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A wireless sensor network based on DFB lasers for water vapor detection

Feng Cao[a,b], Yi-Ding Wang[a,*], Lei Liu[b,*], Meng-Long Cong[a]

[a] State Key Laboratory on Integrated Optoelectronics, College of Electronic Science and Engineering, Jilin University, Changchun 130012, PR China
[b] College of Computer Science and Technology, Jilin University, Changchun 130012, PR China

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ABSTRACT

This paper describes the development of a wireless sensor network for remote water vapor detection. The network is composed of three parts: the base station, the router node, and the end node. The end node is fabricated from distributed-feed-back (DFB) laser water vapor detection systems. Multi-node topology is adopted among the water vapor detection nodes with ZigBee multi-hop mesh routing protocol for communication, and acquisition data are transmitted to the data center through wireless communication. The network can detect water vapor down to 1 ppm, and an excellent stability is observed in 100 days. The system has been put into an actual test application, and it will be used to monitor environment change with a high precision.

1. Introduction

Wireless sensor networks (WSNs) are increasingly demanded for inflammable-gas inspection, air-quality detection, environmental monitoring and personal security [1]. Compared with traditional wire sensor systems, WSNs have features of easy installation, convenient maintenance and flexibility for information inspection [2–4]. WSNs are very suitable for the applications which are difficult for cabling, accessing for persons, or some temporary monitoring [5–7]. Simultaneously, the cost of installing wires for a single sensor in a building is estimated to average $ 200, this implies huge commercial possibilities for WSNs in the near future [8]. WSNs are typically consisted of a number of small, inexpensive, locally powered sensor nodes that communicate detected events wirelessly through multi-hop routing [9–13]. Accordingly, sensors are vital in WSNs as they provide the link between the physical and digital domains, and it is self-evident that in the absence of sensors with appropriate specifications, the deployment of WSNs is not possible [14–17].

Humidity sensors are very important for its diverse applications in industrial processes such as the baking and drying of food, in equipment storage, in civil engineering to detect water vapor ingress in soils or in the concrete in civil structures, in medical applications and so on [18–20]. Researchers have developed humidity sensing architectures that use changes in capacitance, wave intensity, frequency, refractive index, and impedance as sensing mechanisms [21,22]. Among the reported sensors, distributed-feed-back (DFB) laser-humidity sensors are known for their ultra-reliability and high compatibility with electrocircuits and other modules such as digital-signal-processor (DSP) and global-positioning-system (GPS) [23,24]. However, there is almost a complete absence of DFB laser-humidity sensor networks in the literature [25].

Herein, we propose a wireless sensor network based on DFB lasers for water vapor detection. DFB lasers are widely chosen in detecting equipment for their low cost, small size and easy installation. And this type of lasers can work at room temperature, which means the remove of liquid nitrogen cooling [25]. The network is composed of three node types. One is base station which is also the coordinator of the ZigBee network, another is router node, and the other is end node (DFB laser water vapor detection system). The data center can obtain and analyze the sensor data real-timely. The large detection range and high precision suggest this network is a good candidate for practical humidity monitoring.

2. Theoretical principles

Laser absorption spectroscopy (LAS) of target gas species, which is based on the Beer-Lambert absorption law, effectively

* Corresponding authors. Tel.: +86 431 85168385; fax: +86 431 85168270.
E-mail address: qlcf0722@gmail.com (Y.-D. Wang).

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determines real-time gas concentrations. Beer Lambert law [26] states:

$$I = I_o e^{[-\delta(\nu)NL]} \quad (1)$$

where I is the intensity of light passing through the absorbing medium, I_o is the input intensity, N is the molecular density, L is the optical pathlength, ν is the radiation frequency, and $\delta(\nu)$ is the absorption cross-section. When WMS (wavelength modulation spectroscopy) is referred, the diode laser injection current is sinusoidal modulated with angular frequency $\omega = 2\pi f$ to produce laser frequency modulation (FM), and the light intensity is simultaneity modulated (IM) as well as the wavelength:

$$I_0 = I_{dc}(1 + i(\cos\omega t + \psi)) \quad (2)$$

$$\nu = \nu_{dc} + \Delta\nu_m \cos(\omega t) \quad (3)$$

in which I_{dc} is the laser frequency without modulation, $\Delta\nu_m$ is the amplitude of the frequency modulation, i is the coefficients to fit the observed intensity-frequency relationship for the specific laser used, normalized by the average laser intensity, with ψ as FM/IM phase shifts.

Therefore, the formula (1) can be expressed as:

$$I = I_{dc}[1 + i_0(\cos\omega t + \psi)]\exp\{-\delta[\nu_{dc} + \Delta\nu_m \cos(\omega t)]NL\} \quad (4)$$

After the logarithmic amplification, the formula (4) can be changed to:

$$\ln I = \ln I_{dc} + \ln[1 + i_0(\cos\omega t + \psi)] - \delta[\nu_{dc} + \Delta\nu_m \cos(\omega t)]NL \quad (5)$$

Then Fourier expansion is employed and following formula is obtained.

$$\ln\ I = \ln I_{dc} + \sum_{n=0}^{\infty}(f - CLS_n)\cos(n\omega t) \quad (6)$$

where fn and Sn are the Fourier coefficients of $\ln[1 + i_0(\cos\omega t + \psi)]$ and $\delta(\nu)$ respectively. The $\ln I$ is processed by the lock-in amplifier and detection circuit, and the output second harmonic signal can be displayed as:

$$D_2 = f_2 - CLS_2 \quad (7)$$

The relationship between the water vapor concentration and the second harmonic signal (D_2) is linearity. By calibrating the known gas concentration, the values of f_2 and S_2 can be calculated, and therefore the concentrations of target gases can be obtained.

3. Experimental

Fig. 1 shows the schematic of a DFB laser water vapor detection system. A temperature controller is fabricated based on a thermoelectric cooler (Tes1 1702L Hainan) to quantify the frequency-swept output from the laser. The laser source is a DFB quantum well diode laser fabricated by the Institute of Semiconductors, Chinese Academy of Sciences, emitting single mode at 1859 nm (25 °C, 35 mA). An InGaAs/InP medium based on non-identical quantum wells is grown by low pressure metal organic vapor-phase epitaxy (MOVPE), yielding a bandwidth of 115 nm. With this gain medium, the DFB laser with varied Bragg gratings in serial is fabricated by use of modified holographic exposure technology [27]. The wavelength of 1859.7930 nm of the current laser is achieved at an operating current of 50 mA. The power of this DFB quantum well diode laser reach 10 mW, both the side-mode suppression ratios (SMSRS) reach 40 dB. The laser device is integrated with the Peltier thermoelectric cooler in a butterfly package together to stabilize the laser emission. The pig-tail of the laser diode is connected to a 200 mm electro-polished, brass absorption cell which is mounted with sapphire windows wedged at 5°

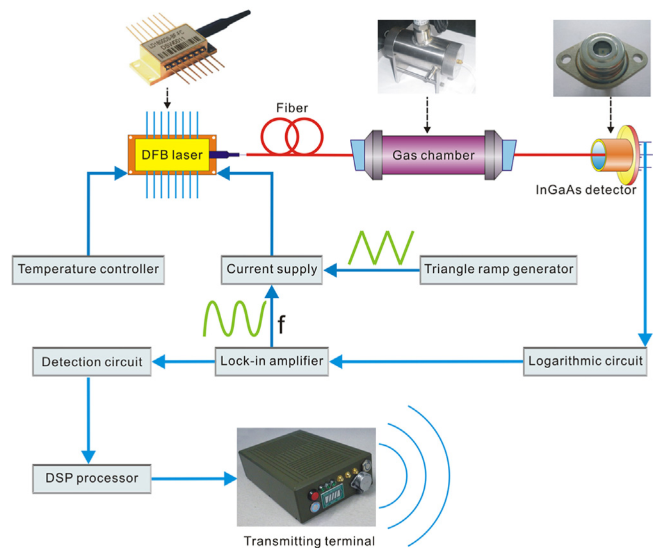

Fig. 1. A experimental schematic image of a DFB laser water vapor detection system.

angle to avoid interference fringes. After exiting the cell, the beam is refocused onto an InGaAs detector (Judson Inc., J23-18I-R01M-2.2). This detector has fast rise times, excellent sensitivities, and good long-term-reliability for the range of 0.8–2.2 um. For the frequency of 1 KHz, a typical D^* of 2.4e+11 cmHz$^{1/2}$/W is given. To avoid notorious etalon fringes related to residual reflections, all fiber connections are either fusion-spliced or made with angle-polished FC/APC (ferrule connector/asperity polishing connector) connectors. The environmental air is aspirated into the chamber by a pump. The flow rate was about 0.8 liters per minute. These measurements are performed after accurate purging the cell to prevent interference from adsorbed–desorbed molecules at the normal air pressure (1.01×10^5 Pa) and room temperature (296 K).

The DFB laser injection current is tuned by a triangle ramp waveform (5 Hz), which is the same as traditional scanned-wavelength direct-absorption detection systems. This design has an effect of repetitively ramping the laser intensity and the laser wavelength across the absorption feature. An additional high-frequency sinusoid (f, 5 kHz) is superimposed on the repetitive injection current ramp to generate an additional high-frequency modulation in both the laser intensity and wavelength. Therefore, absorption affects the shape of the transmitted laser intensity and introduces harmonic components to the detected signal.

The InGaAs-detector signal is passed to a logarithmic circuit and a lock-in amplifier in turn. The logarithmic circuit here is taken before the lock-in amplifier, which makes the residual amplitude modulation (RAM) and absorption spectrum clearly decompose, and this decomposition leads to a much simpler calibration process. Simultaneously, it can also eliminate the influence of average power shift in the second-harmonic amplitude detection, which is caused by fluctuation of driving current and any power loss independent on wavelength. The lock-in amplifier is employed to isolate the second harmonic (2f) signals. It acts by multiplying the detector signal by a reference 2f sinusoid at the frequency of interest, to shift the harmonic components at the frequency of interest to DC. A low-pass filter is then applied to isolate the DC value and eliminate all components outside the filter bandwidth. The 2f signal from the lock-in amplifier is demodulated by a detection circuit, and the peak value of 2f signal, which is related to the water vapor concentration, is translated to changeable DC voltage signal. The relationships between the DC voltage signal and water vapor concentration is calculated by a DSP processor. 100 scans are averaged from each signal concentration measurement in the system. The DSP output