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Dielectric properties of coals in the low-terahertz frequency region

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ABSTRACT

The dielectric properties of Shanxi anthracite and Shandong bituminous coals in China are investigated in the low-terahertz (THz), W-band of frequency from 75 GHz to 110 GHz for the first time. In this frequency range, the complex dielectric constant of coal samples is obtained using the free space method. It is found that both the real parts of the dielectric constant for bituminous and anthracite decrease considerably with increasing frequency from 75 GHz to 110 GHz. The anthracite coals exhibit higher real and imaginary part values than bituminous coals. The imaginary part of the coal samples exhibits a more significantly decreasing trend in the frequency range from 90 GHz to 110 GHz compared with frequencies below 90 GHz. The dielectric properties of all the coal samples are strongly dependent on the moisture content of the coals. Increasing moisture content leads to higher complex dielectric constant values. The effect of moisture on the dielectric properties of coals depends substantially on the influence of moisture content on the transmission and reflection of THz wave in the coals. The results show that the transmission coefficient of anthracite and bituminous exhibits an exponentially decreasing trend with increasing moisture content (from 0% to 10%). However, the reflection coefficient seems to follow a Gaussian-like changing trend with increasing moisture content, reaching a maximum around 4.5%.

1. Introduction

Coal as one of the major fossil fuels plays an important role in the development of commerce and industry, and as such, it impacts man's daily life profoundly. It has been estimated that nearly 42% of the world's electricity is generated by the burning of coal [1]. Coal-related research has received sustained and wide-spread attention in the past, and in recent years it has witnessed a resurgence with the diminishing reserves as well as the ever-increasing demand. However, large-scale extraction of coal remains for the most part a hazardous undertaking. Along with cave-ins and coal dust fire and explosion, methane gas explosion and water in-rush represent the ultimate hazards in today's coalmines [2], which threaten life and property on a daily basis. While a slow accumulation of methane and water can be detected and safety measures taken in time, sudden appearance of methane and water due to inadvertent drilling in coalmine tunnels have claimed thousands of lives and disrupted production worldwide in the last few years alone. To prevent such accident from occurring, a look-ahead device that can penetrate rocks, soil, and coal and forewarn the presence of water and methane gas in large quantity is needed. At present, such a device does not exist. While technologies have advanced enormously, and several candidates for such a purpose look promising, such as ground penetrating radar, transient electromagnetic method, electrical conductivity/resistivity measurement, and ultrasonic wave devices, a reliable working device is still years away [3]. Recently, our laboratory has been engaged in the research and development of a low-terahertz (THz), i.e., W-band electromagnetic wave imaging Radar which measures resonances in the absorption of the THz radiation by water molecules and CH_4 molecules in order to detect the presence of pockets of water and/or methane gas up to several meters through rock, soil, and coal, from the radar receiving antenna. The design of such a THz device requires the fundamental grasp of physical properties of coal, especially its complex dielectric permittivity (including real and imaginary parts of it, corresponding to the index of refraction, and loss/attenuation, respectively). It is therefore of great importance to study dielectric characteristics of electromagnetic waves propagating in coal. While such studies have been carried out to some extent in the RF and microwave frequency bands, in conjunction with work on ground penetrating

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radar and transient electromagnetic methods [4–7], to date no work has been done in the required W-band and beyond. In fact, with the development of microelectronics technology, more sophisticated apparatus and instruments became available for measurement of the dielectric properties of coal in the last decade. Some factors affecting the permittivity of coal such as rank, anisotropy, pyrite concentration and distribution, moisture content, temperature and mineral matter concentration were investigated in the past few years [8–19]. However, the electrical complex permittivity measurements of coals in THz band are not yet available. The present study is undertaken to attempt to fill this void.

THz wave is an electromagnetic wave that occupies a middle spectral region between microwaves and infrared light waves (wavelength ranges from 0.03 mm to 3 mm). The research of THz has received a great deal of attention in recent years [20–25]. THz technology has been widely applied in a number of areas such as molecular recognition (many vibration modes of complex and biological molecules lie in the THz range) [21], security screening and non-destructive analysis of materials. As the transmitted frequency of radar reaches millimeter wave and THz band, numerous physical, chemical and biological systems have clear absorption spectral features in the THz region. In addition, water is strongly absorptive of THz radiation. Therefore, utilizing these characteristics to study the dielectric properties of coals in the THz band can help solve some problems for design of penetrating ground radar in different frequency band. In this paper, we investigate the effects of THz radiation in the frequency range from 75 GHz to 110 GHz and the moisture content on the dielectric permittivity of anthracite and bituminous coals commonly found in China by using the free space method.

As one of the non-resonant methods, and unlike the open-ended probe [18,19] and resonant cavity methods, the free space method has been widely used for many years [26–35]. It has many advantages over other resonant methods and open-ended probes methods: (1) it is particularly attractive for nondestructive test in some construction industry for its noncontact modality [26]; (2) it only requires moderate sample preparation since the sample can be sufficiently large to reduce edge diffraction effects and thin sample may induce sagging effect; (3) in order to improve accuracy of measurements, its calibration method is simple compared with other methods; (4) it is very convenient to test the relationship of coal permittivity with temperature since resonant method and open-ended probes are limited in waveguide and require more complex system structure for temperature determination. Last but not least, using the free space method together with the new millimeter/submillimeter wave Agilent measurement technology and the Virginia Diode Inc (VDI) extension modules [36], it is possible to extend the measuring frequency of the coal dielectric properties to the terahertz (THz) band.

2. Methodology

2.1. Dielectric measurement theory using the free space method

The dielectric property of an isotropic material is subsumed in the complex permittivity in the form [33]

$$\varepsilon = \varepsilon' - j\varepsilon'', \tag{1}$$

where ε' represents the real part, and ε'' the imaginary part of the complex dielectric permittivity. The two parts in Eq. (1) are used to describe the dielectric response of materials in an electromagnetic field. The real part is associated with the capacity of the medium to store electromagnetic energy and the imaginary part relates to the dissipation of the stored energy into heat. The loss tangent is another important parameter that indicates how well a material dissipates stored energy into heat.

$$\tan\theta = \varepsilon''/\varepsilon' \tag{2}$$

When an electromagnetic wave propagates in a lossy dielectric material, its magnitude decreases because of the absorption of power by the material. The penetration depth P_D, can be used to express the rate of decay of the stored energy, which can be expressed as a function of both the real part and the loss tangent by [37]:

$$P_D = \frac{c}{2\pi f\sqrt{2\varepsilon'}\left[\sqrt{1+\tan^2\theta}-1\right]^{1/2}} \tag{3}$$

The quantity P_D is used to describe the distance from the material surface where the intensity of the electromagnetic radiation falls to $1/e$ of its value at the surface.

In general, measured magnitudes of the real and imaginary part in Eq. (1) are relatively low, and the two parts in Eq. (1) are usually re-scaled by dividing them with the permittivity of free space ($\varepsilon_0 = 8.85 * 10^{-12}$ F/m), the resultant quantities are termed the real and imaginary parts of the relative complex permittivity.

It is assumed that the planar coal sample has a transverse (relative to the direction of propagation of the electromagnetic wave) dimension that is large enough compared with the wavelength of the impinging radiation, such that diffraction effects can be neglected. A plane electromagnetic wave of frequency ω travels from the transmitting antenna to the receiving antenna through air and the coal sample of thickness d. The transmission scattering parameter (S_{21}) and reflection scattering parameter (S_{11}) are measured in free space. By applying appropriate boundary conditions at the air-sample interfaces, S_{21} and S_{11} can be expressed in terms of Γ and T as follows [34]:

$$S_{11} = \frac{\Gamma(1-T^2)}{1-T^2\Gamma^2}, \tag{4}$$

$$S_{21} = \frac{T(1-\Gamma^2)}{1-T^2\Gamma^2}, \tag{5}$$

where Γ is the reflection coefficient at the air-sample interface, T is given by

$$T = e^{-\gamma d}, \tag{6}$$

$$\Gamma = \frac{Z_{sn}-1}{Z_{sn}+1}. \tag{7}$$

In Eqs. (6) and (7), Z_{sn} and γ are normalized characteristic impedance and propagation constant of the sample. They are related to ε by the following equations:

$$\gamma = \gamma_0\sqrt{\varepsilon}, \tag{8}$$

$$Z_{sn} = \sqrt{\frac{1}{\varepsilon}}, \tag{9}$$

where $\gamma_0 = j2\pi/\lambda_0$ is the propagation constant of free space, λ_0 is the free-space wavelength.

From Eqs. (7)–(9), it follows that

$$\varepsilon = \frac{\gamma}{\gamma_0}\left(\frac{1-\Gamma}{1+\Gamma}\right) \tag{10}$$

2.2. Experimental setup

Fig. 1a shows a schematic of the dielectric measurement system setup in the THz band by using the free space method. The THz signal is generated by the extension module1 and transmitted by a