

Time-Wavelength Spectroscopy for Chemical Sensing

Jason Chou, Yan Han, and Bahram Jalali, *Fellow, IEEE*

Abstract—Time-wavelength spectroscopy, using a linearly chirped broad-band pulse, eliminates the need for an optical spectrometer and enables real-time analysis. Utilizing digital filtering and matched detection, we demonstrate identification of gas signatures that are entirely masked by highly nonuniform source spectra.

Index Terms—Gas detectors, matched filters, signal processing, spectroscopy, time-wavelength mapping.

I. INTRODUCTION

INFRARED spectral analysis conventionally involves instruments which are bulky and require time consuming scans with moving components. By converting the spectral information into a time-domain waveform, time-wavelength spectroscopy (TWS) eliminates the need for an optical spectrometer [1]. The method uses dispersion to convert the instantaneous spectrum to a temporal waveform, measured by an electronic analog-to-digital (A/D) converter. The concept has its origin in recent work on photonic time-stretch A/D conversion based on time-wavelength transformation [2]. Another group recently demonstrated trace gas detection using time-resolved frequency downchirp from pulsed quantum cascade lasers across a 17-nm bandwidth [3]. In this work, the spectrum is sensed by a supercontinuum (SC) source which provides coherent radiation over a 100-nm wavelength range [4]. Developments in broad-band SC sources for wavelength-division-multiplexing telecommunication applications have achieved bandwidths as wide as 250 nm centered around 1550 nm [4], [5]. In addition, the pulsed nature of SC generation is advantageous for single shot analysis and real-time study of transient spectral phenomena.

In this letter, we demonstrate the use of TWS for the detection and identification of chemical gases. Sensing is performed over spectral regions where gases exhibit “fingerprint” absorption spectra arising from their rotational–vibrational molecular quantum transitions. The broad bandwidth allows a single source to simultaneously encompass a wide range of gases, eliminating the need for multiple tunable lasers. The pulsed nature of TWS allows single shot analysis and the ability to capture ultrafast chemical reactions. Distorting the gas signature, the nonuniform power spectrum of the pulsed source is the main impairment in TWS and prevents detection of weak gas spectra. As a solution, radio-frequency (RF) filtering and matched detection are performed in the digital domain to recover and identify gas fingerprints that are entirely masked out by the nonuniform source spectrum.

Manuscript received August 18, 2003; revised December 2, 2003. This work was supported by the Office of Naval Research through the MURI Program on RF Photonics.

The authors are with the Optoelectronic Circuits and Systems Laboratory, University of California Los Angeles, Los Angeles, CA 90095-1594 USA (e-mail: jalali@ucla.edu).

Digital Object Identifier 10.1109/LPT.2004.824997

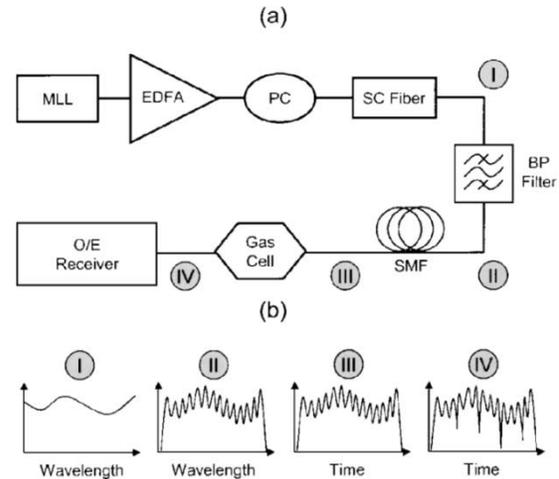


Fig. 1. (a) Experimental setup for time wavelength spectroscopy. MLL: mode-locked laser. PC: polarization controller. BP: bandpass. SMF: single-mode fiber. O/E: optical-to-electrical. (b) Signal evolution through the system.

II. PRINCIPLE OF OPERATION

The experimental setup is shown in Fig. 1(a). A 20-MHz passively mode-locked laser is used to generate an SC [5] which is bandpass filtered (BPF) over a spectral region corresponding to the gas sample’s absorption features. The pulse is chirped using a 20.56-km single-mode fiber to perform wavelength-to-time conversion before propagating through a fiber pigtailed gas cell. Finally, a 60-GHz photoreceiver is used to measure the output signal. Fig. 1(b) illustrates the development of the time-domain spectrum.

Fig. 2(a) and (b) shows the measured time-domain spectrum before and after a carbon monoxide ($^{12}\text{C}^{16}\text{O}$) gas cell, respectively. The latter waveform contains the desired gas signal which is entirely masked by distortion and noise. The signal represents the gas sample’s complex signature of absorption lines resulting from rotational–vibrational molecular overtones. The distortion represents the nonuniform envelope of the time-domain spectrum, which is shaped by the SC spectrum and Fabry–Pérot ripples from the BPF. The noise represents contributions from the optical source, Erbium-doped fiber amplifier (EDFA), and the photodetection. It is expected that the amplified spontaneous emission signal beat noise is the dominant noise contribution.

To recover and identify the gas spectrum embedded in the distortion and noise, we have developed a two-stage RF signal processing technique, illustrated in Fig. 3. Since the SC envelope and the BPF ripples (0.8-nm period) exhibit much broader spectral features than the narrow absorption lines [0.05-nm full-width at half-maximum (FWHM)], they will appear at much lower RF frequencies after wavelength-to-time transformation. Thus, a high-pass digital RF filter is used in the first stage to suppress the distortion. After filtering, the remaining waveform consists of the high (RF) frequency gas

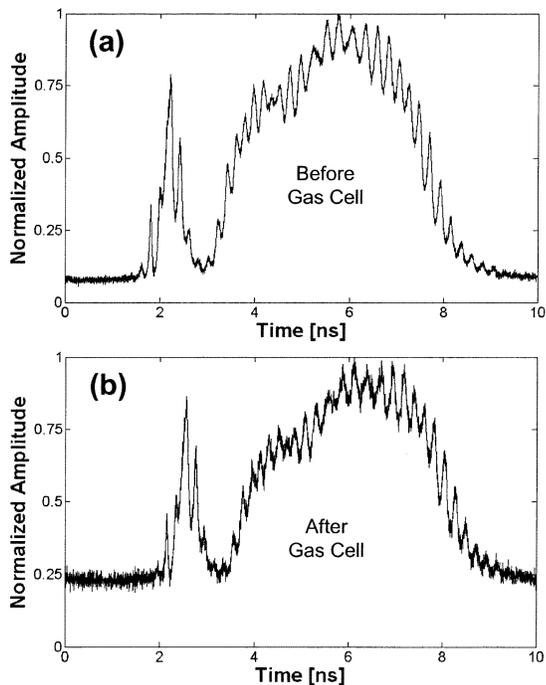


Fig. 2. (a) Time-domain spectrum without CO gas cell. (b) Time-domain spectrum with CO gas cell. The gas absorption spectrum is hidden by distortion and noise.

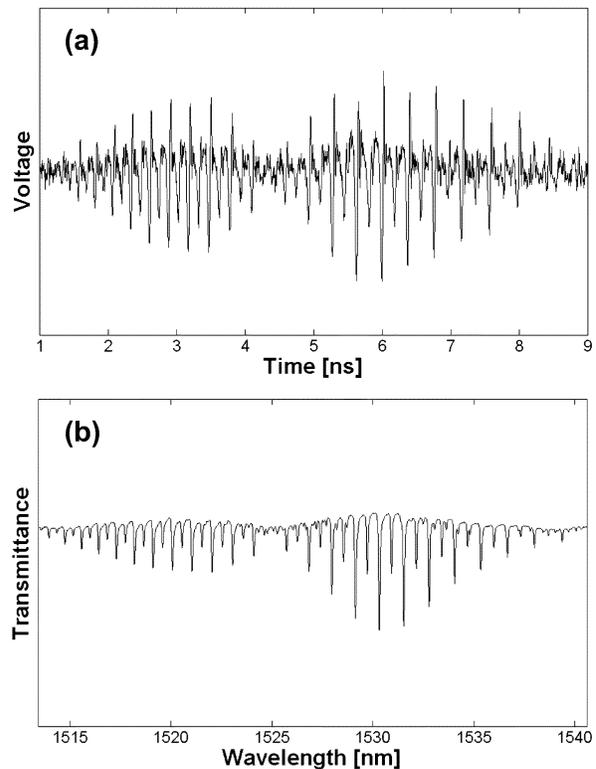


Fig. 4. (a) Spectrum of Acetylene measured in time domain. (b) Spectrum of Acetylene obtained using an optical spectrum analyzer.

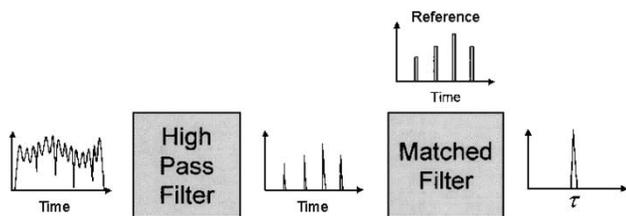


Fig. 3. High-pass filter removes the distortion (envelope) from the time-domain spectrum. A matched filter produces a detection peak when the correct reference waveform is used during correlation.

line signal and broad-band noise. To identify the spectral fingerprint of the gas, in the present of noise, we apply a matched filter in the second stage. The process is equivalent to a cross correlation between the filtered time-domain spectrum and a digitally created reference waveform of the gas spectrum after chirping. After correlation, a threshold detector yields a binary “gas” or “no gas” decision.

III. DISPERSION CHARACTERIZATION

In order to obtain an accurate reference waveform, a proper calibration of the wavelength-dependent group velocity dispersion (GVD) is needed. To achieve this, an Acetylene ($^{12}\text{C}_2\text{H}_2$) gas cell with strong absorption lines is selected to characterize the system chromatic dispersion. The gas yields prominent spectral peaks which are larger than the distortion and noise contributions described above (as much as 90% extinction with 0.01-nm FWHM lines spread over the range 1515–1540 nm). The system dispersion is determined by mapping the spectral absorption lines to the chirped temporal peaks.

Fig. 4 illustrates the linear wavelength-to-time mapping process for an Acetylene gas signature. The time-domain spectrum, in Fig. 4(a), shows good correlation to the measurement

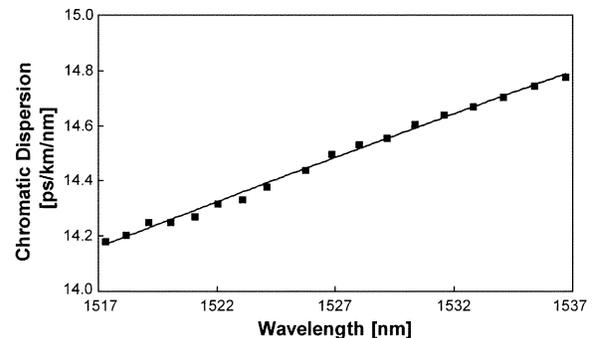


Fig. 5. Measured wavelength dependence of GVD.

obtained by an optical spectrum analyzer, in Fig. 4(b). A digital filter was used to remove the background features described earlier. The peaks associated with each rising edge in the time-domain signal are due to ringing in the electrical circuitry. Fig. 5 plots the wavelength dependence of GVD obtained from Fig. 4. By using the measured GVD, a time-domain reference waveform is generated from the known gas spectrum.

IV. EXPERIMENTAL RESULTS

Fig. 6 shows the experimental results for recovery and identification of carbon monoxide. A gas cell containing carbon monoxide [$^{12}\text{C}^{16}\text{O}$] at a pressure of 133 kPa and total path length of 80 cm] was placed in the TWS setup. After detection and digitization, the two-stage RF signal processing scheme is implemented on the time-domain spectrum, illustrated in Fig. 2(b). First, a simple high-pass filter, whereby frequencies above 10 GHz are attenuated, removes distortion and reveals the absorption lines of carbon monoxide, shown in Fig. 6(a).

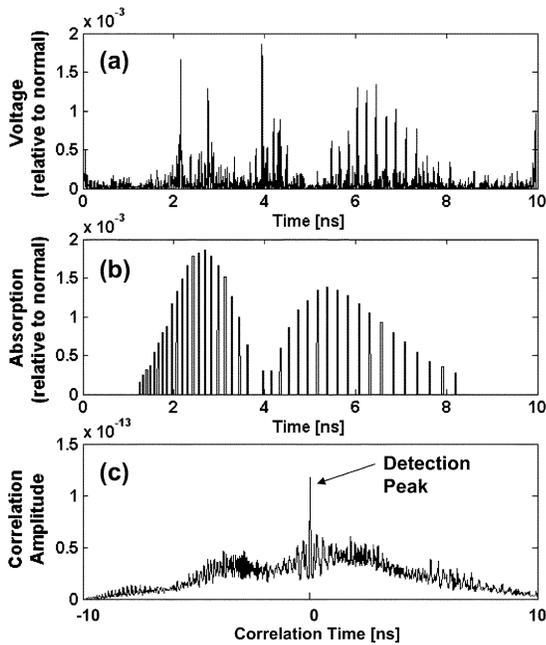


Fig. 6. (a) Filtered time-domain spectrum of CO. (b) Reference waveform of CO. (c) Cross correlation of (a) and (b).

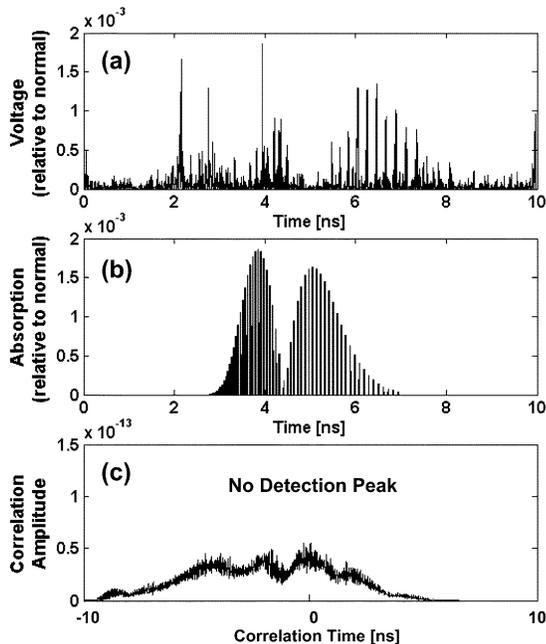


Fig. 7. (a) Filtered time-domain spectrum of CO. (b) Reference waveform of CO₂. (c) Cross correlation of (a) and (b).

Second, a matched filter performs a cross correlation between the filtered waveform and a reference waveform. Fig. 6(b) illustrates the reference waveform for carbon monoxide which is digitally created using the 41 rotational–vibrational absorption peaks exhibited between 1560–1600 nm [6]. These features are weaker by more than 9 dB from Acetylene, which was used for characterization. A clear correlation peak is observed in Fig. 6(c), implying a correct match between the measured carbon monoxide signature and the reference waveform. Estimation of the detection sensitivity, requiring the control of gas

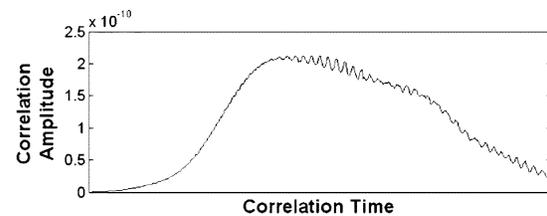


Fig. 8. Cross-correlation function of an unfiltered time-domain spectrum of CO and the reference waveform of CO.

concentrations in the sample cell, will need to be investigated further.

A “no gas” decision is made when the reference does not match the time-domain spectrum of the sample gas. To illustrate this, a reference waveform of another gas, exhibiting absorption lines in the same spectral region, is used for identification. Fig. 7 shows the result when the measured signal from the CO gas cell is correlated with the reference waveform for carbon dioxide (CO₂), shown in Fig. 7(b) [6]. The complete absence of any correlation peaks in Fig. 7(c) clearly demonstrates the ability of the TWS technique to distinguish the two gasses.

The removal of distortion by filtering, before matched detection, is central to the operation. Fig. 8 shows a correlation function between an unfiltered waveform, in Fig. 2(b), with the reference for CO in Fig. 6(b). When an unfiltered waveform is used, the matched filtering does not yield a simple detection peak. This demonstrates the importance of the two-stage signal processing technique to realize accurate gas recognition.

V. CONCLUSION

We have demonstrated a novel detection technique to identify gases using TWS. The technique uses chirped SC pulses as a broad-band source and an A/D converter to measure the spectra in time domain. A two-stage signal processing is proposed and demonstrated yielding a simple binary detection capability. Advantages of the TWS include the elimination of the optical spectrometer and the ability to perform real-time spectral analysis.

ACKNOWLEDGMENT

The authors would like to thank Dr. R. Claps of UCLA for helpful discussions.

REFERENCES

- [1] P. Kelkar, F. Coppinger, A. S. Bhushan, and B. Jalali, “Time-domain optical sensing,” *Electron. Lett.*, vol. 35, no. 19, pp. 1661–1662, 1999.
- [2] F. Coppinger, A. S. Bhushan, and B. Jalali, “Photonic time stretch and its application to analog-to-digital conversion,” *IEEE Trans. Microwave Theory Tech.*, vol. 47, pp. 1309–1314, July 1999.
- [3] M. T. McCulloch *et al.*, “Highly sensitive detection of trace gases using the time-resolved frequency downchirp from pulsed quantum-cascade lasers,” *J. Opt. Soc. Amer. B*, vol. 20, no. 8, pp. 1761–1768, Aug. 2003.
- [4] J. Kim, G. A. Nowak, Ö. Boyraz, and M. N. Islam, *Low Energy, Enhanced Supercontinuum Generation in High Nonlinearity Dispersion Shifted Fibers*. Baltimore, MD: CLEO, 1999.
- [5] G. Nowak, J. Kim, and M. N. Islam, “Stable supercontinuum generation in short lengths of conventional dispersion-shifted fiber,” *Appl. Opt.*, vol. 38, no. 36, pp. 7364–7369, 1999.
- [6] L. S. Rothman *et al.*, “The HITRAN molecular spectroscopic database and HAWKS (HITRAN atmospheric workstation): 1996 edition,” *J. Quant. Spectrosc. Radiat. Transf.*, vol. 60, pp. 665–710, 1998.