Wavelength scanning spectroscopic gas detection based on laser frequency comb enabled by phase-shifted fiber Bragg grating (PS-FBG)

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ABSTRACT

A wavelength scanning scheme enabled by phase-shifted fiber Bragg grating (PS-FBG) is proposed for gas absorption spectroscopy based on optical frequency comb (OFC). The PS-FBG works as an ultra-narrow bandpass optical filter to generate the gas sensing laser probe. To obtain the gas absorption signal, the electronical frequency beating and lock-in amplification are successively performed with the continuous tuning of the PS-FBG by using a piezo transducer (PZT). The intermediate beat note is monitored in real time for lock-in frequency compensation against the repetition frequency drift of the OFC. A carbon monoxide (CO) sensing system in direct absorption spectroscopy (DAS) configuration is developed based on a free-running fiber laser frequency comb. A triangular-wave PZT driving signal of 5 Hz is used for periodical spectrum scanning. At an intermediate beat note of ~ 50 kHz, the DAS signal is obtained with a lock-in constant of 200 μs. The CO detection limit of 0.356% for an integration time of 0.4 s and the minimum detectable absorbance of ~ 0.0021 are achieved, which indicate a better sensitivity performance.

Keywords: Optical frequency comb, Tunable laser spectroscopy, Gas absorption spectroscopy, Optical gas sensing

1. INTRODUCTION

Laser-assisted spectroscopic gas sensing is an exceptionally promising and rapidly developing field of research, which has been practically applied in atmospheric monitoring[1, 2], chemical analysis[3, 4], industrial measurement[5, 6] and medical diagnosis[7, 8]. The spectrum scanning enabled by tunable single-mode laser enables precise, non-invasive and big-spatial-scale gas concentration determination. Despite its superiorities of high sensitivity, good stability and long systematical lifetime over the traditional incoherent broadband spectroscopy, the limited wavelength tuning range of the laser hardly supports multi-molecule interrogation. Consequently, multi-component gas detection using tunable laser absorption spectroscopy (TLAS) is for the most part based on multiple individual laser sources[9, 10], thus leads to increasements of cost and complexity.

Optical frequency comb (OFC), offering both high coherence and broadband spectrum, becomes an excellent alternative to currently used diode lasers for gas absorption spectroscopy. Technologies being explored and adopted for OFC-based spectroscopy mainly include spatial disperser[11, 12], Michelson-based Fourier transform spectrometer[13, 14] and dual-comb spectrometer[15, 16]. Relying on high optical finesse and sophisticated controlling mechanism, such systems generally face challenges on structural bulkiness and poor long-term stability, which confine their practical gas sensing applications[17, 18].

In this manuscript, a wavelength scanning method enabled by phase-shifted fiber Bragg grating (PS-FBG) is proposed for gas absorption spectroscopy based on OFC. The PS-FBG is employed as a narrowband optical filter after the OFC to generate narrow-linewidth laser signal, with its wavelength tuned by using a piezo transducer (PZT). The ultra-fast laser pulse transmitted from the gas medium is detected and demodulated by electronical frequency beating and lock-in amplification to retrieve the absorption signal, facilitating gas concentration determination in direct absorption spectroscopy (DAS) scheme[19-21]. Experimental investigation on carbon monoxide (CO) samples indicates a minimum detectable absorbance as low as ~ 0.0021 for an integration time of 0.4 s, which benefits from the pulse signal processing on radio frequency (RF) level. The FBG-based spectrum scanning configuration enabling all-fiber optical structure holds potential for concise and stable system development, which promotes field applications of the frequency comb spectroscopy.

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2. EXPERIMENTAL SETUP

A schematic of the experimental setup for the OFC-based wavelength-scanning gas detection scheme is shown in Fig. 1, with the systematical signal evolving process depicted as well to expound the method. The configuration consists of an optical part and an electrical part. A free-running fiber laser frequency comb emits laser pulse with repetition frequency of ~ 41.708 MHz at center wavelength of 1560 nm with a bandwidth of ~ 25 nm. After an Erbium-doped fiber amplifier (EDFA), the broadband laser signal goes successively through a tunable optical filter (TOF) and a PS-FBG, with bandwidths of 0.3 nm and 0.03nm, respectively. The TOF here is introduced for suppression of the PS-FBG's transmitting sideband. The PS-FBG is tuned by a PZT, to generate the wavelength-tuning laser probe with a ultra-narrow linewidth. A reflective light-gas interaction length of ~ 2.1 m is provided by a multi-pass gas cell (MPGC), from which the absorbed laser probe is received by a high-bandwidth photodetector (PD). The optical structure is overall fiber-interconnected, ensuring a concise and stable system.

For the electrical part, the PD converts the laser pulse into electrical pulse with a repetition frequency (f_r) of ~ 41.708 MHz. which is down-converted to an intermediate frequency (f_i) of ~ 50kHz by using a frequency mixer. The local oscillator of 41.758 MHz is generated from a RF signal generator. Fig. 1 (b) and (c) plot the output signal of the PD and the frequency mixer, respectively. To extract the intensity of the laser pulse, the beating signal is acquired by a data acquisition (DAQ) card based on a self-developed LabVIEW software platform. A lock-in amplifier (LIA) operating at first harmonic ($1f$) configuration is programmed to measure the amplitude of the frequency component f_i, to obtain the direct-current (DC) absorption signal as shown in Fig. 1 (d). To compensate the repetition frequency drifts of OFC, the actual value of f_i is monitored in real time using a fast Fourier transformer (FFT) and an arbitrary waveform generator (AWG) outputs a corresponding sinusoidal signal to feedback the LIA as the $1f$ reference. Furthermore, the AWG generates a triangular wave of 5 Hz to perform periodical wavelength tuning of the PS-FBG, with an in-phase square wave simultaneously supplied for acquisition trigger. Implementing baseline normalization on the absorption signal as Fig. 1 (d) describes, absolute absorption spectrum is obtained, as shown in Fig. 1 (e).

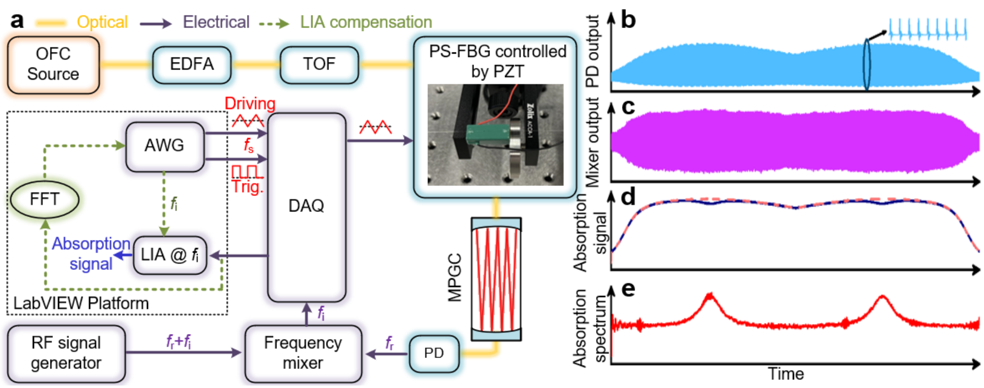

Figure 1. Schematic diagram of the experimental setup. (a) The configuration consisting of an all-fiber-interconnected optical structure, a frequency down-conversion setup and a self-developed LabVIEW-based signal processing platform. (b) The response of the PD to the wavelength-scanning laser pulse signal. (c) The beating signal of the PD output and the local oscillator, which is generated by the frequency mixer. (d) The direct absorption signal generated by the LIA, with the baseline normalization performed on it. (e) The measured gas absorption spectrum.

3. RESULTS AND DISCUSSION

3.1 PS-FBG characterization

The wavelength tuning performance of the PS-FBG filter is tested through recording its transmission spectra under different PZT-driving voltages, as shown in Fig. 2 (a). The DC voltages in the range of 0 – 5V are generated by the DAQ card and further amplified by 15 times before applied on the PZT. Correspondingly, the eleven spectra measured by optical spectrum analyzer show good consistency of the peak width and evenly distributed peak centers. The center wavelengths are extracted and plotted versus the PZT-driving voltages in Fig. 2 (b). A linear functional fitting of the data points is implemented to obtain the wavelength tuning coefficient, which is calculated to be ~ 0.04 nm/V at the wavelength offset of ~ 1567.947 nm. The fitting covariance is observed to be up to 0.99926. The revealed excellent wavelength tuning linearity of the PS-FBG gives promise to precise absorption feature scanning with little distortion. Within the characterized wavelength scanning range, absorption line of CO gas at 1568.03 nm is plotted in Fig. 2 (b) as well. It is noted that the absorption spectrum can be totally covered, thus the spectrum detection in DAS scheme is realizable.

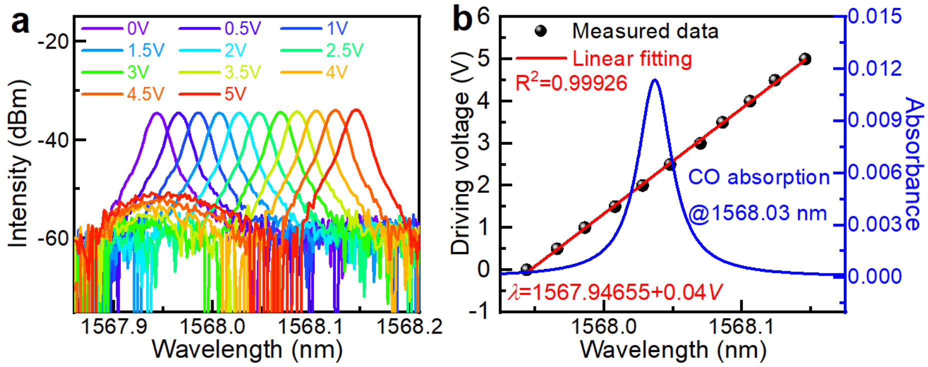

Figure 2. Results of the PS-FBG characterization on wavelength tuning performance. (a) The recorded transmission spectra of the PS-FBG filter under eleven different levels of the PZT-driving voltage in the range 0 – 5 V. (b) Center wavelengths of the PS-FBG filter corresponding to specific PZT-driving voltages, and the linear fitting curve indicating the wavelength tuning linearity. CO absorption line shape in the mentioned wavelength range is also presented.

3.2 Absorption spectrum measurement and gas detection

Choosing CO as the sample, experiments on absorption spectrum measurement and gas detection are carried out. Five samples within a concentration range of 0% - 20% are prepared by diluting a standard CO sample with high-purity nitrogen (N_2) gas. The measured spectra corresponding to various samples are given in Fig. 3 (a). Without any curve smoothing or line shape fitting operation, the curves exhibit obvious response and linearity to the varying gas concentration.

Reading the peak value of the absorbance, CO concentration is continuously calculated according to the Lambert-Beer law at a refreshing rate of 0.4 s, which is decided by the wavelength scanning period and the time consumption of signal processing. For each concentration level, the measurement lasts ~ 5 min and the averaged results are plotted versus the actual concentration in Fig. 3 (b). The error bars on Y-axis are provided according to the standard deviation values of the original data sets, which visually demonstrate the sensitivity of the system to be ~ 0.33%. Furthermore, a linear fitting of the data points with a covariance of 0.99963 indicates high detection linearity.

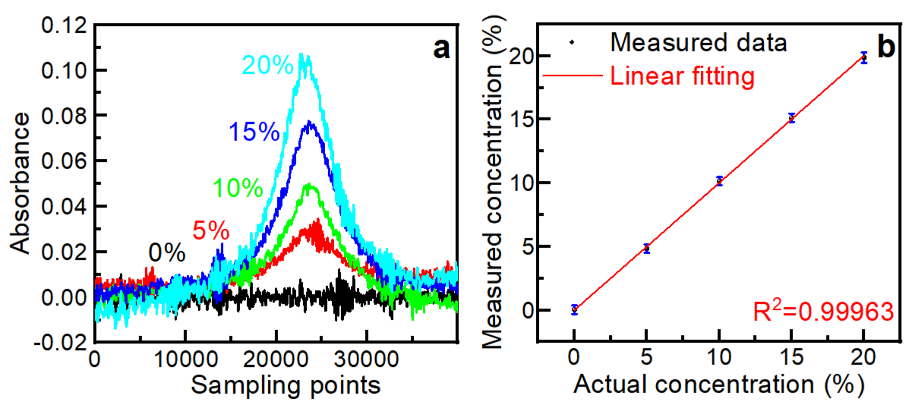

Figure 3. (a) Measured absorption spectra of CO corresponding to different concentration levels. (b) The averaged concentration detection results versus the actual concentrations with error bars indicating the sensitivity, and the linear fitting curve of the data points indicating the sensor linearity.

3.3 Detection limit evaluation

A long-term continuous measurement of N_2 sample is carried out to evaluate the operation stability of the CO sensing system. Fig. 4(a) plots the results obtained with a data integration time of 0.4 s. The overall trend of the dataset is observed to be stable near the zero-concentration level. The fluctuation here is dominated by the systematical noise without disturbance from sample concentration variation, so that the detection limit decided only by the system itself can be determined. An Allan deviation analysis on the concentration sequence numerically characterizes the 1σ detection limit to be ~ 0.356%, as shown in Fig. 4(b). And an optimum averaging time of 28 s further decreases the detection limit to ~ 0.065%. Based on the high-resolution transmission (HITRAN) database, the CO concentration of 0.356% corresponds to a minimum detectable absorbance of ~ 0.0021.

The wavelength scanning spectroscopy demonstrated in the DAS scheme exhibits high sensitivity performance, which is comparable to that of the wavelength modulation spectroscopy (WMS) based on continuous-wave (CW) lasers[22, 23]. It is believed to benefit from the OFC related pulse modulation at RF level, and the sensitivity will be further enhanced by introducing kHz-level wavelength tuning as a second-stage modulation.

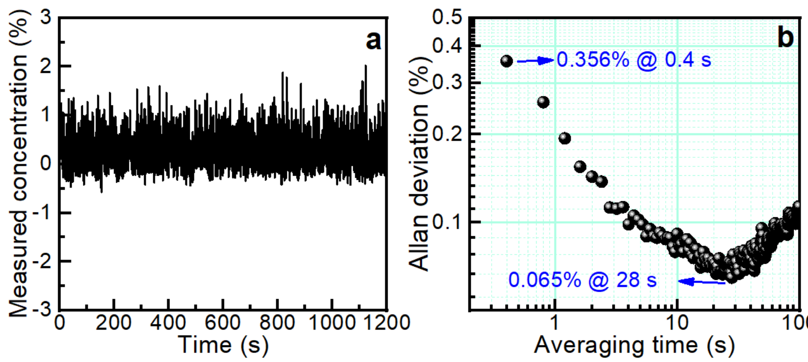

Figure 4. (a) Long-term concentration measurement of a N_2 sample as zero-gas for 20 min to evaluate the detection stability. (b) Allan deviation analyzing result of the measured concentration values.

4. CONCLUSIONS

We propose and demonstrate a wavelength scanning scheme based on PS-FBG for frequency comb spectroscopy. A CO detecting system is developed accordingly in the DAS scheme. The FBG enabled wavelength tuning promotes the construction of an all-fiber-interconnected and concise optical system. A lock-in frequency compensation setup is further established for stable operation under repetition frequency drifts of the free-running OFC. Benefiting from the pulse signal processing on RF level, a CO detection limit of ~ 0.356% for an integration time of 0.4 s is observed through a long-term zero-gas measurement, which corresponds to a minimum detectable absorbance as low as ~ 0.0021. At an optimum averaging time of 28 s, the detection limit is reduced to ~ 0.065%. With the proposed method, multi-channel sensing configuration based on OFC can be flexibly established by cascading PS-FBGs with different transmission windows. By employing small-range spectrum scanning for each channel, a high-efficiency multi-species gas detection can be realized. Moreover, the potential for concise and stable system development will promote field applications of the frequency comb spectroscopy.

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REFERENCES

[1] Siozos, P., Psyllakis, G., Samartzis, P. C. and Velegrakis, M., "Autonomous differential absorption laser device for remote sensing of atmospheric greenhouse gases," Remote Sens. 14(3), 460 (2022).
[2] Xin, F. X., Li, J., Guo, J. J., Yang, D. W., Wang, Y., Tang, Q. H. and Liu, Z. S., "Measurement of atmospheric CO_2 column concentrations based on open-path TDLAS," Sensors 21(5), 1722 (2021).
[3] Viljanen, J., Sorvajzrvi, T. and Toivonen, J., "In situ laser measurement of oxygen concentration and flue gas temperature utilizing chemical reaction kinetics," Opt. Letters 42(23), 4925-4928 (2017).

[4] Liu, Z. W., Zheng, C. T., Zhang, T. Y., Zhang, Y., Wang, Y. D. and Tittel, F. K., "High-precision methane isotopic abundance analysis using near-infrared absorption spectroscopy at 100 Torr, " Analyst 146(2), 698-705 (2021).
[5] Zhang, Z. R., Pang, T., Yang, Y., Xia, H., Cui, X. J., Sun, P. S., Wu, B., Wang, Y., Sigrist, M. W. and Dong, F. Z., "Development of a tunable diode laser absorption sensor for online monitoring of industrial gas total emissions based on optical scintillation cross-correlation technique," Opt. Express 24(10), A943-A955 (2016).
[6] Tzanetakis, T., Susilo, R., Wang, Z. Y., Padmanabhan, A., Davis, B. R. and Thomson, M. J., "Optical absorption measurements of hydrogen chloride at high temperature and high concentration in the presence of water using a tunable diode laser system for application in pyrohydrolysis non-ferrous industrial process control," Appl. Spectrosc. 69(6), 705-713 (2015).
[7] Abbaszadeh, A., Makouei, S. and Meshgini, S., "Ammonia measurement in exhaled human breath using PCF sensor for medical applications," Photonic. Nanostruct. 44, 100917 (2021).
[8] Bayrakli, I., "A portable N_2O sensor based on quartz-enhanced photoacoustic spectroscopy with a distributed-feedback quantum cascade laser for medical and atmospheric applications," Opt. Quant. Electron. 53(11), 642 (2021).
[9] Feng, Y. W., Chang, J., Chen, X. H., Zhang, Q. D., Wang, Z. L., Sun, J. C. and Zhang, Z. W., "Application of TDM and FDM methods in TDLAS based multi-gas detection," Opt. Quant. Electron. 53(4), 195 (2021).
[10] Jiang, J., Wang, Z. W., Han, X., Zhang, C. H., Ma, G. M., Li, C. R. and Luo, Y. T., " Multi-gas detection in power transformer oil based on tunable diode laser absorption spectrum," IEEE T. Dielect. El. In. 26(1), 153-161 (2019).
[11] Kowzan, G., Charczun, D., Cygan, A., Trawinski, R. S., Lisak, D. and Maslowski, P., "Broadband optical cavity mode measurements at Hz-level precision with a comb-based VIPA spectrometer," Sci. Rep. 9, 8206 (2019).
[12] Klose, A., Ycas, G., Cruz, F. C., Maser, D. L. and Diddams, S. A., "Rapid, broadband spectroscopic temperature measurement of CO_2 using VIPA spectroscopy," Appl. Phys. B-Lasers O. 122(4), 78 (2016).
[13] Meek, S. A., Poisson, A., Guelachvili, G., Hansch, T. W. and Picque, N., "Fourier transform spectroscopy around 3 μm with a broad difference frequency comb," Appl. Phys. B-Lasers O. 114(4), 573-578 (2014).
[14] Dubroeucq, R. and Rutkowski, L., "Optical frequency comb Fourier transform cavity ring-down spectroscopy," Opt. Express 30(8), 13594-13602 (2022).
[15] Meek, S. A., Hipke, A., Guelachvili, G., Hansch, T. W. and Picque, N., "Doppler-free Fourier transform spectroscopy," Opt. Lett. 43(1), 162-165 (2018).
[16] Coddington I., Newbury, N. and Swann, W., "Dual-comb spectroscopy," Optica 3(4), 414-426 (2016).
[17] Coburn, S., Alden, C. B., Wright, R., Cossel, K., Baumann, E., Truong, G. W., Giorgetta, F., Sweeney, C., Newbury, N. R., Prasad, K., Coddington, I. and Rieker, G. B., "Regional trace-gas source attribution using a field-deployed dual frequency comb spectrometer," Optica 5(4), 320-327 (2018).
[18] Ycas, G., Giorgetta, F. R., Friedlein, J. T., Herman, D., Cossel, K. C., Baumann, E., Newbury, N. R. and Coddington, I., "Compact mid-infrared dual-comb spectrometer for outdoor spectroscopy," Opt. Express 28(10), 14740-14752 (2020).
[19] Perdue, N., Sharp, Z., Nelson, D., Wehr, R. and Dyroff, C., "A rapid high-precision analytical method for triple oxygen isotope analysis of CO_2 gas using tunable infrared laser direct absorption spectroscopy," Rapid Commun. Mass Spectrom. 36(21), e9391 (2022).
[20] Li, Z. T. and Mevel, R., "Uncertainty quantification for high-temperature gas sensing using direct laser absorption spectroscopy," Appl. Phys. B-Lasers O. 128(10), 189 (2022).
[21] Zhang, L., Li, Y. F., Wei, Y. B., Wang, Z. W., Zhang, T. T., Gong, W. H. and Zhang, Q. D., "SNR enhancement of direct absorption spectroscopy utilizing an improved particle swarm algorithm," Photonics 9(6), 412 (2022).
[22] Qu, Z. C. and Schmidt, F. M., "In situ H_2O and temperature detection close to burning biomass pellets using calibration-free wavelength modulation spectroscopy," Appl. Phys. B-Lasers O. 119(1), 45-53 (2015).
[23] Liu, Z. W., Zheng, C. T., Xie, H. T., Ren, Q., Chen, C., Ye, W. L., Wang, Y. D. and Tittel, F. K., "A near-infrared carbon dioxide sensor system using a compact folded optical alignment structure," Proc. SPIE 10821, 108210l (2018).