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Gas Sensor Using a Robust Approach under Time Multiplexing Scheme with a Twin Laser Chip for Absorption and Reference *

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A tunable diode laser absorption spectroscopy nitrous oxide gas sensor at 2.1 micrometres using one antimonide twin laser chip and one InGaAs photodiode is demonstrated, in which time multiplexing techniques are adopted to acquiring both the absorption and reference signal in a robust fluctuation tolerable scheme. Electronics in analogue modality is developed to extracting absorption information and compensating for fluctuations, resulting in a direct analogue voltage output corresponding to the target gas concentration in real time. The performance of the gas sensor is evaluated experimentally, the validity and feasibility of this scheme is also discussed.

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Among various tunable diode laser absorption spectroscopy (TDLAS) schemes developed so far,[1] the direct absorption is still the most popular approach. Generally speaking, in this approach one MIR laser with wavelength fitting the target gas is used, the laser light was guided using suitable optics through a gas cell, then focus into a photodetector. In this system, to compensate for the possible fluctuations of the laser output and/or optical path, normally calibration measurement with zero air is often needed before or after gas sampling to obtain a base line required for the calculation of absorbance. In some cases such as open path, the zero air calibration becomes impossible, as an alternative, a fixed reference channel could also be adopted for similar purpose as well as locking the absorption line, in this reference channel the light was split from the same laser and the second photodetector should be installed to obtain the reference signal, in this case the path lengths of the two channels are normally different. All these make the construction and operation of the system complex. Furthermore, in this architecture certainly all the components including laser, detector, optics and electronics should be extremely stable, which may make the system even complex and bulky, and therefore costly. As an attempt to simplify the system, an architecture using monolithic twin or multi laser under time multiplexing scheme was proposed,[2] and validated adopting a digital oscilloscope for waveform acquisition and a personal computer (PC) for data processing.[3] In this Letter, we present the demonstration of such a robust gas sensor.

The spectral width of the optical gain profile of semiconductor laser is usually broader than tens of cm^{-1} (normally reaches about 10% of the central wavelength),[4,5] so the possibility of monolithically integrate those two lasers together exists. If the two lasers are monolithic twin on one chip and in the same package, the heat sink temperature will be the same, the stabilization and operation of the laser will be easier. The beams are closer enough or combined, the optics could also be simple. Furthermore, the twin is located on the same chip in the same circumstance, so quite similar short or long term behaviour and even lifetime could be expected, which will be beneficial to the construction of the sensor. To distinguish the signal and reference from the twin by the same optical path, time multiplexing scheme could be used, in this case only one photodetector is needed. That is, the twin laser could be driven alternatively at different time intervals, the response from the photodetector corresponding to the same time interval represents the signal and reference respectively, and therefore the signal and reference could be demultiplexed using suitable electronics. Normally the final sensor signal corresponds to the ratio of the signal to the reference for compensation of possible fluctuations, so in this scheme no special stabilization is needed because both light beams are through the same optics, and detected signal and reference are from the same photodetector and related electronics. In most cases, photodetector operating at room temperature without any temperature control could be used if its noise margin is suitable. Notice that the signal and reference light are from the twin and through the same optical path, their transmission time should also be the same (for a long optical path, this time reaches hundreds of nanosecond), the possible fluctuation should be the same or quite similar, so using this scheme the construction and adjustment of the system should be easier and higher common mode rejection ratio could be expected.

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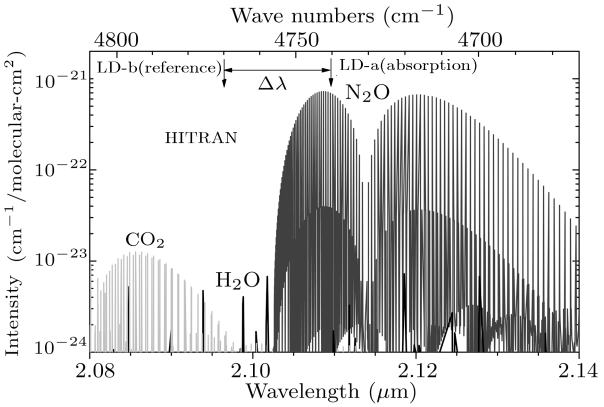

Fig. 1. HITRAN data of N_2O, H_2O and CO_2 around 2.1 μm. Marks indicate the lasing wavelengths of the antimonide monolithic twin laser in experiments.

The architecture of this gas sensor is as follows: a monolithic twin laser chip generating two laser beams with closer but different wavelengths (normally tens of cm^{-1} apart) alternately, one beam was used for obtaining absorption signal of the target gas, the other for obtaining non-absorption reference. In the monolithic twin laser the two laser beams are spatially closer, or combined using waveguide or fibre, so only one light collecting and collimating system is needed. After through the optical path containing the target gas, the two alternating laser beams is received using only one photodiode (PD), time division multiplexing is used to distinguish the absorption and reference signal, from which a direct sensor output could be obtained using simple electronics without adopting data acquisition card (DAC), PC, software, etc. This scheme is fluctuation tolerable, and could also be extended to monolithic multi-laser or laser-array case for sensing more gases simultaneously.

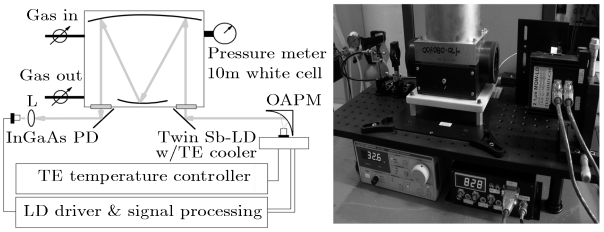

Fig. 2. Schematic and photo of the TDLAS gas sensor prototype.

To demonstrate the gas sensor using above concept, in our initial experiments a antimonide monolithic twin laser at hand is used, this twin laser is based on our molecular beam epitaxy grown InGaAsSb/AlGaAsSb MQW laser lasing around 2.1 μm,[6] which could be cw operated up to 80°C.[7] At this wavelength region N_2O, which is an important green house gas, was chosen to be the target gas. Figure 1 shows the high resolution transmission (HITRAN) data of N_2O in this wavelength region with two connected hills. The slope at the short wavelength side is much steeper than that at long wavelength side.[8] Based on this absorption pattern, tens of cm^{-1} offset of the wavelength is enough to allocate the absorption peak and reference baseline, especially at short wavelength side.

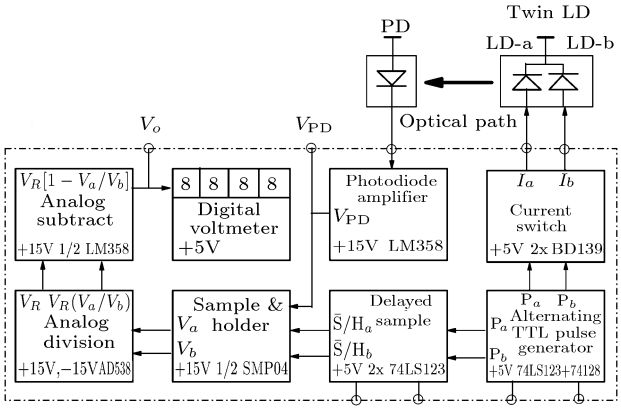

Fig. 3. Schematic drawing of the electronics of LD driver, PD amplifier, signal processor and sensor readout.

The twin laser is of Fabry–Pérot (F-P) ridge waveguide structure, the detailed characteristics of the laser chip are as reported in Refs. [3,7,14]. For antimonide lasers, normally single mode or one-mode dominating lasing could be expected in certain current and temperature region even for F-P structures,[7,9–14] so the lasing wavelength and mode character of this twin laser is calibrated using a Fourier transform infrared (FTIR) spectrometer. The slight different ridge width of the twins results in distinct mode character, for this twin laser, when the heat sink temperature tuning to around 33°C, the single-mode lasing around 4740 and 4770 cm^{-1} for LD-a and LD-b appears respectively. Compare to the HITRAN data of target gas N_2O in this wavelength region as shown in Fig. 1, certainly LD-a could be used to obtain absorption signal through fine tuning to catch one relatively strong absorption line of N_2O in this region, whereas LD-b has deviated from the absorption area of N_2O, so it could be used as reference. Notice that the wavelength of LD-b is located in the area where the absorption intensity of H_2O and CO_2, the most important interference gas in air or sample, is in lower orders. In this area through fine tuning, free of H_2O and CO_2 interference is also possible. To detect the laser light in this wavelength region, an InGaAs PD is used.[15] The PD is operated at room temperature with cut-off wavelength of 2.24 μm; its peak response is just around 2.1 μm. In this single PD sensing scheme the PD is only used to determine the ratio of the absorption to the reference light, also its S/N ratio at room temperature is good enough, so no cooling or temperature stabilization is adopted.

The wavelength scan of the diode laser in this scheme is accomplished using its chirp features, that is, broader rectangle current pulses are used to drive

the laser, during a pulse period the laser was heated up, which causes a temporary temperature raise in its active zone, results in a wavelength shifts towards the red side; when this pulse stops, the laser cools down, the wavelength shifts back towards blue side. Under constant pulse driving condition and fixed heat sink temperature, a stable wavelength scan of the laser could be expected. Calibration measurement show that for this antimonide laser driving under about 200–300 mA current, pulse width of 500 μs causes a wavelength scan of 2–3 cm^{-1}, which is sufficient for catch one absorption line of the target gas in this scheme.

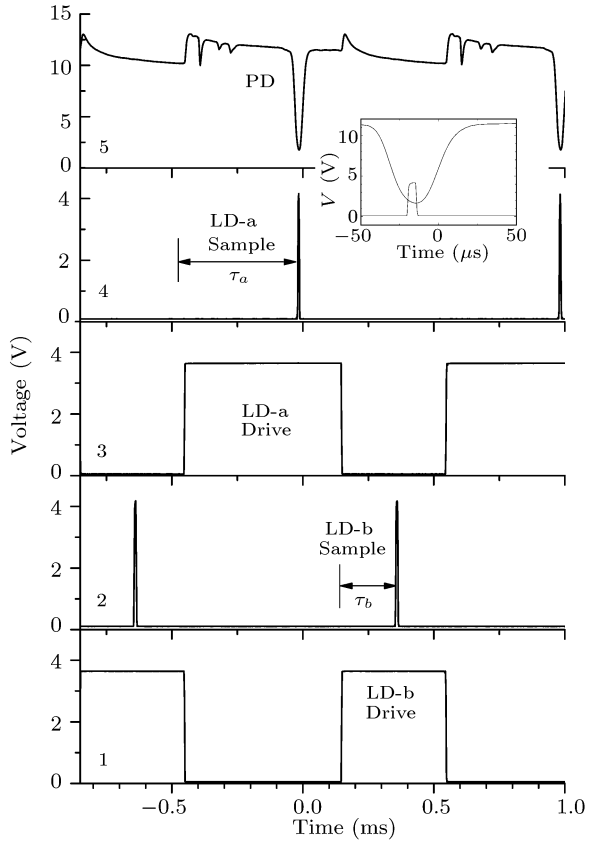

Fig. 4. Measured waveforms and timing relationship of the LD driving pulse (traces 1 and 3), sample and hold pulse (traces 2 and 4) and amplified PD signal (trace 5). The inset is a close look of traces 4 and 5.

The prototype of the gas sensor is shown in Fig. 2, where all the components are mounted on an optical breadboard with $30 \times 60\,cm^2$ footprint. In this simple setup, one 90° off-axis parabolic mirror (OAPM) with diameter of 2 in and focus length of 3 in is used to collect and collimate the two beams from the twin laser through a White cell with path length of 10 m, and then focus to the PD with diameter of 300 μm using a quartz lens. Because the two beams from the twin laser is only 220 μm apart and the entrance beam diameter of this White cell is quite large, so no precise adjustment was needed. A commercial TEC controller is used to stabilize the heat sink temperature of the twin laser within ±0.01°C. The electronics for driving the twin laser, amplifying the PD current and processing the signal for obtaining direct sensor output are schematically shown in Fig. 3, where all the components are installed on a $10 \times 15\,cm^2$ breadboard and packed into an $7 \times 10 \times 16\,cm^3$ aluminium shielding box including a dc switch power supply with +5 V 1 A and ±15 V 0.2 A outputs.

Figure 4 shows the measured waveforms and time relationship from each monitoring connectors using a digital oscilloscope. From Fig. 4, it could be seen that the trace 3 and trace 1 are the complementary TTL driving pulses P_a and P_b for LD-a and LD-b, respectively, the frequency is set to be 1 kHz, the pulse duration for LD-a and LD-b are set to be 600 μs and 400 μs, respectively, for discrimination. Trace 5 is the amplified waveform of V_{PD} from the PD. In the time interval corresponding to LD-b, a smooth output without absorption could be observed. A slight decay of the output amplitude during the pulse could be seen, especially at the beginning of the pulse, this is because of the temperature effects. The temperature raise caused by the heating effect of the broader driving pulse not only results in a wavelength scan, but also bring to a lesser decrease of the laser power. In the time interval corresponding to LD-a, a strong absorption line of N_2O appears as expected, the width of the line is tens of μs in time domain, its absorption intensity corresponds to the concentration of N_2O directly. In this time interval a few small valleys exist at the beginning of the pulse, through tracking those valleys by temperature tuning, those valleys are belonging to the neighbouring absorption line of N_2O.

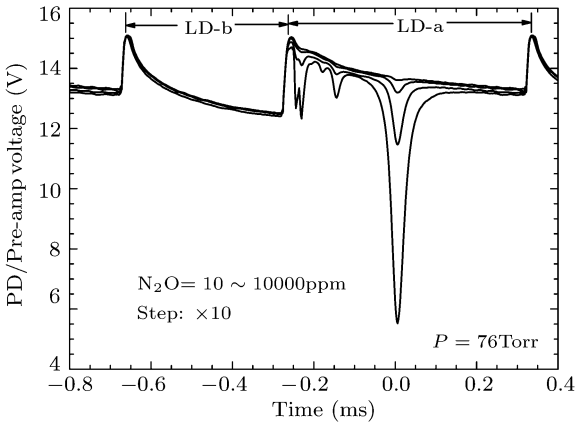

Fig. 5. Measured waveforms of amplified PD signal at different N_2O concentrations of 10, 100, 1000 and 10000 ppm diluted using room air.

To produce a direct sensor signal which is preferably an analogue voltage output corresponding to the target gas concentration, further signal processing were adopted. Firstly, the absorption and reference information should be extracted from the

PD/amplifier output $V_{\rm PD}$, this was accomplished by using an SMP04 sample and holding circuit. To generate the sample-and-hold pulses H_a and H_b for absorption and reference signal respectively, two 74LS123 were used. Those two 74LS123 generates narrower (about 10 μs) sample-and-hold pulses with adjustable delay of τ_a and τ_b from the rise edge of P_a and P_b respectively as shown in the trace 4 and trace 2 of Fig. 4. The sample-and-hold pulses H_a and H_b in conjunction with the output from the PD/amplifier $V_{\rm PD}$ were send into the SMP04. When the falling edge of H_a was aligned to the absorption peak from LD-a as shown in the inset of Fig. 5, and H_b fixed to the flat zone from LD-b, the absorption and reference voltage V_a and V_b formed. Here V_a and V_b are connected to potentiometers, so their amplitudes are adjustable for calibration purpose. Secondly, an AD538 real-time analogue computational unit (ACU) circuit was used to obtain the ratio of V_a/V_b, which is related to the transmittance of the target gas directly, in which the possible common mode fluctuations caused by optics and electronics have been compensated for. The +10V on-chip reference voltage V_R in the AD538 was used to scale the ratio of V_a/V_b, so the range of $V_R(V_a/V_b)$ is 0–10 V. Thirdly, a LM358 op-amplifier was used to carry out an analogue subtract to obtain $(1 - V_a/V_b)$, which is related to the absorbance and therefore the concentration of the target gas as is expected. In the subtracter, V_R was also used, so its full-scale output is 10V. This dc output V_o with refresh rate the same as the driving pulse frequency was sent to a digital voltmeter to have a direct readout and to an output connector as an intuitive sensor signal.

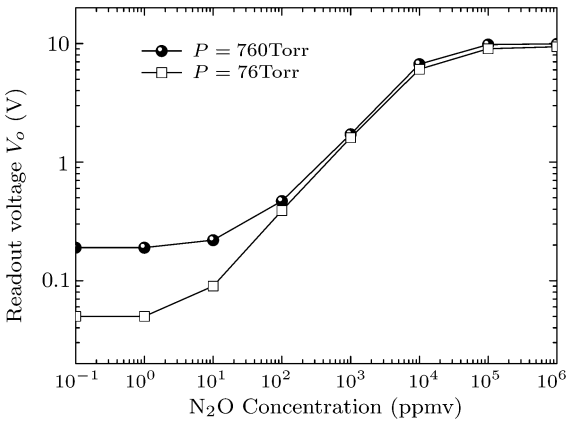

Fig. 6. Measured sensor output voltage versus N_2O concentration at pressure of 76 Torr and 760 Torr.

The calibration of the electronics is quite simple. Firstly, filling the gas cell with a little target gas, adjusting τ_b of sample-and-hold pulse H_b to a flat zone without absorption, then adjusting τ_a to align the falling edge of sample-and-holder pulse H_a to the absorption peak of the target gas to reach a maximum readout. Secondly, pump down the gas cell then adjust the output of V_a or V_b to have zero readout. In the open-path case, insert and then remove a reference cell will be needed. Notice that with the electronics above only a raw sensor output corresponding to the peak absorption of the target gas could be gained, further calibration of the data will be needed to extract detailed concentration information.

Figure 5 shows the recorded waveforms of $V_{\rm PD}$ at different N_2O concentrations from 10 to 10000 ppm diluted using room air at pressure of 76 Torr. It could be seen that, the target gas causes notable absorption peaks to the light from LD-a, its intensity changes with the target gas concentration monotonously, whereas the light from LD-b keeps almost unchanged. At higher target gas concentration, the self-pressure broadening became severe; the saturation of the peak absorption intensity appears. With the electronics described above to processing $V_{\rm PD}$, the readout voltages V_o at different N_2O concentrations diluted using room air from below 1 ppm to 100% at pressures of 76 Torr and 760 Torr were recorded as shown in Fig. 6, which shows quite good reproducibility. At lower pressure of 76 Torr, V_o shows linear behaviour to the N_2O concentration from about 10 ppm to 1%, whereas at atmosphere pressure the linear region becomes much narrower mainly because of the pressure broadening effects. The pulse frequency and therefore the refresh rate of this gas sensor is set to be 1 KHz, it is high enough for most sensor applications.

In conclusion, a robust TDLAS N_2O gas sensor has been demonstrated. Electronics in analogue modality is developed to extract the absorption information and compensating for possible fluctuations, resulting in an analogue voltage output corresponding to the target gas concentration in real time.

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