Frequency Combs and Hyperspectral Sources for Absorption Spectroscopy

CLEO, 5 May 2008

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cite as: S.T. Sanders, "Frequency Combs and Hyperspectral Sources for Absorption Spectroscopy," in *Conference on Lasers and Electro-Optics, CMH3*, 5 May 2008. (<http://digital.library.wisc.edu/1793/28167>)

- Outline:**
- ◆ Overview of hyperspectral design space
  - ◆ Continuous-spectral sources
    - ◆ FDML laser in piston engine at Honda
    - ◆ frequency combs
  - ◆ Discrete-spectral sources
    - ◆ TDM in Ramgen combustor at AFRL
  - ◆ Future work

Overview	Continuous	Discrete	Future

Usual goal: gas thermometry in dynamic (~ 30 kHz) systems

piston engines

shock tubes*

gas turbine burners*

pulse detonation tubes*

♦ * denotes possibility of a **steady pre-test**: slow (e.g. < 100 Hz) sensors are useful prior to (or after) dynamic event. such cases are **$< 100\%$ dynamic**

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Monitoring gas properties with hyperspectral sources

Beer-Lambert Law:

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

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

- ◆ Infer **temperature** from rotational distribution (band shape)
- ◆ Infer **mole fraction** from heights of features
- ◆ Often need ~ 30 nm spectral coverage for best performance
- ◆ Absorption spectroscopy: final results are generally path-integrated

Swept-wavelength sources

- Straightforward spectral encoding in time
- “Continuous-spectral” (source delivers complete spectra without gaps)
- Fast sweeps (e.g., every 10 μs) are needed for dynamic test articles
- We work mostly in the infrared; however, throughout this talk, my charts and language may use visible colors

Fourier-domain source: a “continuous-spectral” alternative

Swept-wavelength:

Fourier domain:

Sample continuous-spectral data

- ◆ emission spectra
- ◆ Fourier-domain approach

Continuous (swept) vs. discrete (TDM)

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

Sample “discrete-spectral” data

Home-built light sources can compete

- ◆ 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

Kraetschmer, Dagel,
and Sanders, *Optics
Letters* **33**(7), 2008

Rapid wavelength-swept (FDML) source

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

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Select “continuous-spectral” sources

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

source	advantage	disadvantage	features of ideal application
tunable ECDL*	single mode	max speed ~ 100 Hz	steady, strong beamsteering, low pressure (long flame)
FDML laser	high speed	multi (spectral) mode	100% dynamic, high-pressure (high-RPM engine)
multiplexed VCSELs*	variable speed to ~ 20 kHz	cost	> 0% dynamic, tomography w/ beam count >= VCSEL count
fs comb pair	spectral access (UV...IR)	cost	as FDML laser but minor species
SLD* (with spectrometer)	ease of use	spectrometer cost	as FDML laser but low beamsteering, single beam

* denotes commercially available

◆ Each of these sources can be ‘best’

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H₂O absorption thermometer applied in HCCI engine

Kranendonk et al, *Optics Express* 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)

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Measured engine spectrum compared to BT2 simulation

wavelength [nm]: 1370

1360

1350

1340

◆ 3x shot noise limit, MDA = 5×10^{-8} Hz^{-1/2}

◆ Peak residual < 10% across entire spectrum (as of Feb 2008)

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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 5-10 K (from ~50K in 2004)
- ◆ Absolute accuracy not yet known, but low residual and agreement with simulation are encouraging

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fs comb (comb Fourier transform spectroscopy: c-FTS)

- Developed by Fritz Keilmann, Max Planck Institut, and Daniel van der Weide, U. of Wisconsin
- expensive, but likely to be used in practical dynamic environment soon

A. Schliesser, F. Keilmann, D. W. van der Weide
Optics Express (2005)

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Inexpensive CW version of comb-FTS

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

- ◆ Inexpensive, but difficulties associated with noise, spectral coverage

Example discrete-spectral wavelength selection: $10-\lambda$

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

Why choose discrete over continuous?

- ◆ Less data to acquire: cheaper DAQ and computation → on-board sensing and control
- ◆ Lower-noise: all else equal, get 7x better temperature precision by spending a longer time measuring the most important parts of the spectrum
- ◆ However:
  - ◆ Susceptible to error, especially in **100% dynamic** or 'quick trial' applications

Select “discrete-spectral” sources

source	advantage	dis- advantage	features of ideal application**
externally modulated & multiplexed fixed- λ lasers*	single mode	pay per wavelength	beam count > wavelength count, low pressure absorber
time-division multiplexed (TDM) source	10s to 100s of wavelengths	narrow linewidth increases cost	high-pressure or broadband absorber, 10 kHz - 10 MHz bandwidth required

* denotes commercially available

** assumes application favors discrete over continuous

- ◆ Including continuous sources, each of these can be ‘best’

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Schematic of 10-wavelength TDM source

see CThL7, Thursday at noon

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

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Photos of 10-wavelength TDM source

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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)

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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 μs (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

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Results from upstream station (CH₄ temperature & mole fraction)

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

Results from downstream station (H_2O temperature & mole fraction)

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

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:

- ◆ Feel free to ask me about spectroscopic sources that '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 can be 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/AFRL: Dr. James Gord, Dale Shouse, Craig Neuroth
  - ◆ ISSI: Dr. Sukesh Roy
  - ◆ Ramgen: Ryan Edmonds
  - ◆ Clemson: Prof. Lin Ma
  - ◆ UW Engine Research Center: Prof. Rolf Reitz, Yu Shi
- ◆ Special thanks to senior students: Thilo Krätschmer, Andrew W. Caswell

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