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Design and performances of a mid-infrared CH_4 detection device with novel three-channel-based LS-FTF self-adaptive denoising structure

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ABSTRACT

A novel mid-infrared (MIR) CH_4 concentration detection device using three-channel-based least-square fast transverse filtering (LS-FTF) self-adaptive denoising structure was proposed. By introducing an additional noise-channel besides the traditional detection-channel and reference-channel, the noises can be well removed using the LS-FTF denoising algorithm. The detection procedure was described, and the key modules including the optical part and electrical part were designed and fabricated. Thorough experiments performed for the fabricated device show that the absolute detection error is less than 5%, and by quantifying the detected voltage using software, the minimum detection level is 8 ppm and the detection sensitivity is 9 ppm within the detection range of 8–1000 ppm. The measured maximum response time is less than 10 s, and the absolute detection error with temperature-compensation is less than 5%. The proposed three-channel-based LS-FTF denoising structure can also be adapted to other similar detection systems for noise elimination.

1. Introduction

Recently, the detection on the inflammable and explosive gas CH_4 [1–4] becomes much important for assuring human life and property especially in the underground mining environment. Within the primary available detection methods, including thermal catalytic [5], thermal conductivity [6], optical interference [7] and infrared (IR) absorption [8], the IR absorption detection approach has been a hot research issue in this field due to the advantages of wide measuring range, high accuracy and longevity [9–11]. The detection device should be fabricated with small minimum detection level, high detection accuracy, high detection sensitivity, high stability, fast response time, low power and self-adjusting function, and these features depend greatly on both the optical part and electrical part. In detection, compared to the laser source [12], the IR incandescence or IR light emitting diode (LED) is much cheaper in price and much easier to be driven and modulated. However, because of the slow response of IR incandescence or IR LED, the modulation frequency is usually below 10 Hz to realize a high modulation depth and a high signal-noise-ratio (SNR). In this case, the interferences and noises resulting from the IR light source, IR detector, electrical components and electrical wires are usually serious, which involve $1/f$ noise, shot-noise and white Gaussian noise. Therefore, to a large extent, eliminating the effects of these noises is important for increasing the SNR and thus improving the detection features.

In the traditional design, the noises and interferences arising from light source and light path can be eliminated using the single-source dual-channel detection method [13–15], and those arising from the electrical components can be reduced using the hardware-based filters or software-based classic digital filters. However, there are still three items that should be addressed. First, the $1/f$ noise is so large that it will result in the drift and flicker of the signal to be processed by processor, and these noises cannot be totally removed by the traditional denoising methods. Second, because the modulation frequency is close to the direct current (DC) frequency, it is hard to design such a strict hardware-based ultra-narrow band-pass filter for getting rid off low frequency noises. Third, the classic digital filters, such as the median smoothing digital filter or average smoothing digital filter, can only remove the spikes but cannot eliminate the DC drift. These three aspects will definitely affect the detection performances including the minimum detection level, detection accuracy, detection sensitivity, response time, etc.

Therefore, in order to eliminate the noises completely and improve the detection performances, we propose a novel mid-infrared (MIR) CH_4 detection device in this paper. The modern self-adaptive digital filter based on the least square fast transverse filtering (LS-FTF) algorithm [16–18] is introduced, and a novel additional noise-channel besides the detection-channel and reference-channel is used. The structure of this paper is orga-

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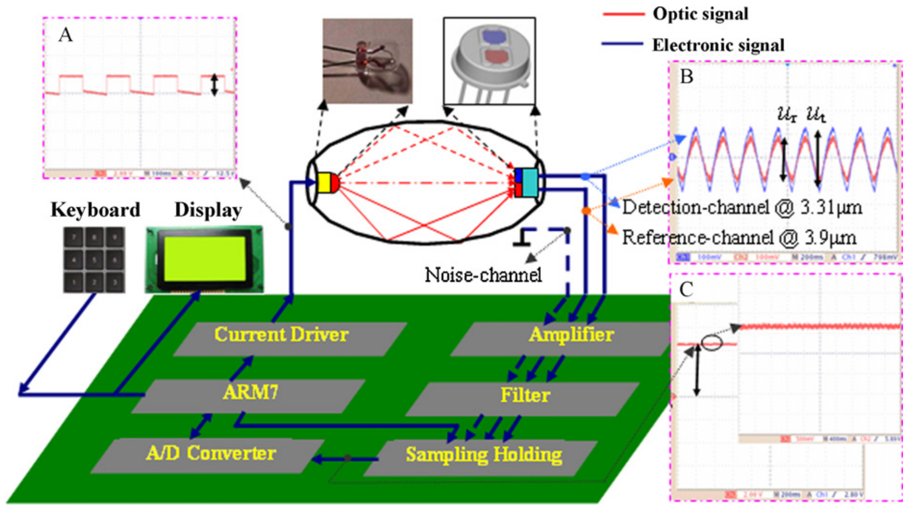

Fig. 1. This figure optionally shows (1) structure of the traditional dual-channel-based (only including detection-channel and reference-channel) MIR CH_4 detection device without using noise-channel or (2) structure of the our proposed novel three-channel-based (including detection-channel, reference-channel and noise-channel shown by the blue dash-line) MIR CH_4 detection device using LS-FTF self-adaptive denoising principle. The sub-figures show the measured waveforms of (A) IR source driving voltage, (B) output signals from dual-channel detector, and (C) polluted peak-to-peak voltage received by A/D converter. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of the article.)

nized as follows. First in Section 2, the influences of noises on the traditional dual-channel-based detection device are analyzed and discussed, and related formulas are deduced. The principle and simulation of the LS-FTF algorithm are described for denoising high-frequency and low-frequency noises. The novel three-channel-based detection structure and its procedure are presented. Then in Section 3, the key modules including the optical part and electrical part are designed and fabricated, and the temperature-compensation principle is discussed. Furthermore in Section 4, experimental results of the fabricated device are demonstrated and analyzed. Finally in Section 5, a comparison between the performances of this novel three-channel-based detection device and those of other three reported traditional dual-channel-based detection devices is performed. Some conclusions are reached at the end of this section.

2. Novel three-channel-based LS-FTF denoising structure

2.1. Noises on the traditional dual-channel-based detection device

We know from the HITRAN 2004 database that CH_4 has the strongest absorption at $\lambda_1 = 3.31\ \mu m$, and almost has no absorption at $\lambda_2 = 3.9\ \mu m$. So based on Beer–Lambert law and single-source dual-channel detection principle, when the reference-channel and detection-channel are used for detection, as shown in Fig. 1, the designed device is named a traditional dual-channel-based device. It contains two primary parts, one is the optical part including the IR source (IRL715 [19], whose photo is shown in Fig. 1) and its constant-current driver, the ellipse light-collector gas cell, and the dual-channel detector (TPS2534, whose photo is also shown in Fig. 1), and the other is the electrical part mainly involving ARM7 processor, liquid crystal display module, keyboard, amplifier, filter, sampling/holding module and A/D converter. The IR light source and dual-channel detector are located at the left and right focal points of the ellipse gas cell, respectively. Considering the response time of IRL715 and the modulation depth of TPS2534, the modulation signal of IRL715 is taken as the 4 Hz square-wave form that is shown in sub-figure (A) in Fig. 1 (measured with an oscilloscope, Tektronix TDS3032C).

For the traditional dual-channel-based detection device, the measured signals output from the dual-channel detector are exhibited in sub-figure (B) in Fig. 1. For the detection-channel, let u_t be the pure peak-to-peak voltage signal output from the detector at the filtering wavelength of 3.31 μm, and for the reference-channel, let u_r be the pure peak-to-peak voltage signal output from the detector at the filtering wavelength of 3.9 μm. The peak-to-peak voltages of u_t and u_r are also labeled in the measured waveforms, as shown in sub-figure (B) in Fig. 1.

In the following we will analyze the influences of noises on the detection performances of the traditional dual-channel-based device.

According to Beer–Lambert law, after the IR light with wavelength λ passing through CH_4, its light intensity I_{out} becomes [20,21]

$$I_{out}(\lambda) = I_0 \exp[-\alpha(\lambda)CL], \tag{1}$$

where I_0 is the initial incident intensity, $\alpha(\lambda)$ is the absorption coefficient at λ, C is the CH_4 concentration, and L is the absorption path length.

For the traditional single-source dual-channel detection method shown in Fig. 1, under the square-wave modulation situation, let i be the peak-to-peak driving current of the IR source, and $I_0(\lambda_1) = K(\lambda_1)i$ and $I_0(\lambda_2) = K(\lambda_2)i$ be the peak-to-peak emitting light intensities at λ_1 and λ_2, respectively, where $K(\lambda_1)$ and $K(\lambda_2)$ be the electro-to-optical conversion coefficients of the IR source at λ_1 and λ_2, respectively. The receiving light intensities at the two filtering windows of the dual-channel detector are, respectively

$$I_t(\lambda_1) = K(\lambda_1)i \exp[-\alpha(\lambda_1)CL - \beta(\lambda_1)], \tag{2a}$$

$$I_r(\lambda_2) = K(\lambda_2)i \exp[-\alpha(\lambda_2)CL - \beta(\lambda_2)], \tag{2b}$$

where $\beta(\lambda_1)$ and $\beta(\lambda_2)$ are the absorption and interference factors from light path and gas cell at λ_1 and λ_2, respectively. Then the two peak-to-peak voltages $u_t(\lambda_1)$ and $u_r(\lambda_2)$ output from the dual-channel detector can be expressed as

$$u_t(\lambda_1) = D(\lambda_1)I_t(\lambda_1), \tag{3a}$$

$$u_r(\lambda_2) = D(\lambda_2)I_r(\lambda_2), \tag{3b}$$

where $D(\lambda_1)$ and $D(\lambda_2)$ are the optical-to-electrical conversion coefficients of the detector at λ_1 and λ_2, respectively.