Fuel 188 (2017) 246–253

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Full Length Article

Dielectric properties of coal in the terahertz frequency region of 100–500 GHz

Wei Fan[a], Tianying Chang[a,b,*], Lingyu Liu[b], Hong-Liang Cui[a]

[a] College of Instrumentation and Electrical Engineering, Jilin University, Changchun, Jilin 130061, China
[b] Institute of Automation, Shandong Academy of Sciences, Jinan, Shandong 250103, China

ARTICLE INFO

Article history:
Received 24 June 2016
Received in revised form 28 September 2016
Accepted 7 October 2016
Available online 13 October 2016

Keywords:
Coal
Dielectric property
THz
Free space method
TDS

ABSTRACT

The dielectric properties of anthracite and bituminous coals were investigated in the terahertz (THz) frequency region from 100 GHz to 500 GHz. We developed two types of THz material measurement systems that can be operated in this frequency region, including one based on a vector network analyzer (VNA) with frequency extension modules, and another based on a THz time-domain spectroscopy (TDS) system. Employing the free-space configuration, we obtained the variation of dielectric property of coals in the frequency region of 100–500 GHz. By comparing the VNA and TDS systems, we evaluated the continuity and consistency of the two systems and verified the dielectric property measurement results of coal in the entire frequency region. We first outlined the fundamental theory of dielectric property with both methods, followed by estimating the measurement error in consideration with the system stability, the time span of the time-domain gating, and measurement uncertainty. We evaluated the dielectric property of coal samples through the measured results of the VNA and TDS systems. Comparison is also made of the variation of measured dielectric property with the lower THz frequency region (W-band) in our previous work. The results show that different coal type exhibited different variation with increasing frequency in the THz band considered.

1. Introduction

In the last few decades, large scale worldwide coal extraction has led to many geo-hazards in underground mines [1–7]. Such accidents have catastrophic effects on people's life, while hampering progress of coal mining projects and coal production. Whereas slow accumulation of water and methane can be effectively forecasted and safety measures taken in time, the inadvertent coal drilling caused sudden release of large quantities of water and/or methane gas has led to the most casualties and property damages [8–21]. To avoid frequent occurrence of such accidents to the greatest extent possible, a large number of detection instruments have been developed in the past, such as ground penetrating radar [22], nuclear magnetic resonance method [23], transient electromagnetic method [24,25], etc. Ground penetrating radar fully utilizes the characteristics of radar to obtain underground information, by data inversion of the effective signal. The analysis of inversed data can make possible to reproduce the two-dimensional or three-dimensional images associated with the geological environment around the coal mine. The inversion data by radar is closely related to the electromagnetic wave propagation in the coal, including reflection, refraction, and attenuation in the coal, which is mainly determined by the dielectric property of coal, i.e., the real and imaginary parts of the complex dielectric constant. Our laboratory has been engaged in the development of a THz imaging radar to detect hidden seams and cracks in coal layers and rock formations—the detection and determination of certain properties of such structures often foreshadow the possible presence of large amount of ground water and gas—whose design the current research of dielectric property in the THz region can help facilitate.

There are currently a variety of methods or techniques for measuring the dielectric property of materials. One such technique is based on the free-space method, using a VNA in conjunction with appropriate frequency extension modules. With the development of semiconductor devices and laser quasi-optical techniques, the transmitting and measurable frequency of this method can reach up to 750 GHz or more [26]. Through this method, the dielectric property reflects the continuous wave response of the material under test, with the results given in terms of the S-parameters (S_{11} and S_{21}) [27]. Another commonly used method involves the

---

[*] Corresponding author at: College of Instrumentation and Electrical Engineering, Jilin University, Changchun, Jilin 130061, China.

E-mail address: tchang@jlu.edu.cn (T. Chang).

http://dx.doi.org/10.1016/j.fuel.2016.10.046
0016-2361/

THz time-domain spectroscopy (TDS) system. The dielectric property is deducted according to the complex refractive index and extinction coefficient of the material, which represents the pulsed wave response of the material [28]. While the operating principles of VNA and TDS are different by design, they can give the same results when working with the same frequency band in theory. However, the measurable frequency of VNA is generally lower than 1 THz, while TDS can typically operate up to a few THz. Therefore, it is convenient to measure dielectric property of a material and validate the measurement results by comparing these methods when possible, especially when the frequency regions they cover overlap.

In a previous work [29], we measured the variation of dielectric property of coals from various regions of China in the low-terahertz band (W-band, covering the frequency region of 75–110 GHz, also known as the millimeter wave band) by the VNA method. To increase the radar working frequency in order to improve the imaging resolution of the THz radar, which is inversely proportionally to the wavelength, it is therefore of great importance to understand quantitatively the dielectric property of coal beyond the W-band.

In this paper, we report on our experimental investigation of the variation of dielectric property of coal samples from a variety of geographical locations in China, with frequency above the W-band, i.e., from 100 GHz to 500 GHz. In all, five different coal samples belonging to two different coal types were measured, and the measurement results and associated errors were analyzed, with regards to instrument performance, and verified the accuracy of the results by comparing the two methods (VNA and TDS) employed when appropriate.

2. Methodology

2.1. Free space theory

For measuring the dielectric property of coal, the free space method based on the transmission line theory is employed from VNA data only. A typical model for dielectric property calculation is shown in Fig. 1. It is assumed that a plane wave is transmitted from free space to the sample shaped as a planar slab, with thickness d. The sum of the electromagnetic waves is consisted of the direct incident wave, the reflected wave from the front surface of the coal sample, the transmitted wave, and multiple reflected wave within the coal sample. The sample is considered to be homogenous, and to have an infinite transverse dimension. The transmitted wave can be expressed as:

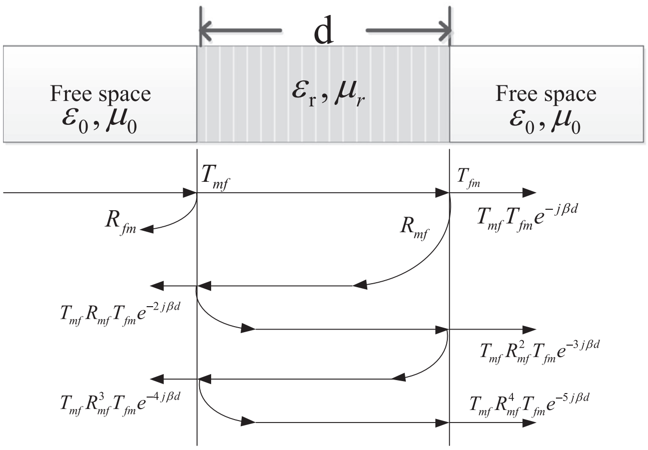

Fig. 1. Calculation model of dielectric property measurement based on the free space method.

$$S_{21} = T_{mf}T_{fm}e^{-\gamma d} + T_{mf}T_{fm}R_{fm}R_{mf}e^{-3\gamma d} + \cdots + T_{mf}T_{fm}(R_{fm}R_{mf})^{n-1}e^{-(2n-1)\gamma d} \quad (1)$$

where T_{mf} and T_{fm} are complex transmission coefficients when an incident wave is transmitted from free space to material and that from material to free space, respectively, R_{fm} and R_{mf} are the corresponding complex reflection coefficients. If the number of multiple reflections $n \rightarrow \infty$, the expression (1) can be simplified as [27]

$$S_{21} = \frac{(1 - R_{fm}R_{mf})e^{-\gamma d}}{1 - R_{fm}R_{mf}e^{-2\gamma d}} \quad (2)$$

$$R_{fm} = R_{mf} = \frac{\gamma_0\mu_r - \gamma}{\gamma_0\mu_r + \gamma} \quad (3)$$

$$\gamma = j\frac{2\pi}{\lambda_0}\sqrt{\varepsilon_r\mu_r} \quad (4)$$

$$\gamma_0 = j\frac{2\pi}{\lambda_0} \quad (5)$$

where γ_0 and γ is propagation constant of free space and sample, $\varepsilon_r = \varepsilon_r' - j\varepsilon_r''$ is the complex relative permittivity of the material, $\mu_r = \mu_r' - j\mu_r''$ is the complex relative permeability of the material, λ_0 is the wavelength in free space. Here, $\mu_r \rightarrow 1$ for nonmagnetic materials, which is the present case. Eq. (2) can be expressed as

$$S_{21} = \frac{4\sqrt{\varepsilon_r}e^{-j\frac{2\pi}{\lambda_0}\sqrt{\varepsilon_r}d}}{(1+\sqrt{\varepsilon_r})^2 - (1-\sqrt{\varepsilon_r})^2 e^{-2j\frac{2\pi}{\lambda_0}\sqrt{\varepsilon_r}d}} \quad (6)$$

The dielectric property of a material can be obtained by giving an initial value for ε_r to commence an iteration process until S_{21} converged to a constant value. Many numerical methods [30–32] can be used to calculate the dielectric property (e.g., bisection, false position, secant, or Newton's method), here we chose Newton's method.

2.2. System setup using VNA

A setup of the measurement system using a VNA (Agilent N5247A) was shown in Fig. 2, as was done in the previous research [29]. The lower frequency electromagnetic wave was first transmitted from the VNA, and then through the VDI frequency extension module to reach up to the THz band, using different matching horn antennas. We used a pair of dielectric lens to spot focus the THz wave on the sample. The distance between the left horn and sample should satisfy the far-field condition given by

$$L \gg 2D^2/\lambda_c \quad (7)$$

where D is the aperture of the horn antenna, λ_c is the center wavelength of the entire frequency band of each extension module. Likewise, the maximum transverse size of the sample should satisfy the condition

$$D_s \gg 2L\tan(1/2Bw) \quad (8)$$

which is far larger than the beam waist, Bw is the full 3 dB bandwidth of the horn antenna.

Measurement system specifications and horn antenna parameters for each frequency range in (7) and (8) are summarized in Table 1. To adjust different minimum L and D_s for different frequency band, a slide rail with 1 μm minimum step increment was used.

Prior to each measurement of S_{21} was undertaken, a two-port gate-reflect-line (GRL) calibration [33] was carried out to eliminate the ambient reflections and multiple reflections between the two horn antennas. The GRL calibration needs two steps to remove