

High accuracy broadband spectroscopy with dual frequency combs

Symposium:
A Revolution in Spectroscopy by the Optical Frequency Comb

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Outline

- Introduction
- Dual-comb spectroscopy
 - Measurements in the NIR
 - Measurements in the MIR (3.34 microns)
 - Performance summary
- Comb-assisted swept laser spectroscopy
 - Tracking a swept laser with a comb
 - Preliminary calibrated swept laser spectroscopy of methane
- Conclusion

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Femtosecond Laser Frequency Combs

A unique source for sensing and spectroscopy

- an array of millions of phase-coherent CW oscillators
- large spectral coverage: 300 nm - 10 microns
- precisely known frequencies (~1 Hz resolution)
- high peak power for efficient nonlinear optics

wavelength (nm)

Ti:Sapphire laser

courtesy of S. Diddams et al.

Er: fiber laser

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Erbium fiber frequency comb

Passively mode-locked Er fiber laser*

- 100 MHz rep rate
- ~100 fs pulses
- ~10 mW output
- All fiber or fiber/free space

Self-referenced "octave-spanning" comb

*L. E. Nelson et al., APB 65, (1997).

Broadband Spectroscopy

Blackbody Source

Supercontinuum source

Frequency Comb

Swept laser

cell

multipass cell

resonant cavity

Fourier Transform Spectrometer

Grating Spectrograph

Grating/VIPA (high res) Spectrograph

Cavity Ring Down Spectrometer

Dispersed Supercontinuum

Dual-Comb spectrometer

Combs + cavity : Thorpe, Science 311, 1595 (2006), APB, (2008), 91, 397; Bernhardt, NP, 4, 55 (2009)
 Combs + FTIR : Adler, OE, 18, 21863 (2010); Mandon, NP 3, 99 (2009)
 Combs + high res. spectrometer: Diddams, Nat. 445, 627 (2007); Thorpe, OE, 16, (2008); Gohille PRL 99, 263902 (2008).
 Dual Comb: Keilmann, et al, Opt. Lett. 29, 1542 (2004), Schliesser, OE, 13, 9029 (2005); Coddington, PRL, 100, 013902 (2008), Giaccari, Opt. Express, 16, 4347 (2008); Bernhardt, NP 4, 55-57 (2009)

Dual-Comb Spectroscopy

Method to access the *amplitude and phase* of each tooth
Use a second comb as a Local Oscillator

Keilmann, et al, Opt. Lett. 29, 1542 (2004)
 Schiller, Opt. Lett. 27, 766 (2002)
 Schliesser, Opt. Exp., 13, 9029 (2005)
 Coddington, PRL, 100, 013902 (2008)
 Giaccari, Opt. Express, 16, 4347 (2008)
 Bernhardt, Nat. Photon., 4, 55-57 (2009)
 Coddington, Opt. Lett. 35, 1395 (2010)
 Coddington, PRA, 043817 (2010)
 Deschenes, Opt. Express, 23358 (2010)

Frequency Domain

Multi-heterodyne spectroscopy
Coherent Spectral Interferometry

Time Domain

Coherent Linear Optical Sampling
Cross-correlation of E-fields
Extends THz time-domain spect.

Coherent Dual Comb Spectroscopy Frequency Domain

Source and LO combs repetition rates differ by Δf_{rep}

Map Optical → RF

Optical frequency (THz)

RF frequency (MHz)

Nyquist Bandwidth Limit: $f_{rep}^2 / \Delta f_{rep} = 10 \text{ THz/m}$

Coherent Dual Comb Spectroscopy Frequency Domain

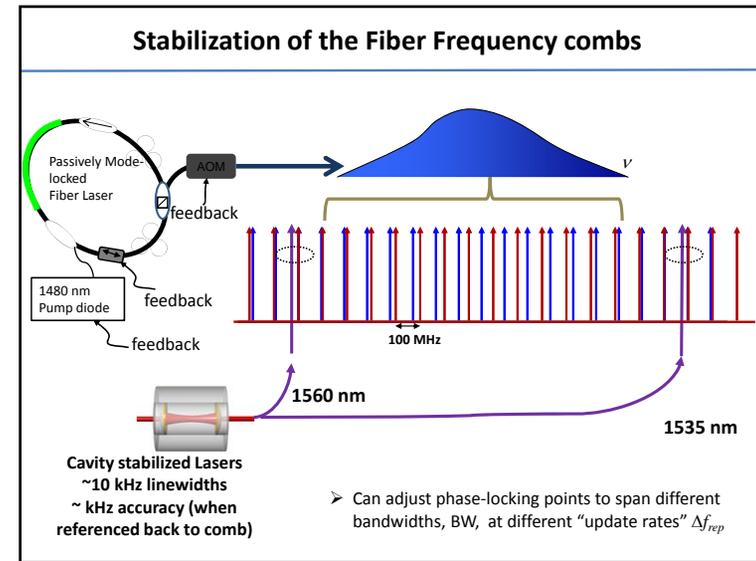
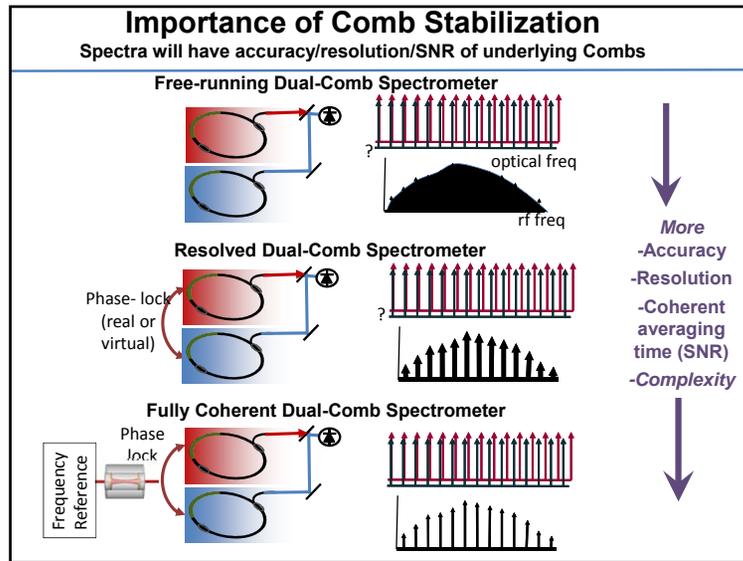
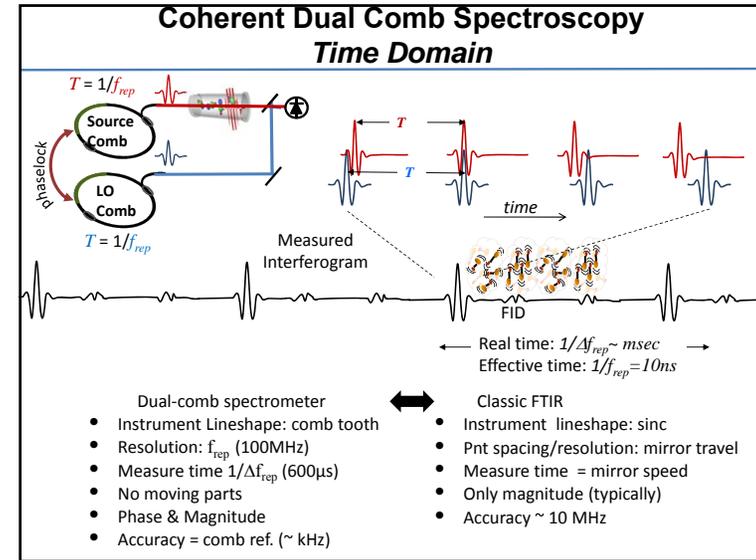
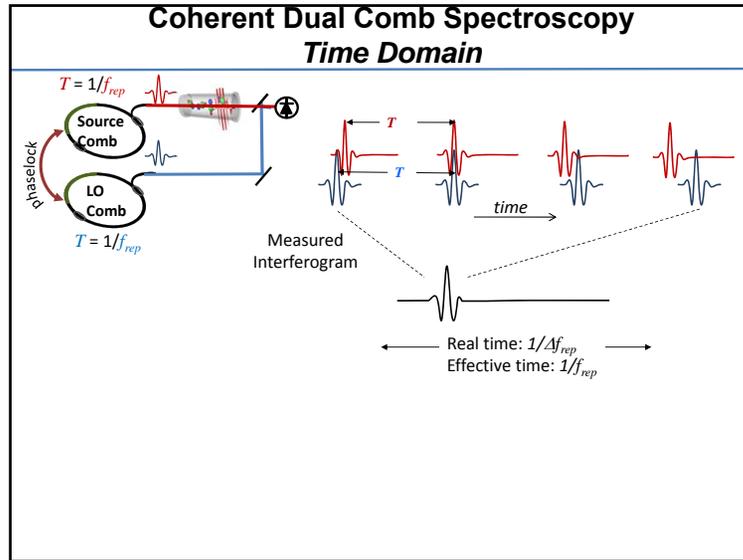
Source and LO combs repetition rates differ by Δf_{rep}

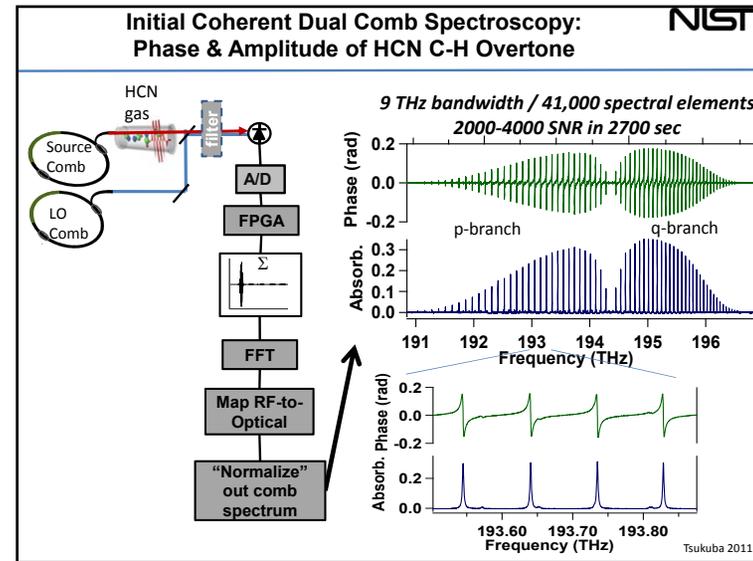
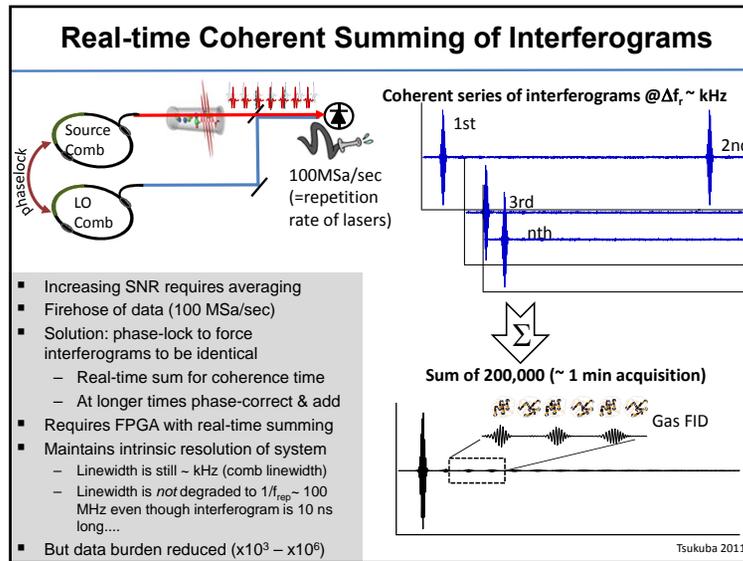
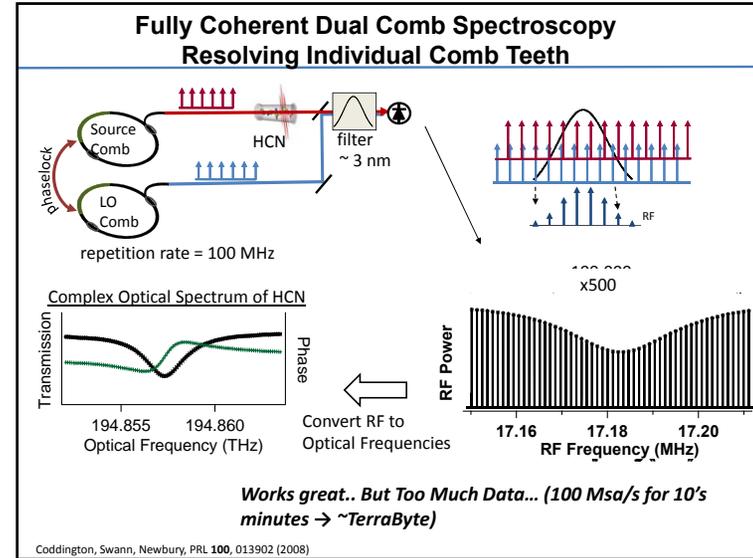
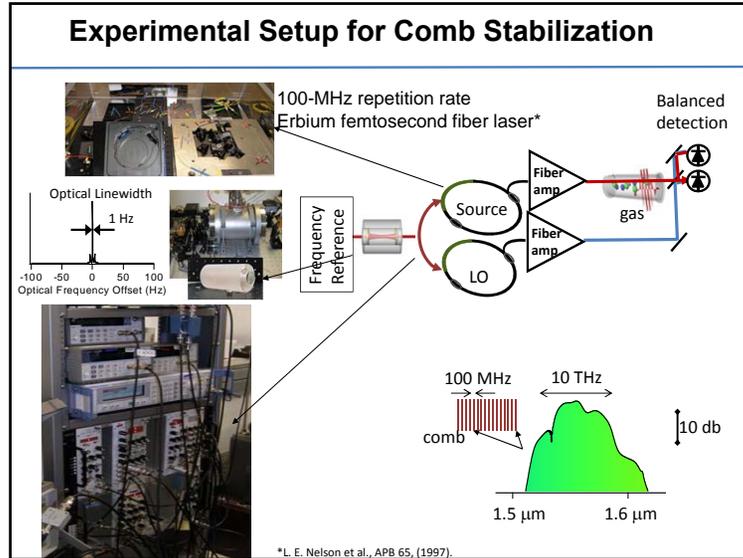
Map Optical → RF

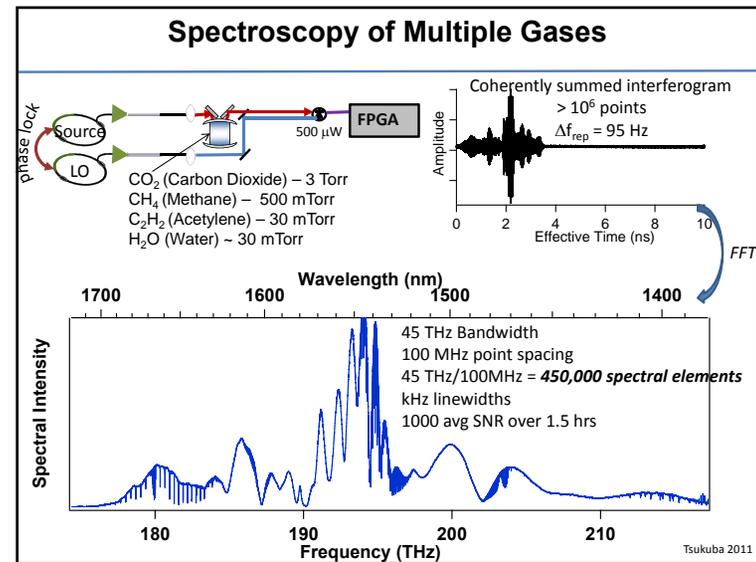
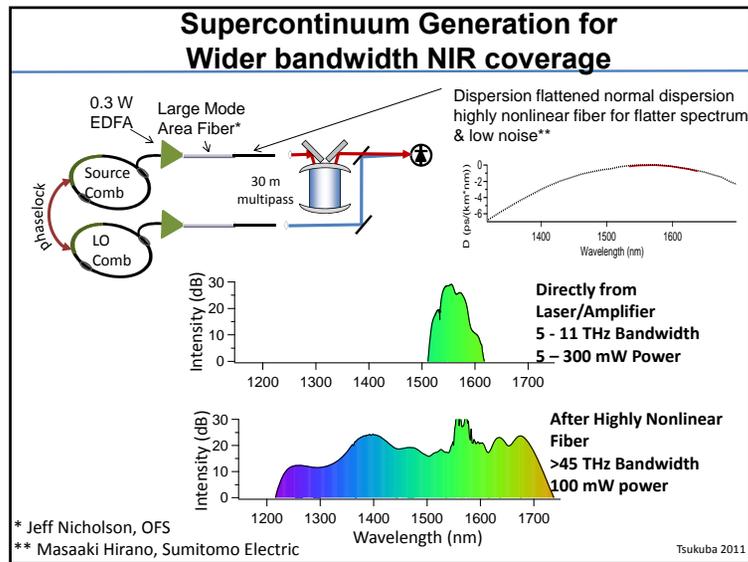
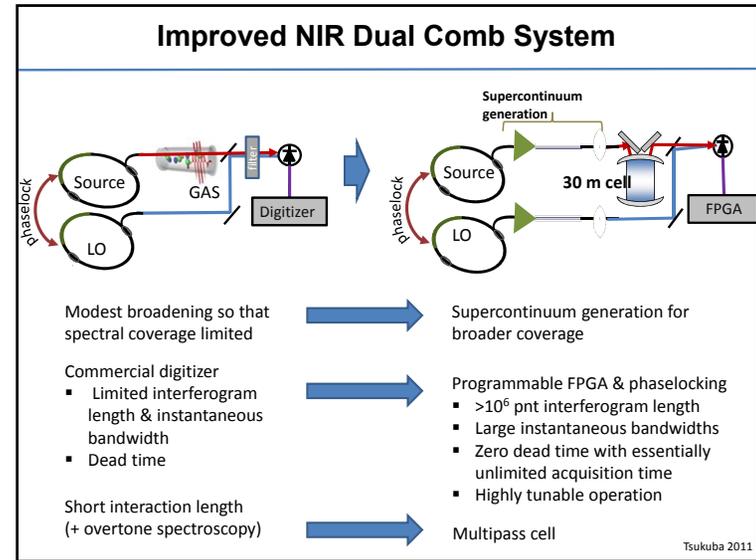
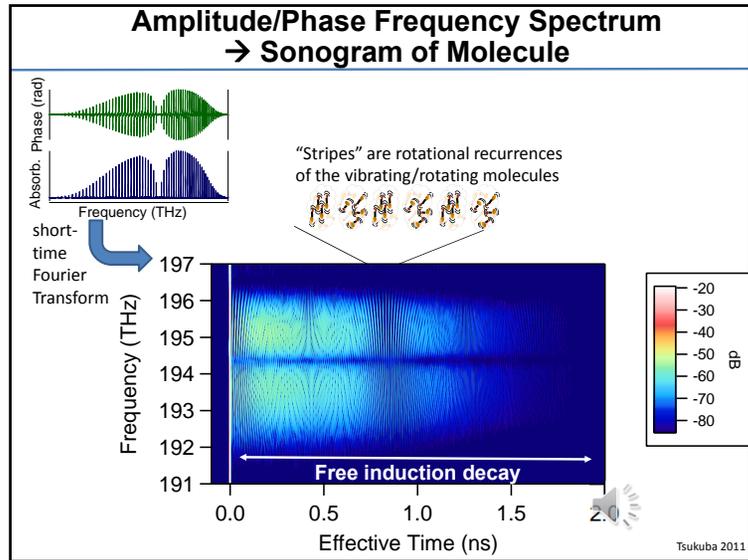
Optical frequency (THz)

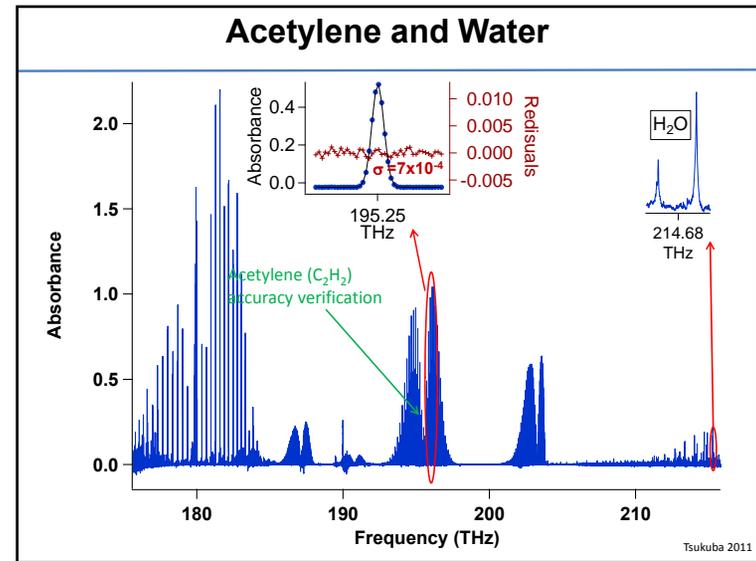
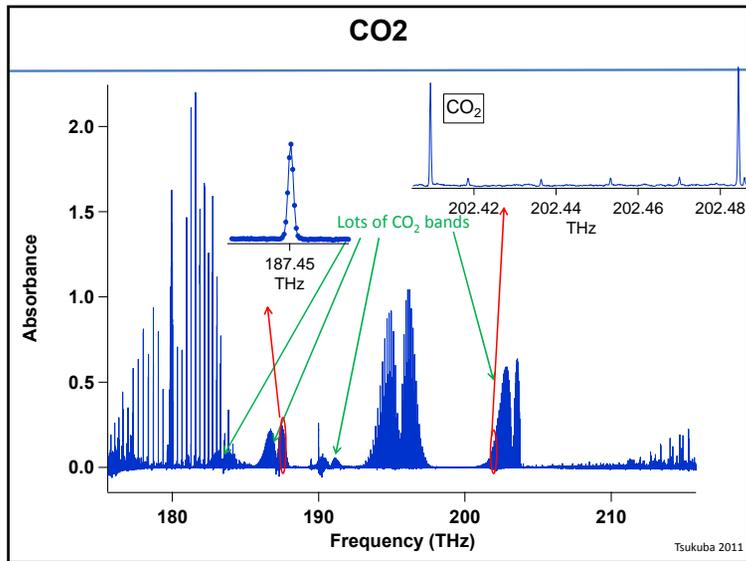
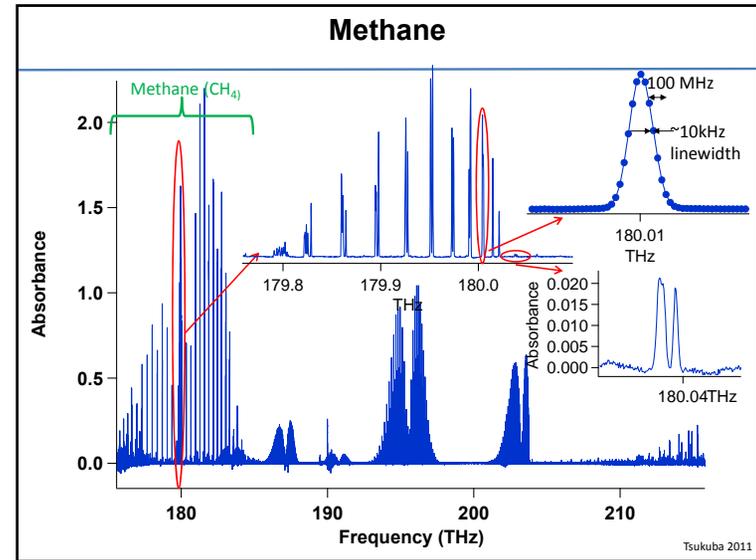
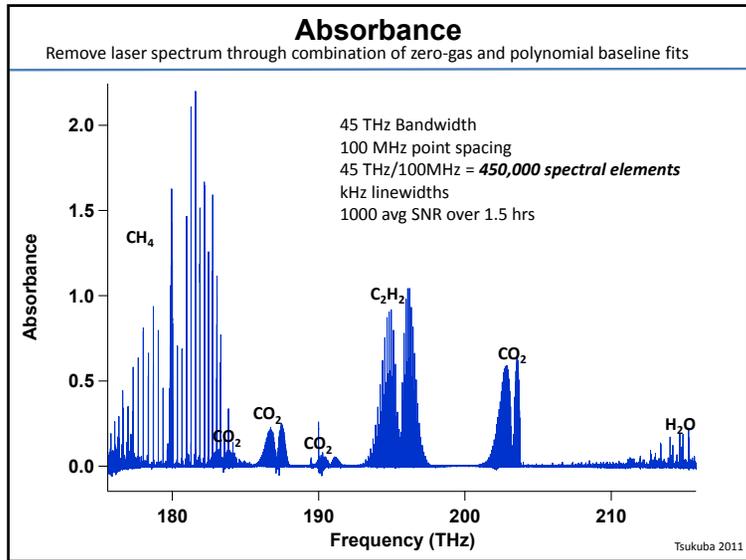
RF frequency (MHz)

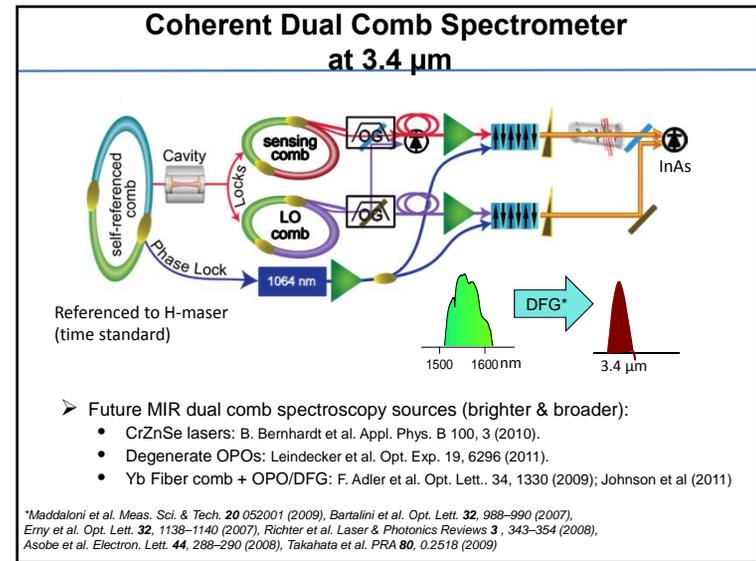
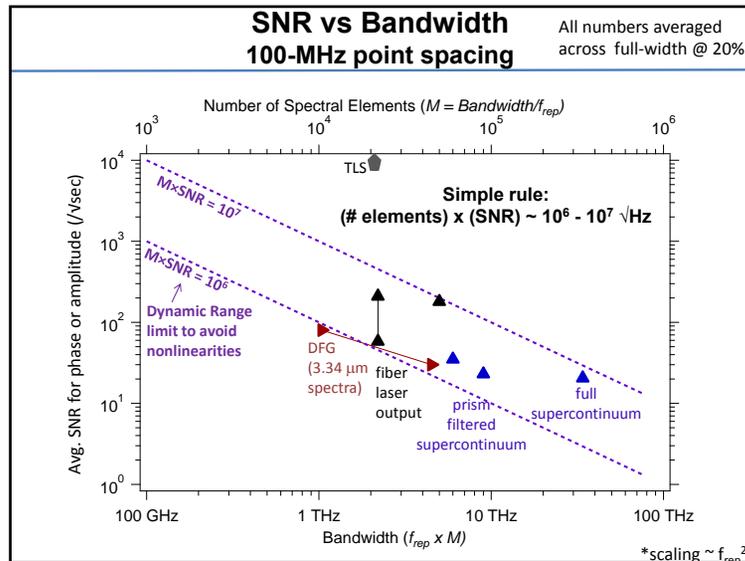
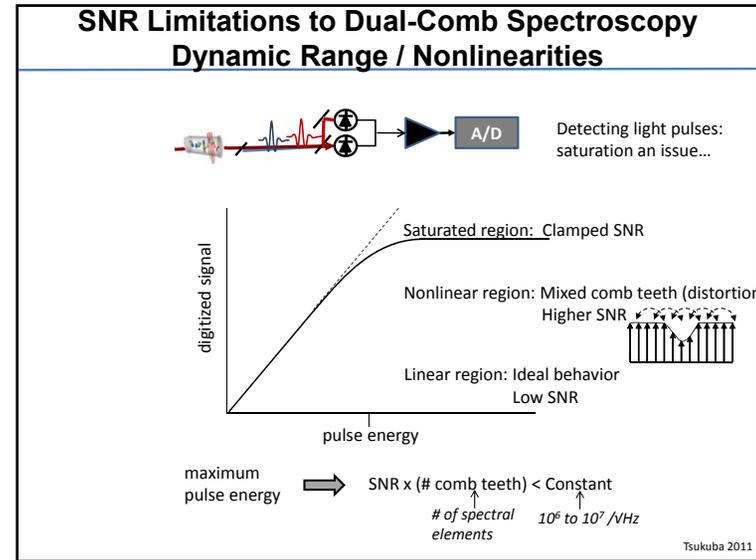
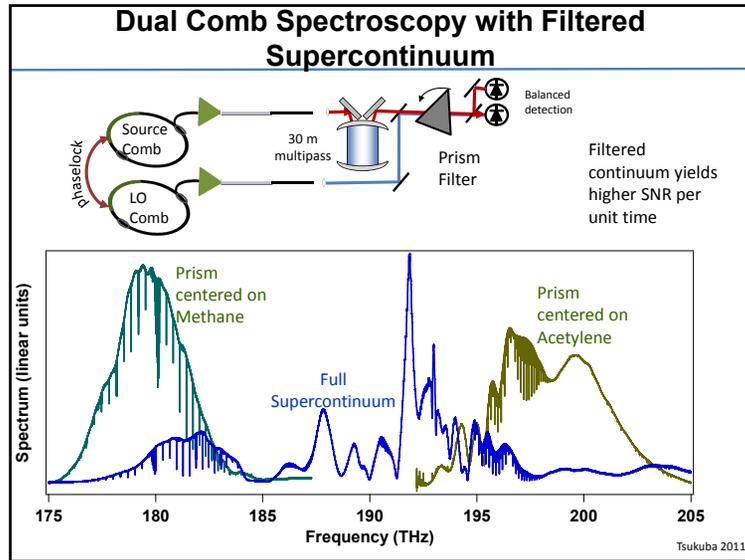
Nyquist Bandwidth Limit: $f_{rep}^2 / \Delta f_{rep} = 10 \text{ THz/m}$

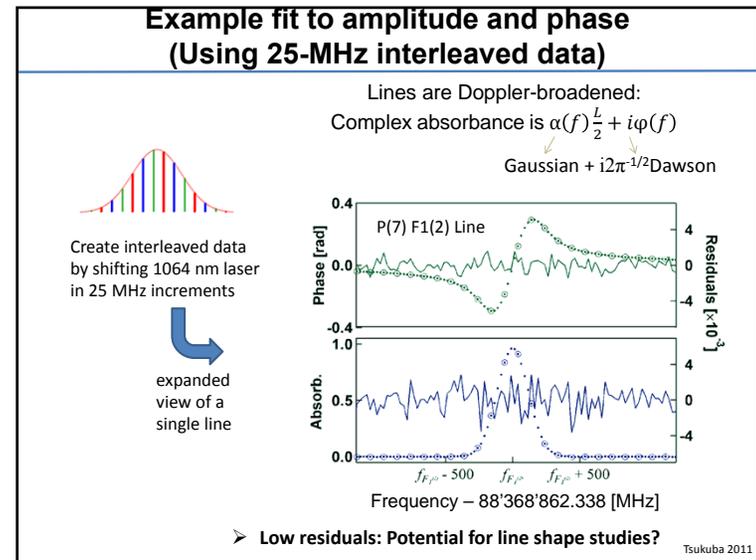
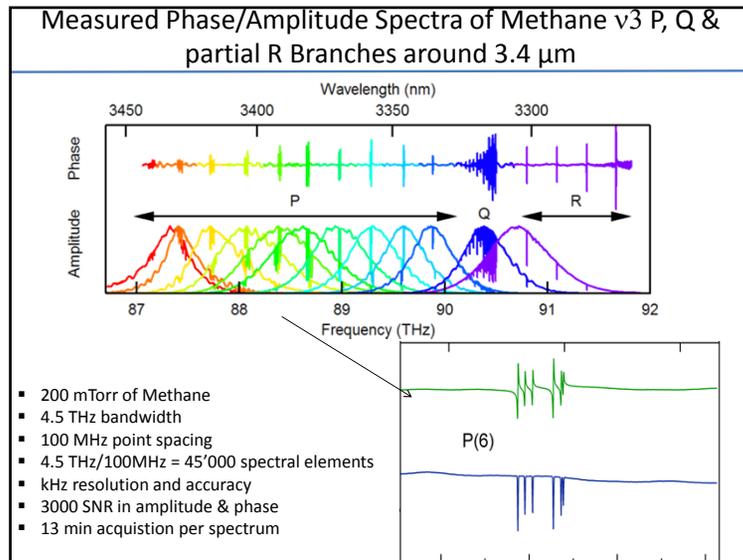
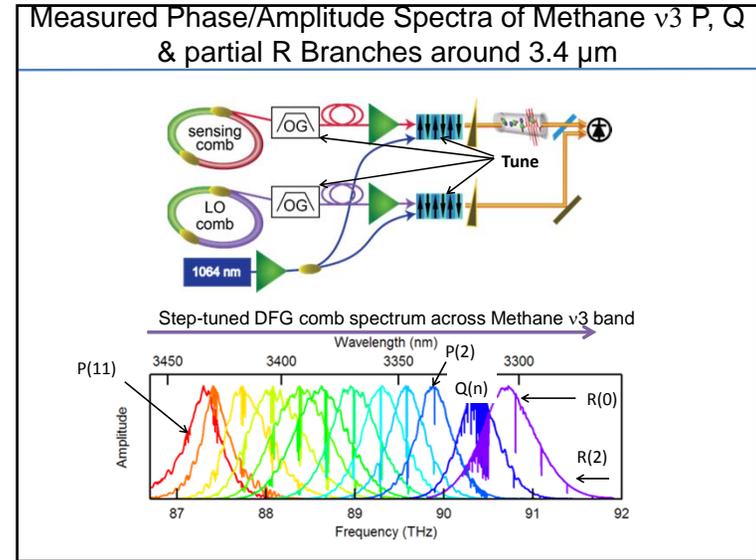
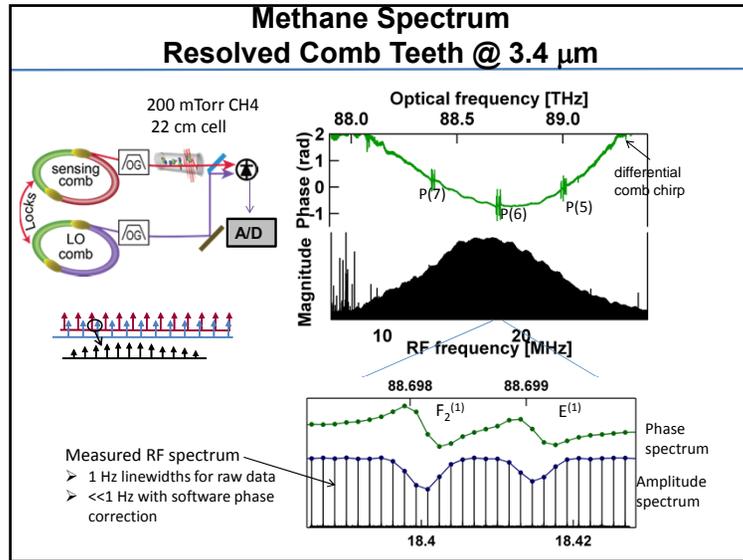


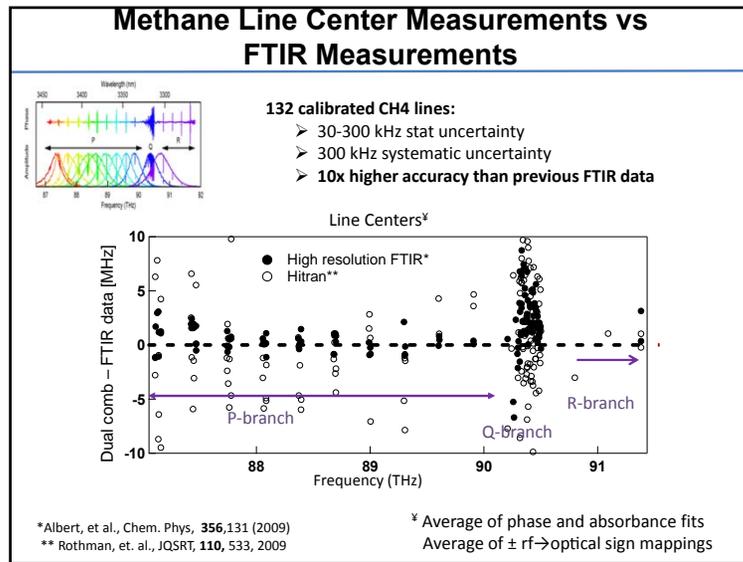
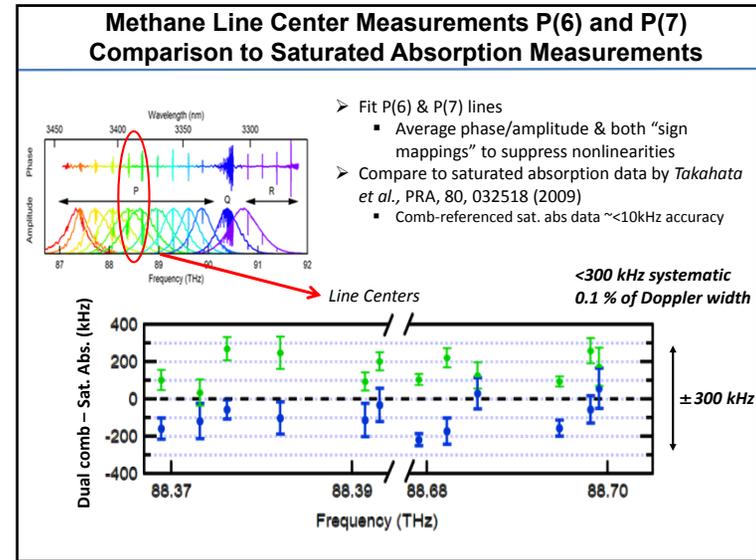
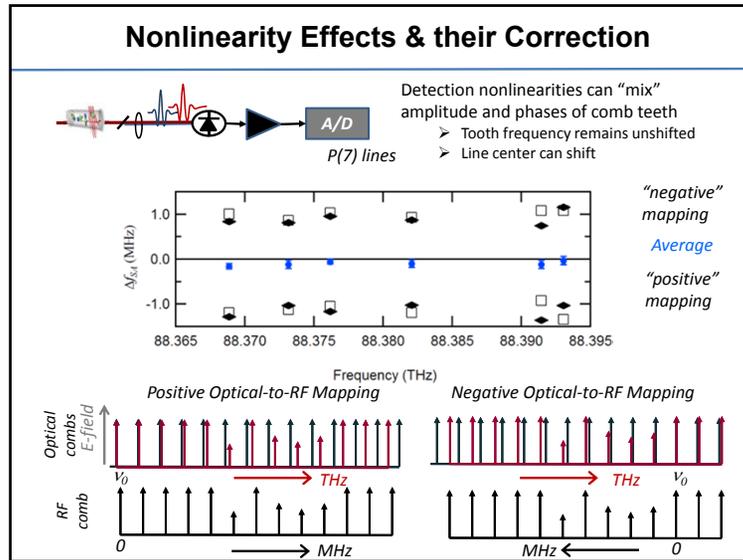












Coherent Dual-Comb Spectrometer Performance

Accuracy

~ 300 kHz (nonlinearities "managed")

~10x better than High-Res FTIR

~10x worse than cw laser sat. abs.

Sensitivity

$10^6 - 10^7 = \langle \text{SNR} \rangle \times (\# \text{ Elements})$

Better than High-Res FTIR

Worse than swept laser (multiplex hit)

Resolution (Instrument Line shape)

~ kHz for optically phase-locked combs

~ 10^5 x better than High-Res FTIR

Same as cw laser spectroscopy

Speed

$f_{\text{rep}}^2 / \Delta f_{\text{rep}} = 10 \text{ THz / ms acquisition}$

Much faster than high-res FTIR

Faster than swept laser

Spectral Coverage

1-100 THz should be possible

>10x broader than swept laser

>10x narrower than FTIR

Complexity

Large electro-optic system

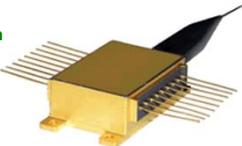
More complex than either FTIR or swept laser (but no moving parts)

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Combing Swept CW Lasers & Combs

Tunable diode lasers offer

- ~100 nm tuning ranges
- Rapid scan rates >1000 THz/s in MEMS or Y-branch design
- >10 mW - many Watts and single mode operation.
- Much higher SNR than direct-comb illumination



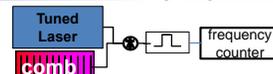
But

- Optical frequency is poorly defined during sweeps (orders of magnitude worse than linewidth)
- Also fastest sweeps will not be linear (but quasi-sinusoidal)

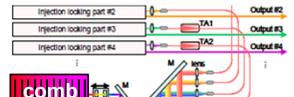
Goal:

- Use frequency combs to track the phase of a swept laser
 - ❖ With high accuracy
 - ❖ At high speeds
 - ❖ Over arbitrary waveforms

Combs & CW Lasers: Many Systems Demonstrated . . .

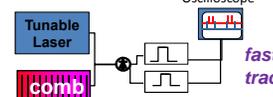


Clocks...
Jiang et al., JOSA B, 24, 2727 (2007)
Takahata et al., PRA, 80, 32518 (2009)



step tuning

Kim et al., OE., 16, 258, (2008); 17, 10939 (2009).
Park et al., OL., 31, 3594 (2006)
Fortier et al. PRL 97 163905 (2006)



fast tracking

Del'Haye et al., Nat. Phot. 3, 529 (2009).

How fast a laser can be tracked with combs....

T.-A. Liu et al., OE 16, 10728, (2008).
Ma et al., JSTQE, 9, 1066 (2003)

absolute frequencies

smooth tuning

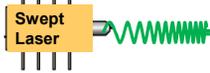
Jost et al., OE., 10, 515 (2002)
Schibli et al., OL., 30, 2323 (2005)
Inaba et al AO, 4910, 45(2006)

Tracking a Fast Swept Laser

Basic Approach: Heterodyne laser against comb & digitize (fast)

Now: Telecom-band External Cavity Laser

Future: Mid Infrared ICL / QCL?

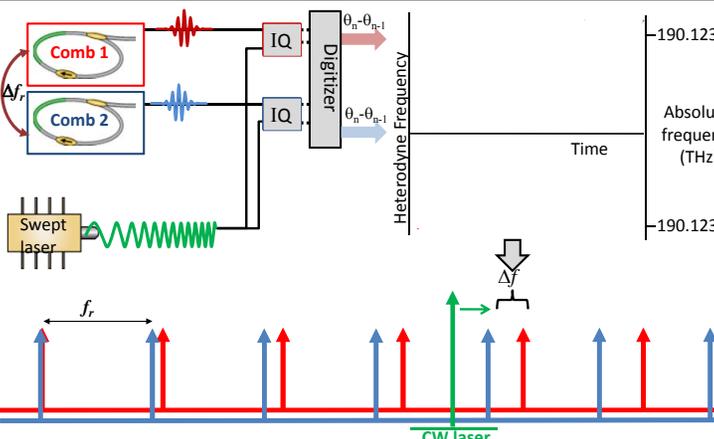


Wavelength meter	➢ Slow ➢ Absolute frequency ➢ Commercial
Etalon + gas cell	➢ Faster ➢ Dispersion limited accuracy/resolution ➢ Simpler
Single Comb Spectrometer	➢ Quite fast (20 nsec/point) ➢ Relative frequency with kHz resolution/accuracy ➢ Complex
Dual Comb Spectrometer	➢ Sub-msec speed ➢ Absolute frequency with kHz accuracy (1000x wavemeter) ➢ More complex

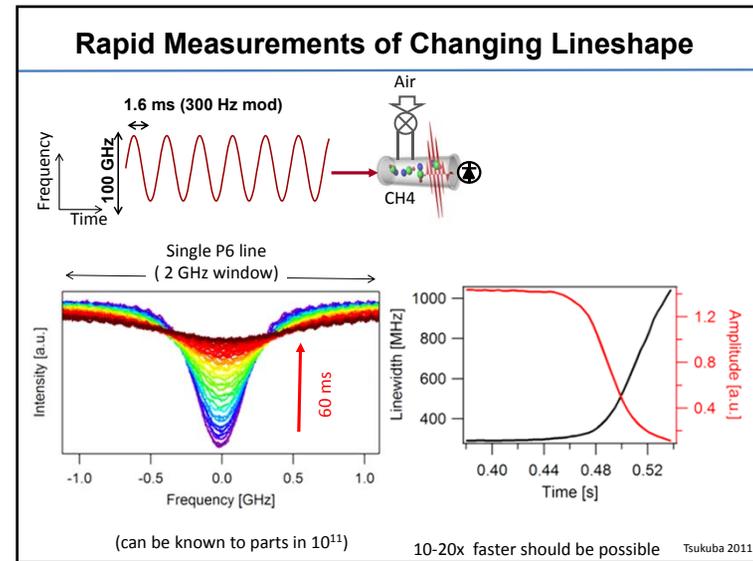
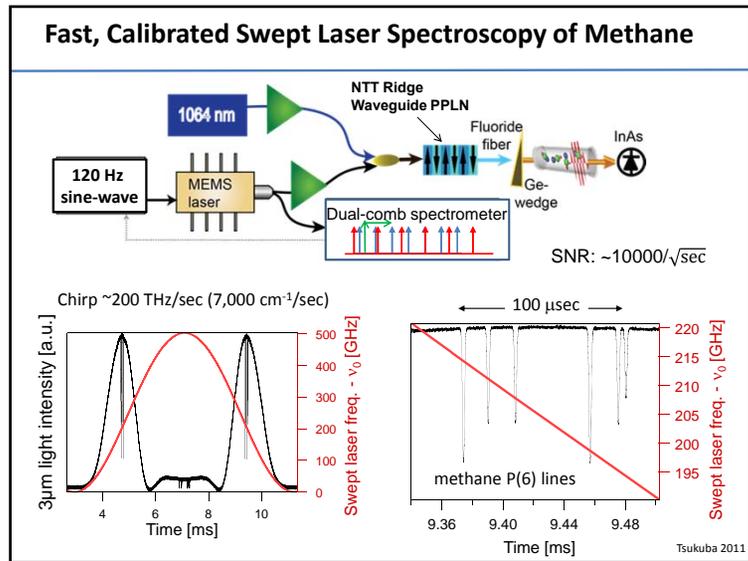
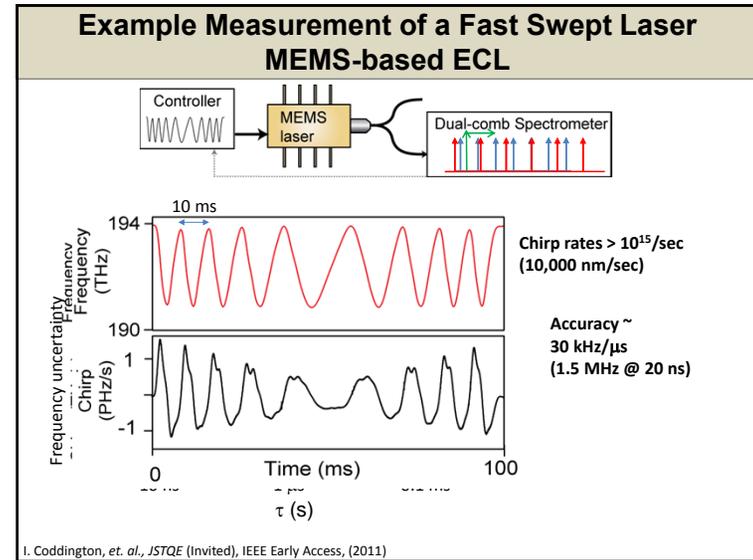
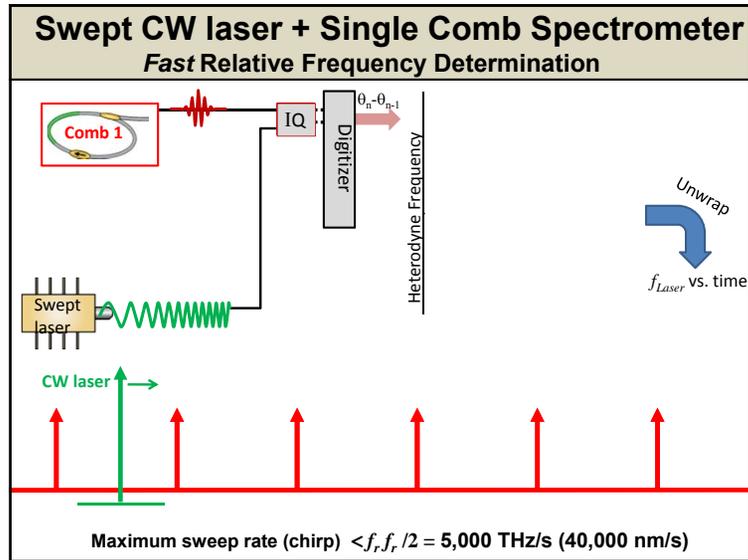
Liu, et al., *Opt. Exp.*, 16, 10728, (2008).
Del'Haye et al., *Nat. Photon.*, 3, 529, (2009).
Giorgetta, et al., *Nat. Photon.*, 4, 853, (2010)
Barber, et al., *Opt. Lett.*, 36, 7, 1152, (2011).
Coddington, et al., *JSTQE* (Invited), IEEE Early Access, (2011)

Swept CW laser + Dual Comb Spectrometer

Absolute Frequency Determination



Maximum sweep rate (chirp) $< f_r \Delta f_r = 0.1-1$ THz/s (0.8-8 nm/s)



Conclusion

- **Coherent dual comb spectroscopy**
 - Can resolve individual comb teeth
 - Measure phase and amplitude
 - Collimated laser beam compatible with long interaction paths
- **Dual comb measurements**
 - Demonstrated in the Near infrared (up to 45 THz)
 - In the Mid-Infrared through DFG
 - Potential applications in highly accurate spectral measurements over broad bandwidths (line centers, line shapes etc.)
 - Overall performance “between” High-Res FTIR and Tunable Laser Spectrometers (in BW and SNR)
- **Comb-assisted cw laser spectroscopy**
 - “Track” tunable lasers at Petahertz/sec rates with arbitrary (and even discontinuous waveforms)
 - Greater SNR than dual comb spectroscopy (if tunable laser exists!)
 - Potential applications in characterization of fast swept lasers & rapid acquisition of highly calibrated optical spectra

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