D_R)]} \right]^2$$

…(1)

where $\lambda_c$, $\lambda_g$ and $k$ are cut-off wavelength, guide wavelength and wave vector, respectively, $r$ is voltage standing wave ratio (VSWR) and $D$ and $D_R$ are the positions of first minima with and without sample, respectively. The samples were filled and pressed manually in 40 cm long waveguide, which was terminated with matched load. The values of $D$, $D_R$ and $\lambda_g$ have been measured using a slotted line. The VSWR was determined using double minimum power method. The soil sample taken for the present study belongs to the Bidar region of Karnataka state. Samples were collected from both irrigated and non-irrigated areas. The physical and chemical properties
of the soil were measured at Soil Analysis Laboratory; Department of Agriculture, Govt. of Maharashtra situated at Parbhani.

The constituents of the soil found in per cent are as follows:

White Soil: Sand 2.39, Silt 35.11, Clay 62.5, CaCO$_3$ 6.22, Na 1.26, Mg 27.95, Ca 37.53
Black Soil: Sand 21, Silt 35, Clay 44, CaCO$_3$ 2.75, Na 1.26, Mg 24.66, Ca 33.36

The gravimetric soil moisture content in percentage $W_c$ (%) is calculated using wet ($W_1$) and dry ($W_2$) soil masses using the following relation:

$$W_c(\%) = \frac{W_1 - W_2}{W_2} \times 100 \quad \ldots(2)$$

Measurements have been carried out at 9.44 GHz. The experimental set-up consist of a 2K25 reflex klystron as the microwave source with maximum output power of 25 mW and frequency range 8.2-12.4 GHz. To avoid the interference between source and reflected signals, the source was connected with a broadband isolator with maximum isolation of 30 dB and insertion loss of 1.25 dB. To control the power at desired level, a variable attenuator is connected after the isolator. A resonance type frequency meter with high $Q$-factor ($Q$~1000) and with 2.5 MHz resolution with dip $\geq$ 1 dB was used to measure the frequency of the signal. The diode detector with square law characteristics with VSWR better than 2:1 was used. The slotted line was employed to measure VSWR and distance. For accurate measurements of minima and VSWR, the probe carriage was mounted with a dial gauge, which has 1 mm range with 0.001 mm scale divisions. Accuracy of measurement of real ($\varepsilon'$) and imaginary ($\varepsilon''$) parts of the complex dielectric constant ($\varepsilon^*$) is ± 0.001 and ± 0.004, respectively.

From the knowledge of dielectric constant and dielectric loss, the ac electrical conductivity and relaxation time are obtained using the relation$^{10,12}$:

$$\sigma = \omega \varepsilon_0 \varepsilon'' \quad \ldots(3)$$

and

$$\tau = \frac{\varepsilon''}{\omega \varepsilon'} \quad \ldots(4)$$

where $\omega$ is angular frequency, $f = 9.44$ GHz and $\varepsilon_0$ is permittivity of free space (8.85×10$^{-12}$ F/m).

### 3 Results and Discussion

The variations in the values of dielectric constant and loss with percentage moisture content have been measured and are shown in Figs 1 and 2 for black and white soil, respectively. Similarly, the electrical conductivity and relaxation time with variation of percentage moisture content are shown in Figs 3 and 4. It is obvious that the relative permittivity of the soils increases with moisture content. From this study, it is observed that the relation between the dielectric
constant and the gravimetric water content is almost non-linear. This is because, for a composite material such as moist soil, the dielectric constant is not a simple function of the values of the individual components. The \(\text{ac}\) electrical conductivity (\(\sigma\)) and relaxation time (\(\tau\)) show a systematic change with increase in moisture content. The higher value of relaxation time for black soil as compared to that of white soil may be due to higher percentage of sand content. According to Debye, when polar molecules are very large, then under the influence of e.m. field of high frequency, the rotary motion of the polar molecules of a system is not sufficiently rapid to attain an equilibrium with the field. The polarization then acquires a component out of phase with the field and the displacement current acquires conductance dissipation energy. Thus, the dielectric loss is proportional to the \(\text{ac}\) conductivity. The increase in relaxation time due to increase in moisture content is due to increasing hindrance to the process of polarization. These results are found to be in good agreement with the earlier work\(^{2,5,13}\).

4 Conclusions

Bound water in soil-water mixtures significantly affects the dielectric properties of mixtures. The relationship between dielectric properties and gravimetric water content is almost non-linear. The \(\text{ac}\) electrical conductivity and relaxation time depend upon the dielectric loss.

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References