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The design of rapid turbidity measurement system based on single photon detection techniques

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A B S T R A C T

A new rapid turbidity measurement system has been developed to measure the turbidity of drinking water. To determinate the turbidity quantitatively, the total intensity of scattering light has been measured and quantified as number of photons by adopting the single photon detection techniques (SPDT) which has the advantage of high sensitivity. On the basis of SPDT, the measurement system has been built and series of experiments have been carried out. Combining then the 90° Mie scattering theory with the principle of SPDT, a turbidity measurement model has been proposed to explain the experimental results. The experimental results show that a turbidity, which is as low as 0.1 NTU (Nephelometric Turbidity Units), can be measured steadily within 100 ms. It also shows a good linearity and stability over the range of 0.1–400 NTU and the precision can be controlled within 5% full scale. In order to improve its precision and stability, some key parameters, including the sampling time and incident light intensity, have been discussed. It has been proved that, to guarantee an excellent system performance, a good compromise between the measurement speed and the low power consumption should be considered adequately depending on the practical applications.

1. Introduction

Turbidity is a measure of the degree to which the water loses its transparency due to the presence of suspended particulates [1]. These suspended particulates, which induce the turbidity in water, are the potential insecurity factors for human health, because of their adsorption of bacteria, viruses, parasites and many other toxic organic compounds and pesticides. The World Health Organization (WHO) establishes that the turbidity of drinking water should not be more than 5 NTU (Nephelometric Turbidity Units), and should ideally be below 1 NTU. Therefore, the demand for low turbidity of water has increased and the method of fast measurement draws more and more attention in the world.

It is well-known that the Mie scattering has been widely employed in turbidity measurement. The scattering intensities will be very low for media with low turbidity according to the principle of Mie scattering. In the traditional turbidity measurement system, there are four types of detectors usually adopted: photomultiplier tubes, vacuum photodiodes, silicon photodiodes, and cadmium sulfide photoconductors [2]. Since their disadvantages of low sensitivity, lots of time has to be spent in waiting for the response of system, accumulating weak signal and averaging multi-measurements to ensure accurate measurements. For example, the precision of 1720E (Hach) is ±5% over the range of 40–100 NTU, while the response time is 60 s and the minimum measurement time is 6 s [9].

Recently, some new techniques have also been introduced in the turbidity measurement. Fiber-optic probes, for instance, are commonly used for in-situ measurement. A. Kramer and Th.A. Paul have analyzed the performance of various fiber-optic probe designs, in which the light exits under an angle of 10–20° [3] and its precision is ±0.1 NTU over the range of 0.1–60 NTU. The application of fiber optic has presented a flexible measurement, allowing measurements to be made online. However, when turbidity is higher than 60 NTU, the probe sensitivity decreases gradually which will result in nonlinearity. Although a bi-exponential calibration fit function is well suited to describe the relation of

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backscattered signal versus turbidity, the number of fit parameters has to be reduced to facilitate calibration.

In our previous works [4], a real-time turbidimeter based on time-correlated single photon counting (TCSPC) was developed to measure low level turbidity for drinking water. The drawback of the design is its nonlinearity at the range of 0.1–400 NTU. In addition, in order to obtain the turbidity, a statistical histogram should be obtained by sorting the echo photons according to their arrival time, and the peak of the histogram should be calculated. The complex signal processing method is not convenient for engineering applications, especially for the fast on-line monitoring. Moreover, the electronics for sorting photons by arrival time is costly.

In this paper, a rapidly straightforward turbidity measurement method for drinking water was proposed on the basis of the single photon detection techniques (SPDT). Since the Geiger mode APD has advantages of high sensitivity and short response time compared with the normal detectors, a high signal to noise ratio (SNR) can be acquired in a short measurement time. Therefore, high precision can be guaranteed while maintaining rapid measurement. Owing to the quantum statistical properties of SPDT, the fluctuation of scattering intensity can be reduced in the process of measurement, which can finally improve the stability of turbidity measurement. The experimental results show that a good linearity can be guaranteed over the range of 0.1–400 NTU, which significantly reduces calibration effort (enabling 2 points calibration). Moreover, the signal processing method is concise. The turbidity can be calculated by quantifying the total intensity of 90° Mie scattering light as the number of photons and utilizing a linear conversion model. In a word, the measurement system has the advantages of rapidity, high precision, high stability and linearity.

2. Principle and setup

2.1. The principle of SPDT based turbidity measurement system

The turbidity measurement principle consists of the 90° Mie scattering and the SPDT. The 90° Mie scattering, which has been identified as the turbidity quantitative determination method by the international water quality standard ISO7027 [5], has been adopted in our turbidity measurement system. In this paper, an 850 nm low power semiconductor laser, which is used as the light source, has been modulated and its modulated light has been projected into measured medium. According to Mie scattering theory, when the distance between the particle and the test point is r, the total intensity of the scattering light I_r can be expressed as [6]

$$I_r = T\frac{I_0}{r^2}\sigma = T\frac{I_0\lambda^2}{8\pi r^2}\left[i_1(k, m, \theta) + i_2(k, m, \theta)\right] \tag{1}$$

where I_r is the intensity of scattering light, I_0 is the intensity of incident light, λ is the wavelength of the incident wave, σ is the scattering coefficient of a single particle, $i_1(k,m,\theta)$ and $i_2(k,m,\theta)$ are scattering light intensity functions, T is the turbidity of the sample, θ is the angle between the scattering light and the incident light, r is the distance between the particle and the test point of the scattering intensity, that is the optical path of the scattering light.

When the angle between the scattering light and the incident light θ is 90°, the Eq. (1) can be simplified as

$$I_r = K_S T I_0 \tag{2}$$

where K_s is the proportionality coefficient.

Thanks to the SPDT, which is rarely reported in the field of turbidity measurement, the total intensity of 90° Mie scattering light has been measured and quantified as the number of photons by avalanche photodiode (APD) in the Geiger model. Moreover, by utilizing the high avalanche gain inside device, the Geiger mode APD can directly generate large amplitude signal without multi-stage amplification, which has advantages of shot-noise-limited detection of single-photon events [8]. In addition, the lack of A/D conversions and multistage amplification can remove quantization errors and the usual non-idealities associated with these components. As shown in Fig. 1, the simplest photon counter consists of a detector, followed by a discriminator and a counter [7]. In this paper, APD is used as a photoelectric detector. A series of single-photon pulses have been produced by the detector when a faint ray of light illuminates to the detector and the avalanche effect occurred. A pre-amplifier can, but need not, be used behind the detector to obtain pulses of sufficient amplitude at the discriminator input. The discriminator with an adjustable threshold, which is set to discriminate the single-photon pulses against the background noise, has been adopted in the photon counter. The discriminator threshold is set well above the noise level, but below the peak amplitude of the photon pulses delivered by the detector. When a single-photon pulse exceeds the selected threshold, the discriminator delivers a pulse of a defined duration and a defined logic level. The discriminator output pulses are counted by the subsequent counter. The photons are acquired for a given time interval, after which the result is read from the counter. And then, a faint ray of 90° Mie scattering light has been quantified as the number of photons. At last, the turbidity of the sample T can be calculated by Eq. (2).

2.2. Experiment setup

To implement the turbidity measurement principle, the experimental setup has been built and its block diagram is shown in Fig. 2.

In the turbidity measurement system, an 850 nm laser diode (L850P010, Thorlabs) has been modulated (f_s=1 MHz, square waves, duty ratio=20%) by a pulse driving circuit, and then pulse laser has been generated. The synchronous signal, which is so called as start-signal, has been generated by the oscillator at the same time. The pulse laser has been projected into sample cell

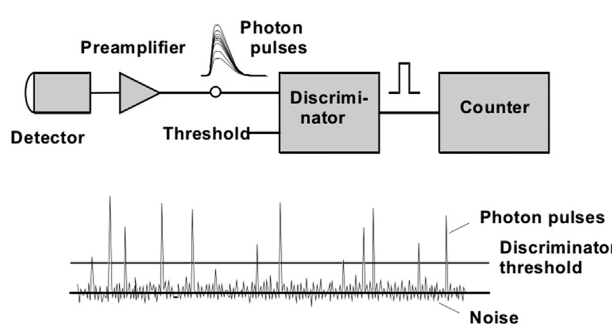

Fig. 1. The block diagram of SPDT based signal processing [7].

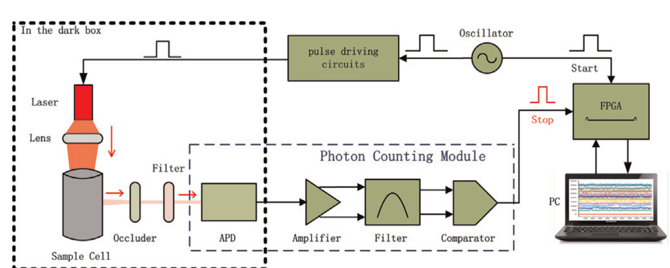

Fig. 2. The block diagram of SPDT based turbidity measurement system.