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Quantitative Assessment of Rock-Coal Powder Mixtures by Terahertz Time Domain Spectroscopy

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The enormous risk that mine environments impose to the staff directly involved in the mineral extraction process makes the use of automated technologies extremely relevant, in order to minimize the risk of operators [1]. Coal still represents a significant proportion of the fuel supply in several countries such as China, and mining it is an activity of tremendous economic importance [2]. In this letter, we present terahertz (THz) spectroscopy [3–5] as a potential tool for the quantitative recognition of rock-coal mixtures in powder form. This could lead to the implementation of appropriate sensors for in-line feedback to mining equipment in order to avoid or, at least, minimize the extraction of unwanted surrounding rock without the direct presence of human operators.

Terahertz spectroscopy is a technology that has evolved dramatically over the last three to four decades. In particular, the development of compact and robust systems that can now be operated outside laboratories under uncontrolled, and even relatively harsh environmental conditions, is opening the possibility of this technology to be used in industrial [6, 7], agricultural [8], or even more unpredictable settings [9]. We recently demonstrated the potential of the THz time-domain spectroscopy (TDS) as technique for the recognition of mineral powders [10]. In addition, we were able to provide evidence that the analysis of only three frequencies suffice in order to distinguish between the minerals studied. That result showed the possibility of using

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terahertz as a tool in the mining process. However, in order to have a real application potential, it is not enough to distinguish between a “pure” rock and a “pure” coal sample. Additionally, it must reveal the proportion of rock present in the coal being extracted in order to modify the trajectory of the scrapper machine when a given threshold of rock content is exceeded in the mixture. In the coming paragraphs, we discuss why it can be theoretically expected to see differences in the terahertz transmission as a function of the mixture fraction of minerals. We also provide experimental evidence that a combination of the transmittance at three frequencies is enough to estimate the coal-rock mixture proportion. For this study, we used the coal known as anthracite (CA) [11] and the rock carbonaceous mudstone (RCM) [12], which are typical materials of the two types found in mines.

The Mie theory of scattering [13] allows us to calculate the scattering cross-section σ of a spherical particle of radius a with a given refractive index as a series of terms that involve the spherical Bessel and Newmann functions. While we will not discuss the details here, this allows us to calculate the transmittance of a particle powder layer, by approximating the particles by spheres. In order to model our powder mixture experiment, where particles of similar sizes but different refractive indices are combined, it can be demonstrated that the transmittance of such sample is given by

$$T = \exp\left(-\frac{\sigma_{\mathrm{CA}} d N \eta + \sigma_{\mathrm{RCM}} d N (1-\eta)}{2}\right), \tag{1}$$

where $N = a^{-3}$ is the density of particles, d is the powder layer thickness, the cross-sections for CA σ_{CA} and RCM σ_{RCM} are calculated for the complex refractive indices shown in the inset to Fig. 1a, which correspond to CA and RCM respectively, and η is the fraction of anthracite particles. Using this equation, we modeled the transmittance as function of the relative fraction of anthracite, which is shown in Fig. 1a. The plots are made as an average of transmittance for particles in the diameter range from 75 to 275 μm. The plot shows that there is a clear dependence of the transmittance spectrum with η. This means that in principle it is reasonable to say that the terahertz spectra of a mixture of rock and coal powders can be used to quantify the fraction of each of the two minerals.

In order to experimentally confirm the statements of the previous paragraph, CA and RCM were pulverized using an agate mortar and pestle. The powders were separated by grain size using a series of sieves with different hole size. The particle sizes were measured using an optical LEICA microscope. Based on the experience we had in previously reported experiments, we chose the samples with grain size between 75 and 275 μm, which, as we found empirically, is the range with the best separation between materials. Subsequently, nine samples where prepared, with fractional content of CA (from 0 to 100%) and RCM (from 100% to 0). The powder mixtures were placed into cuvettes made up of polythene windows, with a spacing of 3.6 mm between them.

Terahertz transmission spectra of the powder mixtures were measured by using a fiber coupled terahertz time-domain spectroscopy system [14]. The measured spectra are presented in Fig. 1b. The figure shows a clear dependence of the transmission with the mixture fraction. Although the dependence is a little larger than theoretically predicted, the trend and the general shape of the spectra do match reasonably well.

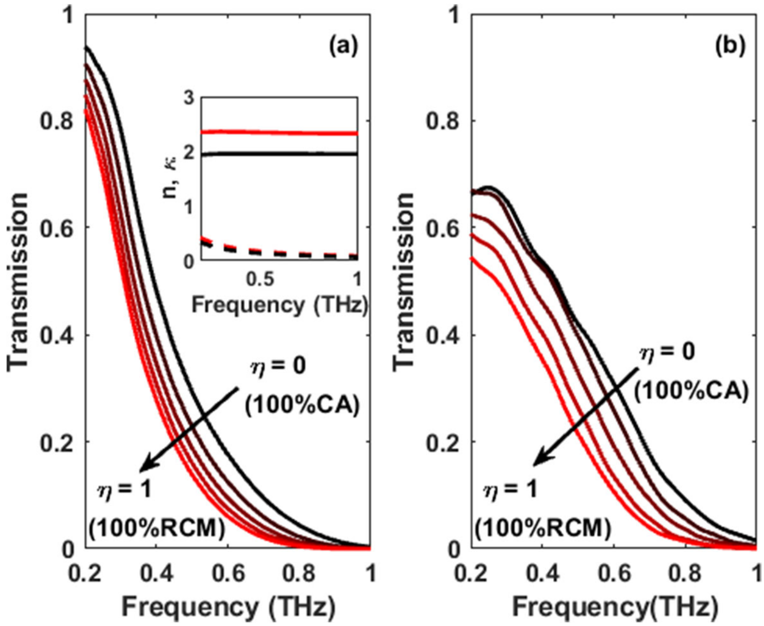

Fig. 1 **a** Theoretical and **b** experimental transmission spectra for different mixture fractions of anthracite and carbonaceous mudstone. The inset to (a) shows the real (continuous) and imaginary (dashed) parts of the refractive indices for RCM (red) and CA (black)

Once the spectra were acquired, we adopted an approach similar to the one reported in [10]. In order to distinguish the mixtures, we can construct two parameters as follows $P_1 = T(0.2\,\mathrm{THz})/T(0.5\,\mathrm{THz})$ and $P_2 = T(0.8\,\mathrm{THz})/T(0.5\,\mathrm{THz})$. The frequencies used, i.e., 0.2 THz, 0.5 THz, and 0.8 THz, are chosen such that the maximum separation between P_1 and P_2 is obtained for the two materials. With these parameters, we produce the plot shown in Fig. 2. This graph shows that the two parameters are sufficient to classify the powder mixtures according to their content of CA and RCM. The error bars represent the maximum absolute deviation of the two parameters for a total of 15 measurements in 3 different positions for each sample. The result demonstrates that, although coarsely, it is possible to quantify the ratio of the two minerals in the mixture by using the transmission at only 3 frequencies with a resolution of about 15 to 20% in RCM content.

In summary, we presented a method to quantify the mix ratio between coal and rock in a mineral powder mixture by relying in only three terahertz frequencies. If the preparation of the powder scraped material from a mine in a reasonably fast and continuous fashion, our approach can represent a potential quantitative sensor to provide quasi-real-time feedback to scraping equipment in mines about the composition of the mineral being extracted. This would allow coal-rock-interface identification without the intervention of human operators, provided that the terahertz technology can be adapted to the environmental conditions of a mine.

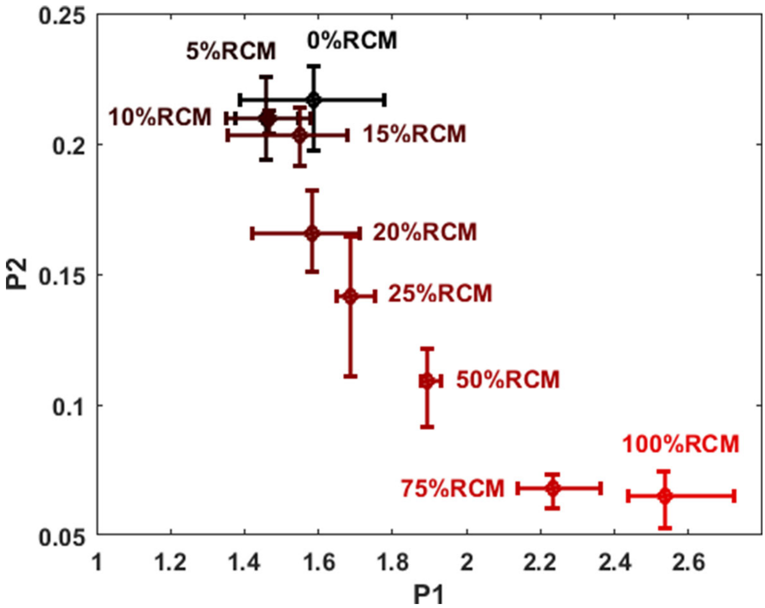

Fig. 2 Parameters P_1 vs P_2 calculated from the experimental spectra for different concentrations of anthracite and carbonaceous mudstone. The plot shows that it is possible to quantify the concentration of coal and rock from the terahertz transmission at three particular frequencies. The resulting points are shown in 5% increments between 0% and 25% RCM content, which is the most relevant part, and in 25% increments after that just to show the trend at high rock contents

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