Designs and applications of hyperspectral light sources

Prof. Scott T. Sanders

Current students contributing: Andrew W. Caswell, Thilo Kraetschmer, Keith D. Rein, Benjamin L. Conrad

Alumni contributing: Laura A. Kranendonk, Renata J. Bartula, Christopher L. Hagen

cite as: S.T. Sanders, "Designs and applications of hyperspectral light sources," in *Laser Applications to Chemical, Security, and Environmental Analysis*, LWC1, 19 March 2008. (<http://digital.library.wisc.edu/1793/24391>)

University of Wisconsin, Mechanical Engineering, Engine Research Center

Outline:

- ◆ Overview of hyperspectral sources
- ◆ Selected applications:
  - ◆ FDML in piston engine at Honda
  - ◆ TDM in Ramgen combustor at AFRL
- ◆ Future work

Overview	FDML	TDM	Future

Swept-wavelength spectroscopy

swept-wavelength sources are a subset of hyperspectral sources

- Time $\leftrightarrow$ wavelength (spectral encoding in time)
- Fast sweeps (e.g., every 10 μ s) are needed for dynamic test articles
- We work mostly in the infrared; however, throughout this talk, my charts and language may use visible colors
- 'blue' means 'higher-frequency side of the spectrum'

Swept-wavelength H₂O absorption spectroscopy

Beer-Lambert Law:

$$T_{\lambda} = (I/I_0)_{\lambda} = \exp(-k_{\lambda}L)$$

$$k_{\lambda} = f(T, P, X)$$

- ◆ We generally use the 1330-1380 nm range (roughly the R branch)
- ◆ Infer **temperature** from rotational distribution (band shape)
- ◆ Infer **mole fraction** from heights of features
- ◆ Path-integrated: can be appropriate in HCCI (homogeneous charge) engines

Historical perspective: swept-wavelength sources

Sanders, *Optics and Photonics News*, May 2005

♦ I've been building my own lasers for spectroscopy for ~ 8 years

♦ Motivation was to make measurements that were not easily made using traditional TDLs

As you know...

♦ **advantages:** flexible, inexpensive, in control

♦ **disadvantages:** more time and effort required, undercharacterized & poor performance, failures

Home-built light sources can compete (and win)

- ◆ Tunable diode lasers (TDLs) are no longer the only option for high-quality 'sensor light'
- ◆ Traditionally: Based on available TDLs, design a sensor

$\lambda_{\text{mr1}} = 1290 \text{ nm}$ (soot)
 $\lambda_1 = 1343.299 \text{ nm}$ (H_2O)
 $\lambda_2 = 1391.672 \text{ nm}$ (H_2O)
 $\lambda_3 = 1799.179 \text{ nm}$ (H_2O)
 $\lambda_{\text{mr2}} = 1643 \text{ nm}$ (soot)

Sanders, Baldwin, Jenkins, Baer, and Hanson,
Proc. Comb. Symp. **29**, 2002.

- ◆ Now: Starting from sensor requirements, design the source

Time-division multiplexed (TDM) source

Rapid wavelength-swept (FDML) source

Hyperspectral sources: see also <http://chyp.erc.wisc.edu/>

name	need	advantages	disadvantages	motion?
chirp	polychromatic pulses large <u>dispersion</u>	broad coverage	too fast	N
fs comb (Max Planck Institute)	2 stable fs lasers	nonlinear conversion to 0.2 ... 10 um	\$\$\$\$\$	maybe
FDML (MIT)	gain medium Long low- <u>dispersion</u> cavity (typ 2 km) rapidly tunable filter		telcom range only	Y
CW comb	gain medium high <u>dispersion</u> cavity OR 2 stable cavities		gain competition phase noise	N
Raman soliton	ultrafast pulses positive <u>dispersion</u> medium rapid intensity modulation		low resolution	N
rapidly-tunable laser (many)	gain medium tunable filter	some commercial availability	stability?	Y
modeless rapidly tuned laser	gain medium tunable filter cavity length modulation		stability?	Y

Chirp

IMRA μ Jewel Laser	
Center wavelength	1557 [nm]
Energy per pulse	1.5 [μ J]
Pulse duration	800 [fs]
Repetition rate	200 [kHz]

75 km
of fiber

Hagen and Sanders, SAE-2006-01-1200, 2006.

Hyperspectral sources: see also <http://chyp.erc.wisc.edu/>

name	need	advantages	disadvantages	motion?
chirp	polychromatic pulses large <u>dispersion</u>	broad coverage	too fast	N
fs comb (Max Planck Institute)	2 stable fs lasers	nonlinear conversion to 0.2 ... 10 um	\$\$\$\$\$	maybe
FDML (MIT)	gain medium long low- <u>dispersion</u> cavity (typ 2 km) rapidly tunable filter		telcom range only	Y
CW comb	gain medium high <u>dispersion</u> cavity OR 2 stable cavities		gain competition phase noise	N
Raman soliton	ultrafast pulses positive <u>dispersion</u> medium rapid intensity modulation		low resolution	N
rapidly-tunable laser (many)	gain medium tunable filter	some commercial availability	stability?	Y
modeless rapidly tuned laser	gain medium tunable filter cavity length modulation		stability?	Y

fs comb

- Developed by Fritz Keilmann, Max Planck Institut, and Daniel van der Weide, U. of Wisconsin
- 'comb Fourier transform spectroscopy' or 'c-FTS'

A. Schliesser, M. Brehm, F. Keilmann, D. W. van der Weide
Optics Express **13**(22) 2005

Overview

FDML

TDM

Future

Hyperspectral sources: see also <http://chyp.erc.wisc.edu/>

name	need	advantages	disadvantages	motion?
chirp	polychromatic pulses large <u>dispersion</u>	broad coverage	too fast	N
fs comb (Max Planck Institute)	2 stable fs lasers	nonlinear conversion to 0.2 ... 10 μm	\$\$\$\$	maybe
FDML (MIT)	gain medium long low- <u>dispersion</u> cavity (typ 2 km) rapidly tunable filter		telcom range only	Y
CW comb	gain medium high <u>dispersion</u> cavity OR 2 stable cavities		gain competition phase noise	N
Raman soliton	ultrafast pulses positive <u>dispersion</u> medium rapid intensity modulation		low resolution	N
rapidly-tunable laser (many)	gain medium tunable filter	some commercial availability	stability?	Y
modeless rapidly tuned laser	gain medium tunable filter cavity length modulation		stability?	Y

CW comb

Kraetschmer, Walewski, and Sanders, *Optics Letters*, **31**(21) 2006

Hyperspectral sources: see also <http://chyp.erc.wisc.edu/>

name	need	advantages	disadvantages	motion?
chirp	polychromatic pulses large <u>dispersion</u>	broad coverage	too fast	N
fs comb (Max Planck Institute)	2 stable fs lasers	nonlinear conversion to 0.2 ... 10 μm	\$\$\$\$\$	maybe
FDML (MIT)	gain medium long low- <u>dispersion</u> cavity (typ 2 km) rapidly tunable filter		telcom range only	Y
CW comb	gain medium high <u>dispersion</u> cavity OR 2 stable cavities		gain competition phase noise	N
Raman soliton	ultrafast pulses positive <u>dispersion</u> medium rapid intensity modulation		low resolution	N
rapidly-tunable laser (many)	gain medium tunable filter	some commercial availability	stability?	Y
modeless rapidly tuned laser	gain medium tunable filter cavity length modulation		stability?	Y

Raman soliton

Walewski, Borden, and Sanders,
Applied Physics B, **79** 2004

Overview

FDML

TDM

Future

Hyperspectral sources: see also <http://chyp.erc.wisc.edu/>

name	need	advantages	disadvantages	motion?
chirp	polychromatic pulses large <u>dispersion</u>	broad coverage	too fast	N
fs comb (Max Planck Institute)	2 stable fs lasers	nonlinear conversion to 0.2 ... 10 μm	\$\$\$\$\$	maybe
FDML (MIT)	gain medium long low- <u>dispersion</u> cavity (typ 2 km) rapidly tunable filter		telcom range only	Y
CW comb	gain medium high <u>dispersion</u> cavity OR 2 stable cavities		gain competition phase noise	N
Raman soliton	ultrafast pulses positive <u>dispersion</u> medium rapid intensity modulation		low resolution	N
rapidly-tunable laser (many)	gain medium tunable filter	some commercial availability	stability?	Y
modeless rapidly tuned laser	gain medium tunable filter cavity length modulation		stability?	Y

rapidly tunable laser

Booster Optical

100 nm)
p to 200 Hz
PC 1 GHz

Monitoring

Output

Overview

FDML

TDM

Future

Hyperspectral sources: see also <http://chyp.erc.wisc.edu/>

name	need	advantages	disadvantages	motion?
chirp	polychromatic pulses large <u>dispersion</u>	broad coverage	too fast	N
fs comb (Max Planck Institute)	2 stable fs lasers	nonlinear conversion to 0.2 ... 10 μm	\$\$\$\$	maybe
FDML (MIT)	gain medium Long, low- <u>dispersion</u> cavity (typ 2 km) rapidly tunable filter		telcom range only	Y
CW comb	gain medium high <u>dispersion</u> cavity OR 2 stable cavities		gain competition phase noise	N
Raman soliton	ultrafast pulses positive <u>dispersion</u> medium rapid intensity modulation		low resolution	N
rapidly-tunable laser (many)	gain medium tunable filter	some commercial availability	stability?	Y
modeless rapidly tuned laser	gain medium tunable filter cavity length modulation		stability?	Y

modeless rapidly tuned laser

- ~16 kHz vibrating mirror
- cavity length changes so quickly that modes do not build up

Kranendonk, Bartula, and Sanders,
Optics Express, 13(5) 2005

Hyperspectral sources: see also <http://chyp.erc.wisc.edu/>

name	need	advantages	disadvantages	motion?
Fourier-MEMS	polychromatic light		multiplex disadvantage?	Y
Fourier-PEM (US Army)	effective length modulation		multiplex disadvantage?	
Fourier-stretch (Observatoire de Paris)				
swept dispersion mode locked (DML)	gain medium <u>high-dispersion</u> cavity (electrical) chirp generator		limited speed	N
multi-wavelength DML	gain medium <u>high-dispersion</u> cavity comb generator		gain competition	N
matched stretcher /compressor	gain medium matched stretcher/compressor pattern generator	suitable for discrete spectroscopy		N

Overview	FDML	TDM	Future

swept dispersion mode locked

Peak-hold spectrum

Temporal waveform

Yamashita, S. and Asano, M., *CLEO 2006*

Overview

FDML

TDM

Future

Hyperspectral sources: see also <http://chyp.erc.wisc.edu/>

name	need	advantages	disadvantages	motion?
Fourier-MEMS	polychromatic light		multiplex disadvantage?	Y
Fourier-PEM (US Army)	effective length modulation		multiplex disadvantage?	
Fourier-stretch (Observatoire de Paris)				
swept dispersion mode locked (DML)	gain medium <u>high-dispersion</u> cavity (electrical) chirp generator		limited speed	N
multi-wavelength DML	gain medium <u>high-dispersion</u> cavity comb generator		gain competition	N
matched stretcher /compressor	gain medium matched stretcher/compressor pattern generator	suitable for discrete spectroscopy		N

Overview	FDML	TDM	Future

multi-wavelength DML

Kraetschmer, Lan, and Sanders, *IEEE Photonics Technology Letters*, **19**(20) 2007.

Overview

FDML

TDM

Future

Hyperspectral spectrometers are also possible

- ◆ ~ 500 mW depolarized, slit-compatible broadband source based on 10 SOAs
- ◆ Inefficient due to beamsteering and the spectrometer slit; even less efficient when the spectrometer is fiber-coupled
- ◆ Our latest grating spectrometer system runs at 46 kHz

Hyperspectral spectrometers are also possible

- ◆ “Spatial heterodyne spectroscopy” allows a unique combination of high spectral resolution and high throughput

Hyperspectral spectrometers are also possible

♦ SHS can revolutionize problems which commonly involve grating spectrometers

- ♦ greater resolution
- ♦ greater throughput

Bartula, Ghandhi, Sanders, Mierkiewicz, Roesler, and Harlander, *Applied Optics* 46(36) 2007.

Overview

FDML

TDM

Future

H₂O absorption thermometer applied in HCCI engine

Kranendonk et. al., *Optics Express* 15(23) 2007

- FDML = Fourier-domain mode-locked (laser) {collaboration with MIT}
- laser cavity is 2 km long (storage of scans)
- scans 1333-1377 nm in 5 μ s, repeats every 10 μ s (50% duty cycle for split-pulse referencing)

Overview

FDML

TDM

Future

Measured engine spectrum compared to BT2 simulation

- ◆ 3x shot noise limit, MDA = 5×10^{-8} Hz^{-1/2}
- ◆ Peak residual < 10% across entire spectrum (as of Feb 2008)

Results: 100 kHz thermometry in Honda engine, Japan

- ◆ Each spectrum (one every 10 μ s) compared to precomputed library of BT2 spectra to infer temperature vs. time
- ◆ RMS temperature precision ~ 5 K (from ~ 50 K in 2004)
- ◆ Absolute accuracy not yet known, but low residual is encouraging
- ◆ This is an old result: slopes in H_2O trace have since been removed; flatness of H_2O trace is useful for quality control

Careful attention to noise is required

An incomplete list of noise sources:

1. Inherent optical noise
  - a. Shot noise
  - b. **Polychromatic beating noise (shown below for FDML)**
2. Optical handling noise
  - a. Beamsteering noise
  - b. Vibration noise
  - c. Fiber mode noise
3. Detection noise
  - a. Johnson noise
  - b. Amplifier noise
4. Acquisition noise
  - a. Digitization noise
  - b. Bit noise

Polychromatic beating noise

Walewski et al, Applied Spectroscopy, 2008; Filipa et al, Applied Spectroscopy, 2008

Polychromatic beating noise

Walewski et al, Applied Spectroscopy, 2008; Filipa et al, Applied Spectroscopy, 2008

◆ Key point: Beating noise worst at high spectral and temporal resolution

Remedy to polychromatic beating noise?

?

Overview

FDML

TDM

Future

Split-pulse referencing reduces common-mode noise

- scans 1333-1377 nm in 5 μ s, repeats every 10 μ s (50% duty cycle for split-pulse referencing)
- storage in fiber delay line
- split-pulse referencing is a key enabler: allows home-built lasers in high-performance spectroscopy

Overview

FDML

TDM

Future

Engine spectrum vs. BT2, HITRAN / HITEMP

- ◆ BT2 yields a better match to measured spectra

Engine FTIR useful for further improvement of spectroscopic databases

- ◆ Spectra represent many-cycle average
- ◆ So far, demonstrated only thermal emission spectroscopy, but full FTIR capabilities are now possible in the engine cylinder

Rein, Sanders, Lowry, Jiang, and Workman, *Measurement Science and Technology* **19** 2008.

Comparison of measured and simulated engine spectra

- ◆ Residual (measured spectrum – simulated spectrum) retains H_2O features
- ◆ Systematic errors (blue = 'cold lines' appear as valleys and red = 'hot lines' appear as peaks) → concerns of errors in inferred properties: T and $X_{\text{H}_2\text{O}}$

Comparison of measured and simulated engine spectra

- ◆ Residual (measured spectrum – simulated spectrum) retains H_2O features
- ◆ Systematic errors (blue = 'cold lines' appear as valleys and red = 'hot lines' appear as peaks) → concerns of errors in inferred properties: T and $X_{\text{H}_2\text{O}}$

Initial update of our spectral broadening model

- ◆ 'Aggregate' widths of features vary by factor of ~ 2 over our spectral range

Better treatment of spectral broadening improves residual

- ◆ We use a rudimentary spectral lineshape modeling approach

- ◆ Old residual: one feature width uniform across the whole spectrum

- ◆ Present residual: 16 independent feature widths fit across the spectrum

Results improved by better treatment of broadening

- ◆ Flat H_2O mole fraction, reduced MSE signify improvement

Wavelength-swept vs. time division multiplexed (TDM)

- ◆ Spend more 'integration time' on most important wavelengths

Example TDM wavelength selection: 10- λ sensor

- ◆ R = 'reference'; TSF = 'temperature-sensitive feature'; B = 'broadening'

Why do we want less information?

- ◆ Less data to acquire: cheaper DAQ, efficient computation → on-board, real-time sensing and control
- ◆ Lower-noise: all else equal, get 7x better temperature precision because we spend a longer time measuring the most important parts of the spectrum
- ◆ There are still many instances in which a complete spectrum is desirable

Schematic of 10-wavelength TDM source

- physical length of fiber laser cavity ~ 3.5 km
- repetition rate ~ 29 kHz

Photos of 10-wavelength TDM source

Overview

FDML

TDM

Future

Photos of 10-wavelength TDM source

10 temperature-controlled FBGs

- temperature of gratings controlled within 0.1 K (= 0.0015 nm = 0.008 cm⁻¹ = 200 MHz)

Results: 10-wavelength time-division-multiplexed (TDM) output

- A sequence of pulses, each at a unique wavelength

time trace:

spectrum:

- ◆ This pulse pattern repeats every 35 μ s (25% duty cycle)
- ◆ Noise in pulse pattern is irrelevant: cancelled by split-pulse referencing down to near shot noise limit (MDA $\sim 1 \times 10^{-4}$)

A separate, 4-wavelength TDM source for fuel & T measurements

- ◆ The pulse pattern repeats every $35 \mu\text{s}$, just like the H_2O TDM system, so it is easily time-multiplexed with the 25% duty cycle H_2O TDM output

Combined use of H₂O/fuel TDM laser in Ramgen rig at AFRL

- ◆ In total: monitor 4 parameters using 14 wavelengths at 30 kHz

Fiber installation in Ramgen rig at AFRL January 10, 2008

- ◆ All-fiber access design successful: just bolt in place and begin testing

Overview

FDML

TDM

Future

Results from upstream station (CH₄ temperature & mole fraction)

- ◆ Timing of fuel arrival, other dynamics useful to Ramgen

Results from downstream station (H_2O temperature & mole fraction)

- ◆ Known noise sources in these datasets will be reduced in next measurements

Future work: still more near-IR hyperspectral sources

- ◆ ~WMS hyperspectral source for sensitive measurements, e.g., source with constant power but with a wavelength that does this:

- ◆ We are always interested in which spectroscopic sources 'you wish you had'

Future work: Extension of hyperspectral systems to mid-IR and UV

- ◆ There are obstacles, such as component availability and fiber delay limits:

- ◆ But opportunities such as wavelength-conversion of hyperspectral sources, e.g., in PPLN, also exist

Future work: Hyperspectral Tomography

- ◆ Images courtesy Hugh McCann, University of Manchester:

- ◆ Each laser beam (projection) through the test article is expensive (e.g., \$3000) whereas each wavelength is inexpensive (e.g., \$300)
- ◆ Collaborating with Prof. Lin Ma, Clemson University and Dr. Sukesh Roy, ISSI. Prof. Ma's simulations show promising performance, e.g., for continuous low-spatial-resolution temperature imaging at 30 kHz using ~ 20 beams and ~ 20 wavelengths

Acknowledgements

- ◆ Sponsors: US DOE, Honda, NSF, US Air Force SBIR program
- ◆ Collaborators:
  - ◆ Honda: Yasuhiro Urata, Yasuhiro Okura, Toshiyuki Suga
  - ◆ MIT: Prof. James Fujimoto, Dr. Robert Huber (now at U. of Munich)
  - ◆ WPAFB: Dr. James Gord, Dale Shouse, Craig Neuroth
  - ◆ ISSI: Dr. Sukesh Roy
  - ◆ Ramgen: Ryan Edmonds
  - ◆ Clemson: Prof. Lin Ma
- ◆ Senior students: Thilo Krätschmer, Andrew W. Caswell

Overview

FDML

TDM

Future