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NEW METHOD FOR PAPER BASIS WEIGHT MEASUREMENT BASED ON TERAHERTZ TIME DOMAIN SPECTROSCOPY

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Abstract: Measurement of basis weight which is one of the most important physical indexes of paper sheet is of decisive importance in paper making process. However, this problem has not been well solved so far. Terahertz time domain spectroscopy is a newly developed spectroscopy technique based on femtosecond laser technology, and has been studied in some other research fields. The purpose of this work is to study the feasibility of applying terahertz time-domain spectroscopy technique to the measurement of paper sheet basis weight. Two principles were presented in this study. One was based on terahertz amplitude attenuation and the other was on terahertz delay time. Experiments were carried out to verify the theoretical analysis and compare the performances of these two proposed principles. The experimental results show that delay-time-based method is better than amplitude-attenuation-based method in terms of linearity and accuracy. The research work indicates that the method based on terahertz delay time is feasible for paper basis weight measurement. And it may provide a new solution for paper basis weight measurement.

Key words: terahertz wave; time domain spectroscopy; basis weight; relative error
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基于太赫兹波时域光谱的纸页定量检测新方法

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摘要:纸页的定量值是纸页的重要参数之一,此参数的测量对造纸过程具有重要意义.但这个问题到目前并未得到很好解决.太赫兹时域光谱是一种新发展起来的基于飞秒激光技术的光谱测量技术,目前已被初步应用于很多其它领域.本文研究应用太赫兹波时域光谱技术进行纸页定量测量的可行性.提出了两种方法,一种是基于太赫兹信号幅度衰减,另一种是基于太赫兹信号的延迟时间,并比较了两种方法的性能.实验结果表明基于延迟时间方法的线性性能优于基于幅度的方法.给出了这两种方法的相对误差,结果再次表明基于延迟时间的性能优于基于幅度衰减的方法.研究表明应用太赫兹波信号的延迟时间进行纸页定量检测是可行的,此方法有可能为纸页定量检测提供一种新的解决方法.

关 键 词:太赫兹波;时域光谱;定量(单位面积纸的重量);相对误差

Introduction

The practical paper making is a complicated industrial process, in which many important physics indexes must be well measured. Basis weight, the total weight per unit area of paper sheet, is one of the most

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important characteristics which determine the quality of the produced paper[1]. At present, the most popular method to measure the basis weight of paper sheet is β-rays gauge in which the basis weight is measured based on the attenuation of β-rays transmitted through or reflected from the surface of the paper sheet. But it is difficult to measure the basis weight of thin paper. And it has large radiation pollutions[1-5]. X-ray sensor can also be used to sense basis weight, but it is often used in coating basis weight determination. Moreover, it also has a high safety hazard for the operators [6,7]. There are some other methods for the measurement of basis weight, such as capacitance sensors, ultrasonic caliper sensors and so on, but they all have more or less disadvantages and they are not widely used[7]. The measurement of paper sheet basis weight has not been well solved, and further research should be undertaken in this area.

Terahertz (THz) wave is the electromagnetic spectrum situated between microwave and infrared wave. For a long time, terahertz spectroscopy has been hindered for lack of suitable generation and detection methods of terahertz wave[8]. Over the last decade, advance in ultrafast pulse laser has led to coherent generation and detection of sub-picoseconds, broadband (0.1 ~ 10THz) pulses. Terahertz wave has some unique properties[9]. Therefore, THz-TDS technique has been studied and applied in many fields, such as gas spectroscopy[11,12], explosive identification[13,14], pharmaceutics[15-17], T-ray imaging[18,19], pesticide identification[20] and so on. However, in paper making process, few researches on the application of terahertz technique have bean published.

In this work, a novel method to measure the basis weight of paper is proposed based on terahertz time domain spectroscopy. The work is arranged as follows: section 2 illustrates the experimental setup and gives the experimental conditions; section 3 describes two principles for paper sheet basis weight measurement based on terahertz time domain spectroscopy, one is based on terahertz amplitude attenuation and the other is based on terahertz delay time; section 4 presents the experimental results and discussions; in section 5, the research work is summarized.

1 Experimental setup

Transmission terahertz time domain spectroscopy system is used. Details of the setup is described in [9].

The paper sheets to be investigated are put on the position labeled Sample. The experiments are performed with produced paper. The room temperature is 25℃ and the relative humidity of the atmosphere is about 40%.

2 Principles for paper sheet basis weight measurement

When terahertz wave propagates through paper sheet, it will be attenuated due to the effects between the radiation and the paper sheets. As a result, the amplitude and phase of the terahertz wave will be changed. Note that the phase change is related to the delay time of terahertz wave. The changes of both the amplitude and the delay time provide useful information for the characterization of the paper sheet under test[21].

Suppose the density of the paper sheet is ρ, and the thickness of the measured paper sheets is d. As is defined, basis weight is the total weight per unit area of paper sheet, i.e., the product of ρ and d is the basis weight of the paper sheet. For a certain kind of paper, the density ρ can be considered constant, that is, to determine the basis weight of the paper is to determine its thickness.

2.1 Principle of amplitude attenuation

If terahertz wave is mainly attenuated by absorption in the sample, the transmitted terahertz wave should satisfy the Lambert-Beer law [22,23]. The intensity of the transmitted terahertz wave can be calculated by

$$I = I_0 \exp(-\mu\rho d) \quad , \tag{1}$$

where I and I_0, obtained by FFT of the time domain data, denote the intensity of terahertz wave transmitted through the paper sheets and the air, respectively. And μ is the mass absorption coefficient of the measured paper sheets. The following equation can be obtained from (1)

$$d = \frac{1}{\mu\rho}\ln(I_0/I) \quad . \tag{2}$$

Obviously, d is proportional to (I_0/I).

2.2 Principle of delay time

It is known that optically gated detection enables direct measurement of the terahertz transient electric field [24]. By comparing the reference waveform with the sample waveform, delay time Δt at the peak of the two waveforms can be obtained. Suppose the average refractive indexes of air and the paper sheet are n_a and n_p respectively, the thickness of paper sheets is d, and the velocities of terahertz wave in air and the paper are v_a and v_p. Our experiments were performed at room temperature, so n_a and n_p can be considered to be approximately constant for a certain kind of paper sheet[25]. Then the following equations can describe the propagating process of terahertz wave within the paper

$$\begin{cases} \Delta t = \dfrac{d}{v_a} - \dfrac{d}{v_p} \\ v_p = c/n_p \\ v_a = c/n_a \end{cases} , \qquad (3)$$

from the equations above, the thickness d can be represented by

$$d = \frac{c\Delta t}{n_p - n_a} = \frac{c}{n_p - n_a}\Delta t , \qquad (4)$$

it depicts the relationship between the thickness of the paper sheet and the peak delay time of terahertz wave transmitting through the paper. It is clear that d is proportional to Δt.

3 Experimental results and discussion

In our experiments, seven kinds of paper, with basis weight of $70g/m^2$, $80g/m^2$, $100g/m^2$, $130g/m^2$, $160g/m^2$, $180g/m^2$ and $200g/m^2$, are used to verify the above theoretical analysis. Figure 1 presents the terahertz signals for multiple paper sheets of $70g/m^2$. In figure 1, the curve labeled 0 is the signal for reference and those labeled $k(k = 1,2\ 8)$ are signals for k pieces of paper sheets respectively. Figure 2 illustrates the linearity of the terahertz signal of the investigated paper sheet. The solid line in the figure is the theoretical curve obtained from section 2 and the dots denote the experimental results. From Figure 2, it can be seen that the linearity of the THz delay time is better than that of the THz amplitude attenuation. The cases for paper sheet of $80g/m^2$, $130g/m^2$, $180g/m^2$ and $200\ g/m^2$ all support the above results.

To further compare the performance of these two principles, the error of the predicted thickness of the paper sheet from its actual thickness is analyzed. The relative error e is an important factor for describing the performance of a measurement system. It is defined as follows

$$e = \frac{d_{pre} - d_{act}}{d_{act}} \times 100\% , \qquad (5)$$

where d_{per} and d_{act} denote the predicted and actual thickness, respectively. The maximum relative errors for each kind of paper sheet are plotted against their basis weight in Figure 3. From the figure, one can tell that the relative errors for terahertz amplitude attenuation are mostly positive, while for terahertz delay time the number of positive and negative values are approximately equal. The figure implies that the delay-time-based method is more accurate than the amplitude-attenuation-based method. These results show that the performance of THz delay time is better than that of THz amplitude attenuation.

The above research comes to a conclusion that the performance of the method based on terahertz delay time is better than that of the one based on terahertz amplitude. The reason may be that the amplitude of terahertz wave will be changed not only by absorption but also by other effects between terahertz wave and the paper sheets. It is known that terahertz wave has low attenuation in paper and the thickness of paper sheet is very small, as a result it will be impacted by multiple reflections[26]. Therefore, the Lambert-Beer law can't

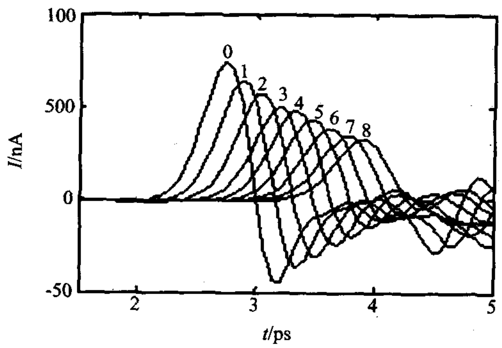

Fig. 1 Terahertz signal for paper sheets of $70g/m^2$
图 1 $70g/m^2$纸的太赫兹信号

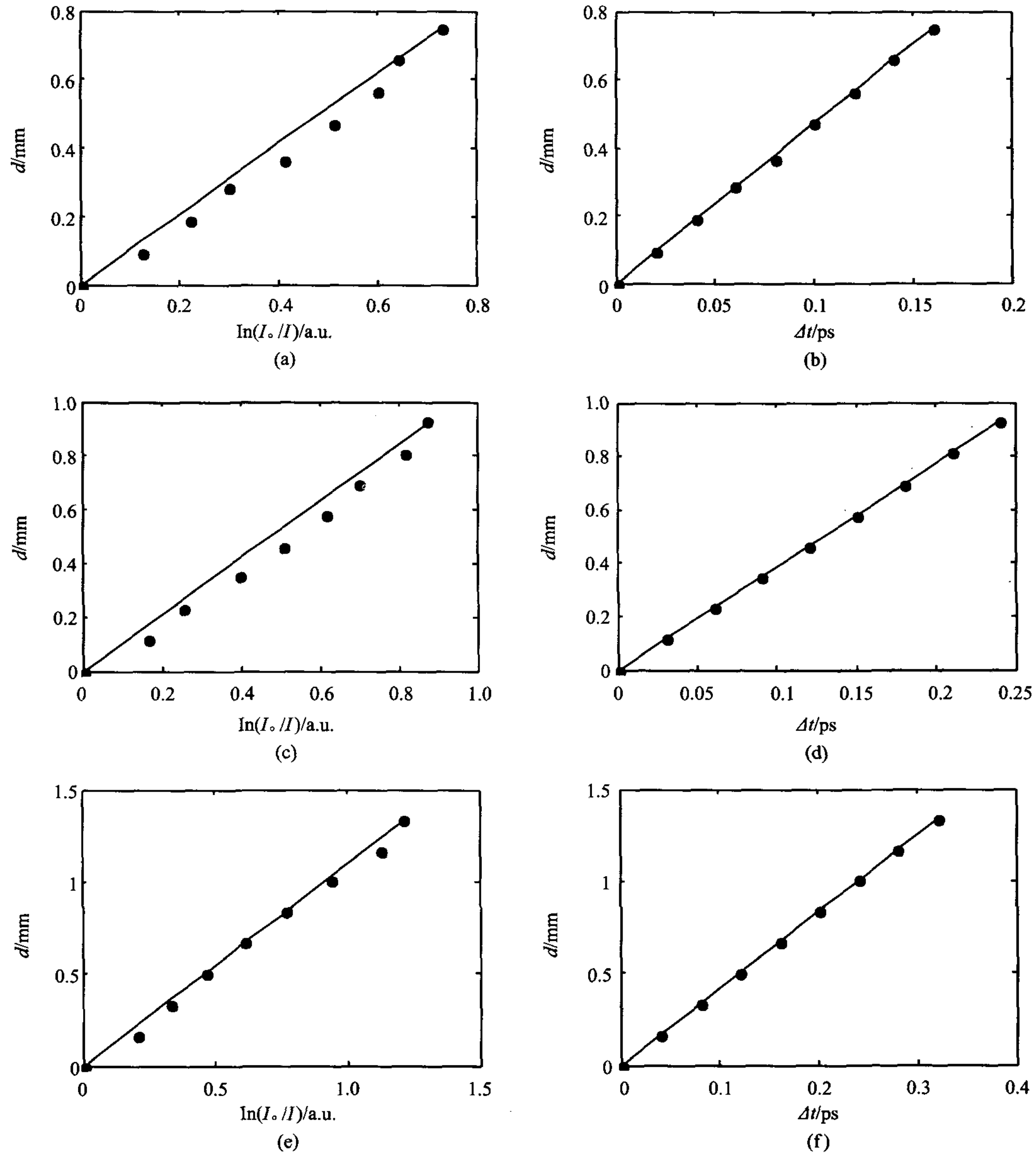

Fig. 2 Comparison between the principle of THz amplitude attenuation and THz delay time. (a), (c), (e) are THz amplitude attenuation of $70g/m^2$, $100g/m^2$, $160g/m^2$ (b), (d), (f) are THz delay time for $70g/m^2$, $100g/m^2$, $160g/m^2$

图2 基于幅度和太赫兹延迟时间方法的比较 (a),(c),(e)为$70g/m^2$,$100g/m^2$,$160g/m^2$纸的幅度衰减;(b),(d),(f)为$70g/m^2$,$100g/m^2$,$160g/m^2$纸延迟时间

well describe the effects between terahertz wave and the paper sheets to be investigated. However, the delay time, which is related to terahertz phase, is less influenced by multiple reflections and mainly related to refraction index and the thickness of the paper sheets. Consequently, it is inherently more accurate to characterize paper sheet basis weight by delay time than by amplitude attenuation.

4 Conclusion

A novel method for measurement of paper sheet basis weight is introduced by using terahertz time-domain spectroscopy. Two principles of measuring paper basis weight based on amplitude attenuation and delay time are presented and compared experimentally. The results show that the performance of delay time is better than that of amplitude attenuation. This new method has several advantages. First, the delay time of the transmitted terahertz wave can be measured conveniently by using terahertz time domain spectroscopy. Second, terahertz delay time of paper sheet is relatively stable because it is less influenced by other factors like

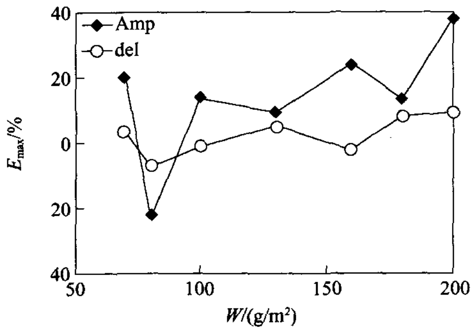

Fig. 3　Comparison of the maximum relative error between THz amplitude attenuation and THz delay time (W is basis weight, E_{max} is max relative error)
图 3　基于幅度和太赫兹延迟时间方法的响度误差(W 是单位面积纸画的重量, E_{max} 是最大相对误差)

the multiple reflections. Finally, terahertz wave is a safe radiation, so persons exposed to this radiation will not get slightly hurt.

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