AOSP Kickoff Meeting
PAWG via Spectral Synthesis - (SPAWG)

Team:
University of Central Florida-CREOL
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J. Abeles

Essex Corp
T. Turpin

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Outline

- Goal
- General Methodology
- Description of Component Technology
  - Clock – Comb Generator
  - Modulator Technology
  - DWDM Mux-De-Mux Technology
- Preliminary Results

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Motivation -Goal

- To develop an arbitrary waveform generator by spectrally synthesizing a time domain waveform using dynamic Fourier techniques.

- Identify a path for full chip-scale integration
  - Coherent combs from modelocked lasers
  - Use modelocked semiconductor lasers
  - Passive, low loss semiconductor based filter technology

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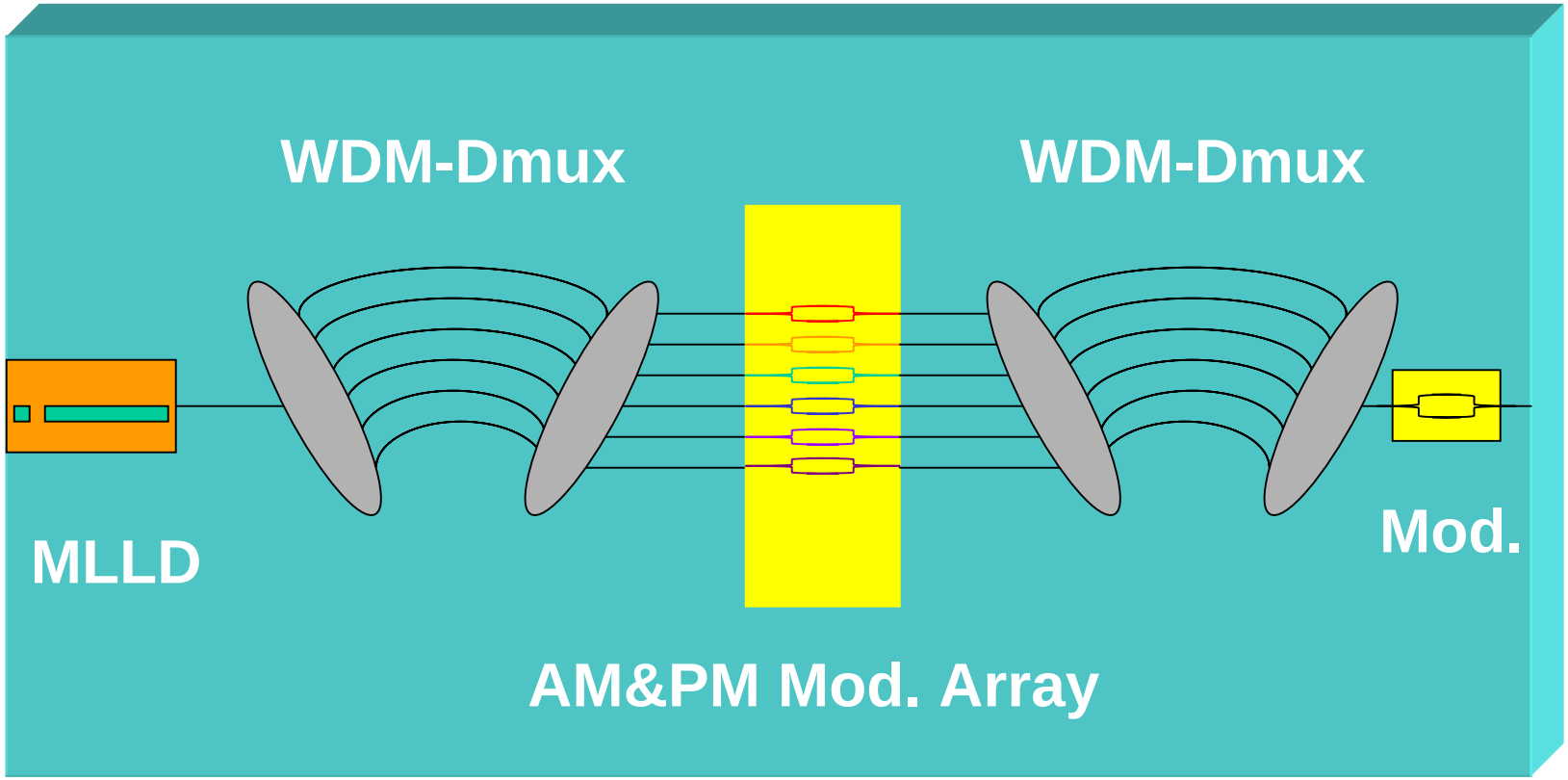
Arbitrary Optical Waveform Generation

Agile analog and digital signal generator



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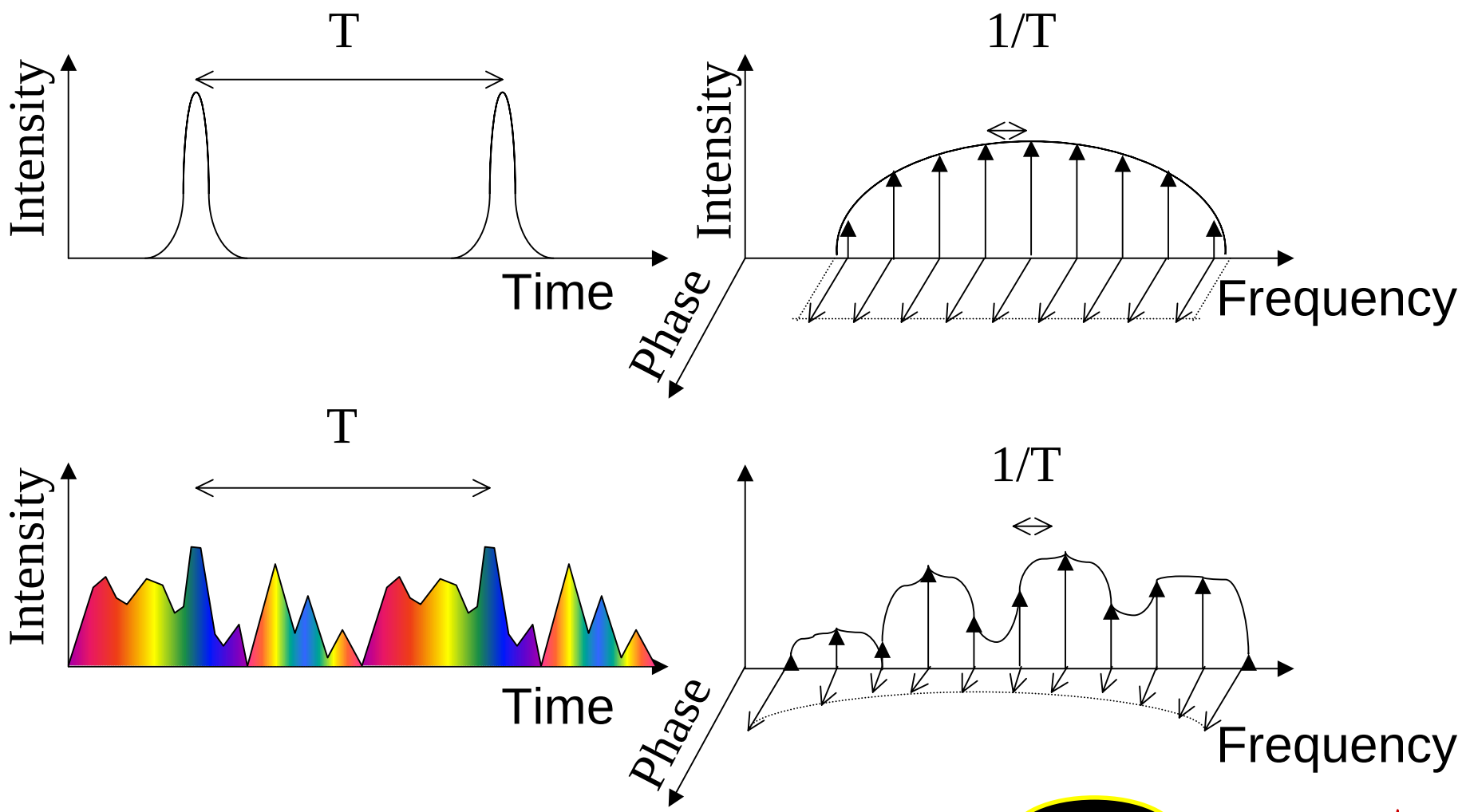
Concept of Photonic Arbitrary Waveform Generation

Static Fourier Analysis



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Concept of Photonic Arbitrary Waveform Generation

Static Fourier Analysis

$$f(t) = \frac{A_0}{2} + \sum_{k=1}^{K} A_k \cos(k\omega_0 t + \alpha_k)$$

k : periodic frequency components
A_k: amplitude of the kth frequency component
α_k phase of the kth frequency component

<u>Performance Characteristics</u>
Limited to Periodic Signals
Minimum Periodicity ~ Mode Spacing/Filter Spacing

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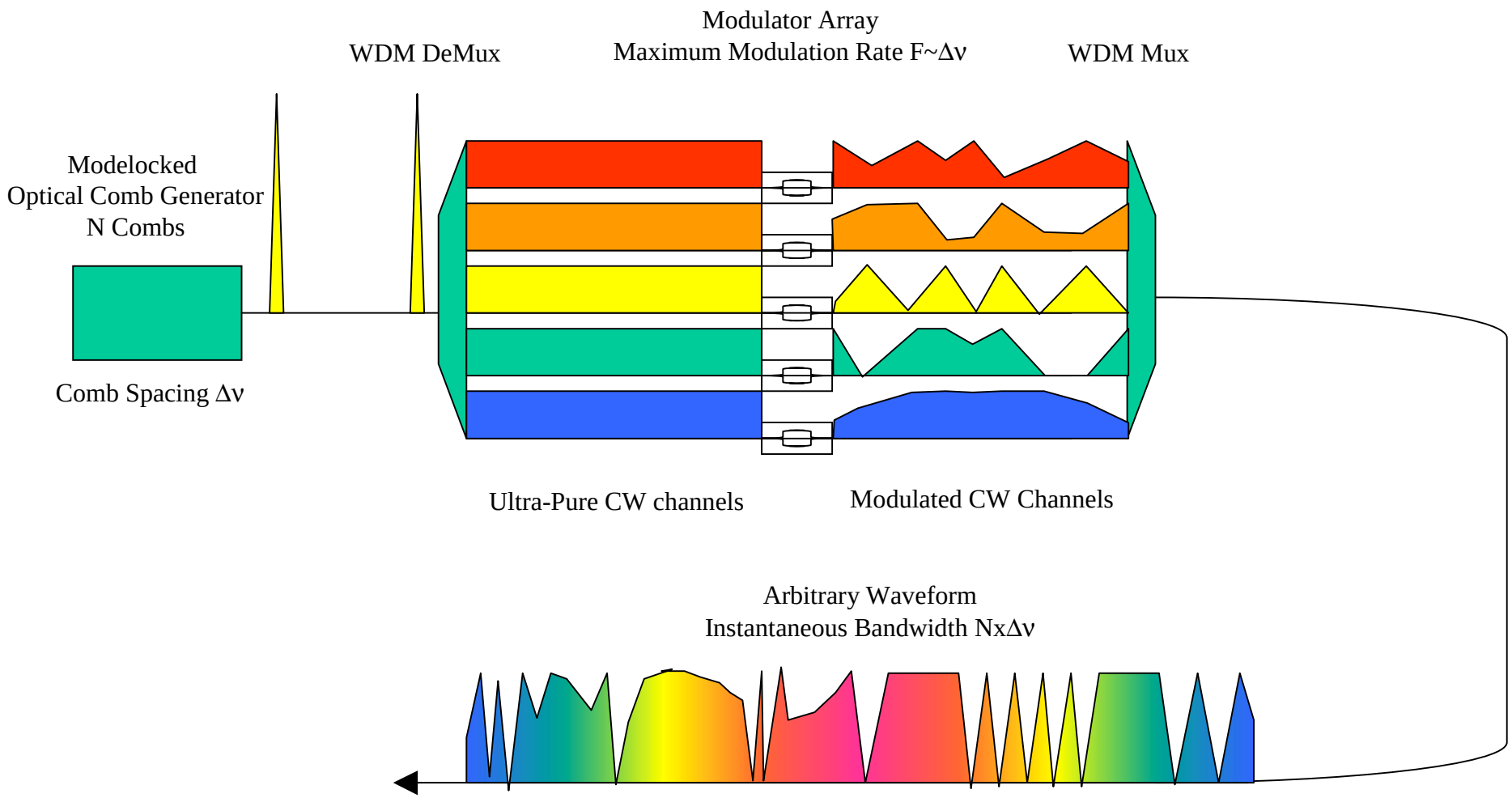
Concept of Photonic Arbitrary Waveform Generation

Dynamic Fourier Analysis



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Concept of Photonic Arbitrary Waveform Generation

Dynamic Fourier Analysis

$$STFT(\omega,t)=\frac{1}{\sqrt{2\pi}}\int f(\tau)g(\tau-t)\exp(-j\omega\tau)d\tau$$

Performance Characteristics
Benefits- Dynamic; More Arbitrariness
Imaging Radar – Signal Synthesis/Analysis based on Ambiguity Distribution
(Special Case of STFT)

$$f(t)=\frac{1}{2\pi f^*(0)}\int\frac{M_{SP}(\theta,t)}{A_g(-\theta,t)}\exp(-j\theta t/2)d\theta$$

$$M_{SP}(\theta,\tau)=\iint|STFT(\omega,t)|^2\exp(j\theta t+j\tau\omega)dtd\omega$$
$$=A_f(\theta,\tau)A_g(-\theta,\tau)$$

where

$$A_S(\theta,\tau)=\int s^*(t-\frac{1}{2}\tau)s(t+\frac{1}{2}\tau)\exp(j\theta t)dt$$

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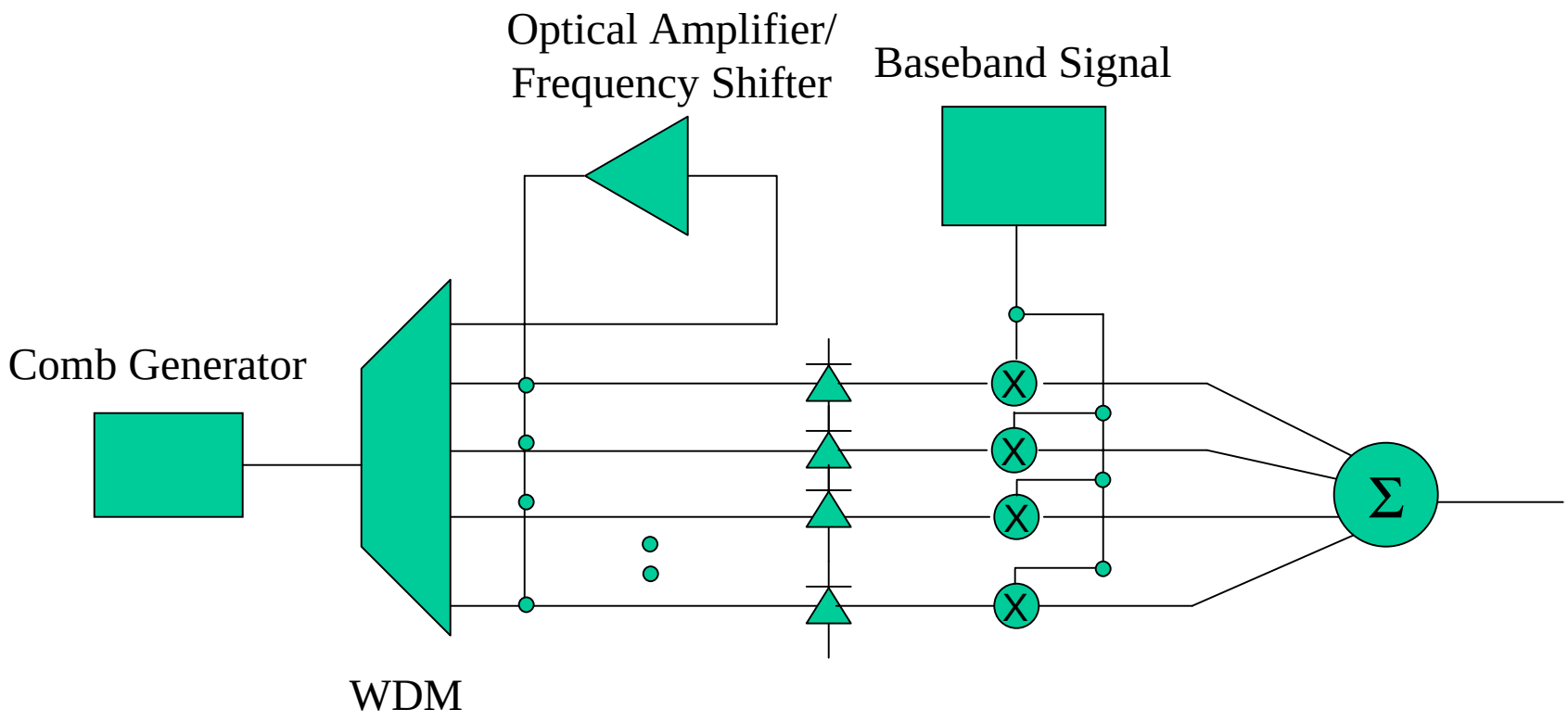
Photonic Arbitrary Waveform Generator

Frequency Shifted Architecture



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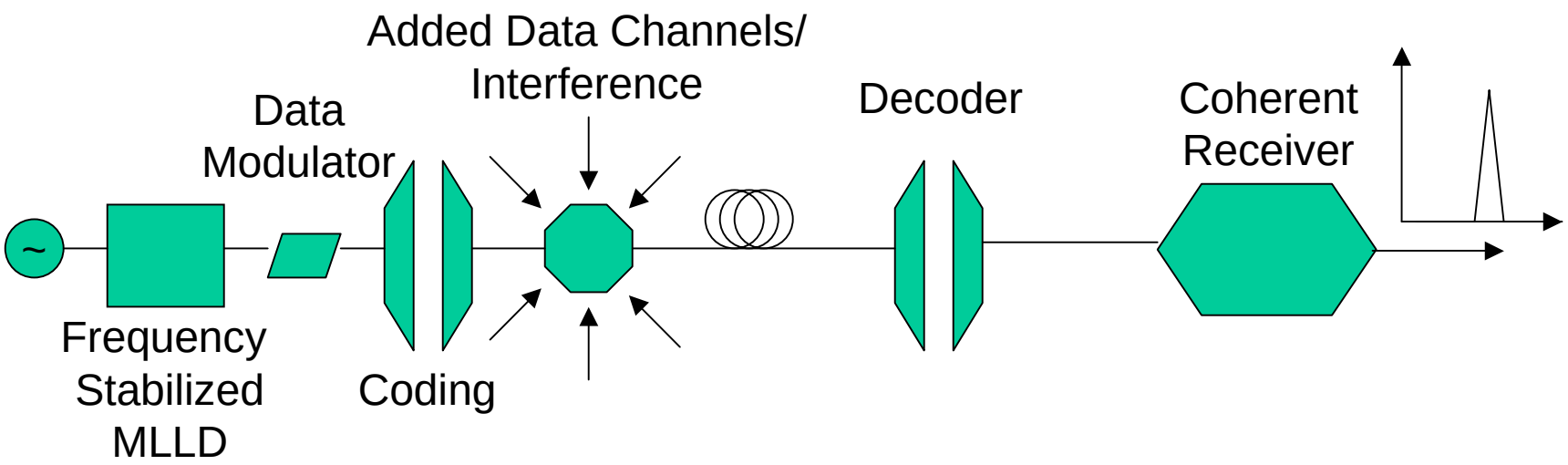
Photonic Arbitrary Waveform Generator

Direct Sequence Spread Spectrum



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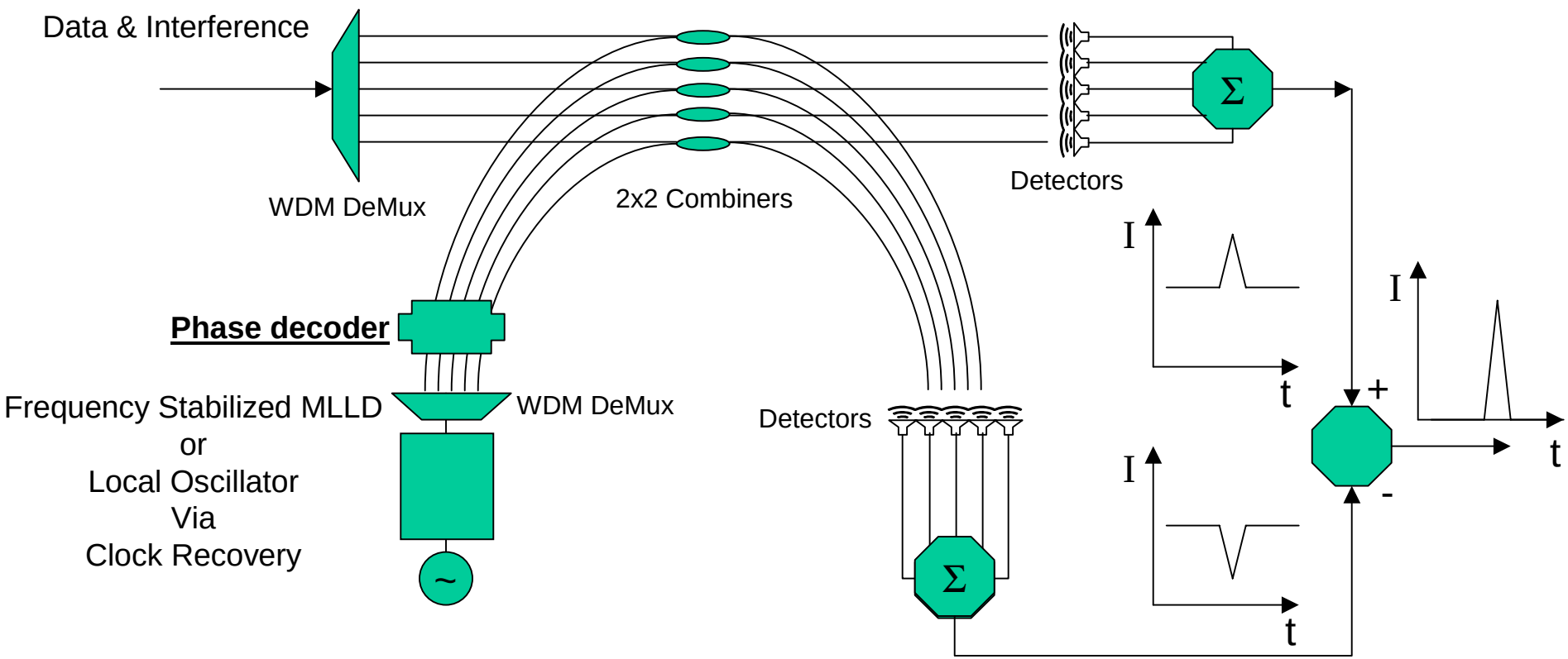
Photonic Arbitrary Waveform Generator

Matched Filtering

Coherent Receiver



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Clock Technology

Coherent Comb Generator
School of Optics – CREOL & Sarnoff Corp

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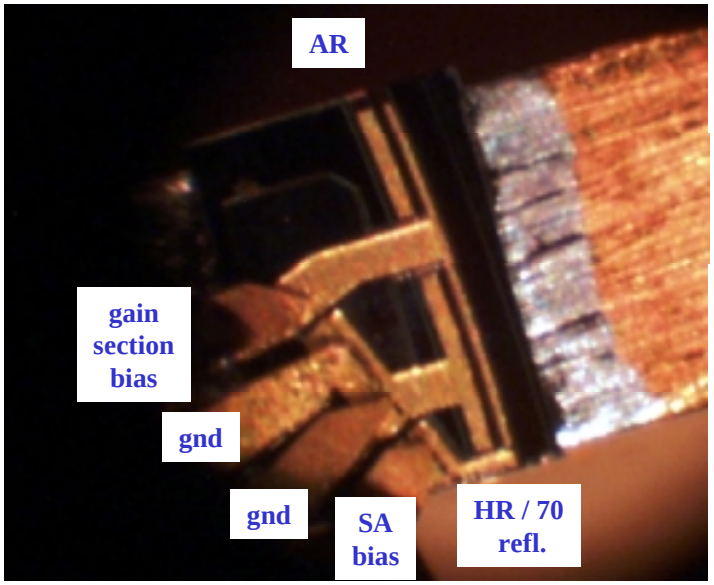
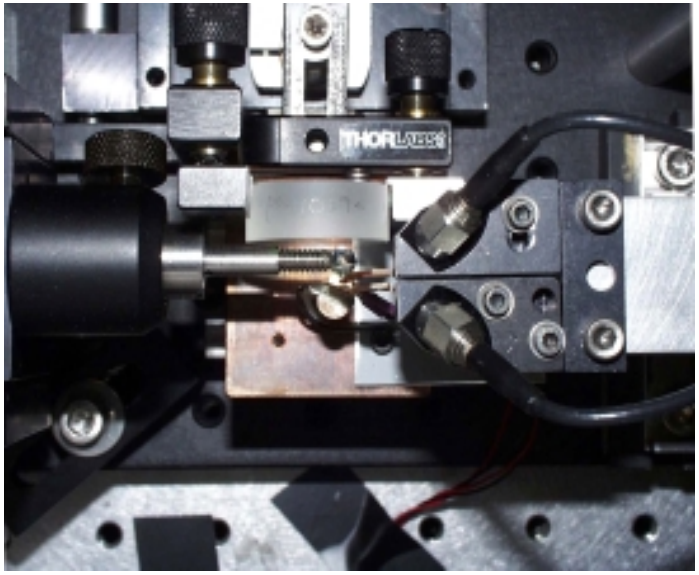
Two-section Bent Waveguide Device

Compact 10 GHz Modelocked External Linear Cavity Semiconductor Laser





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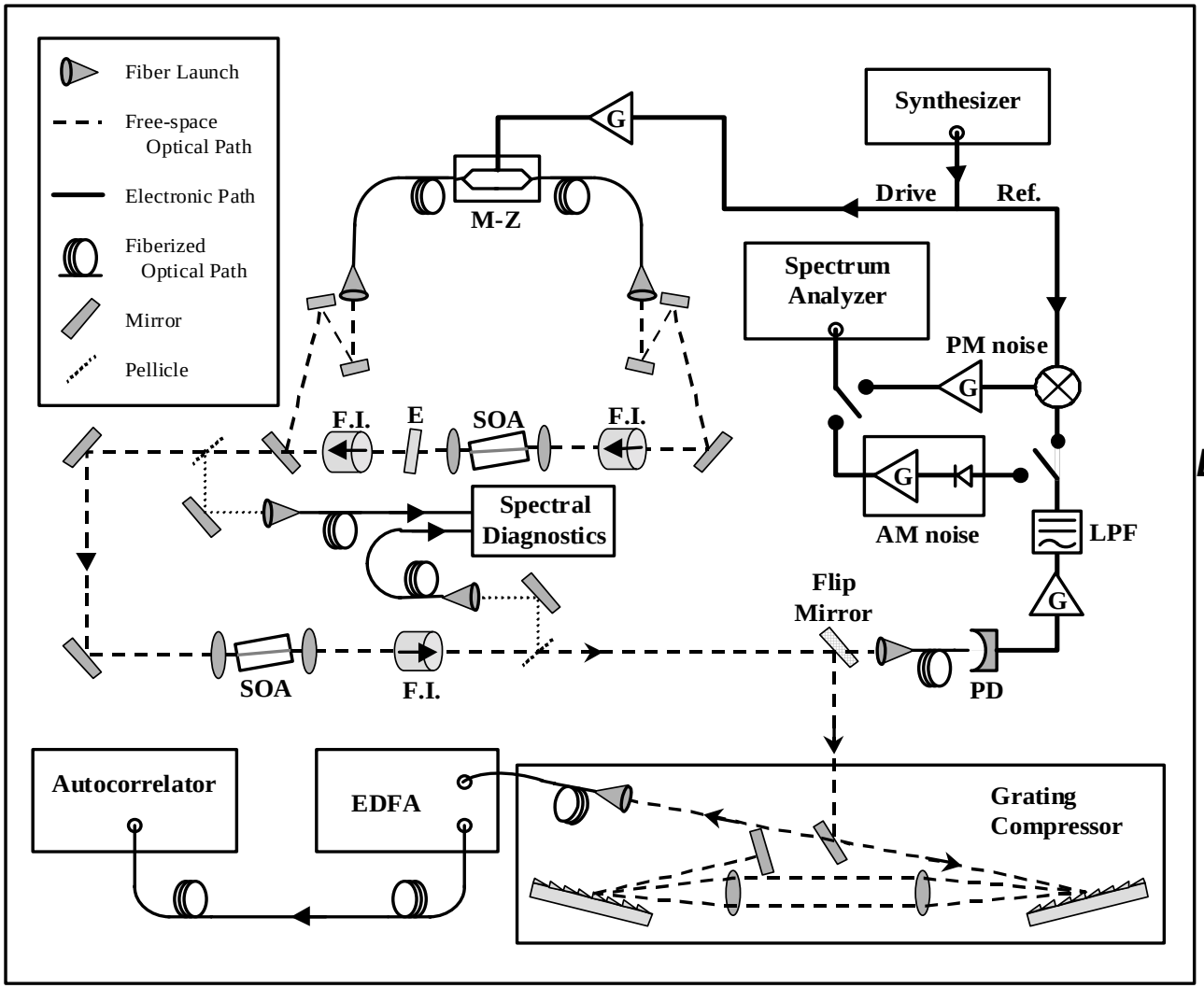
Low-Noise Modelocked Semiconductor Diode Laser

Experimental Setup



Loss modulated; Ring cavity; Dispersion comp.

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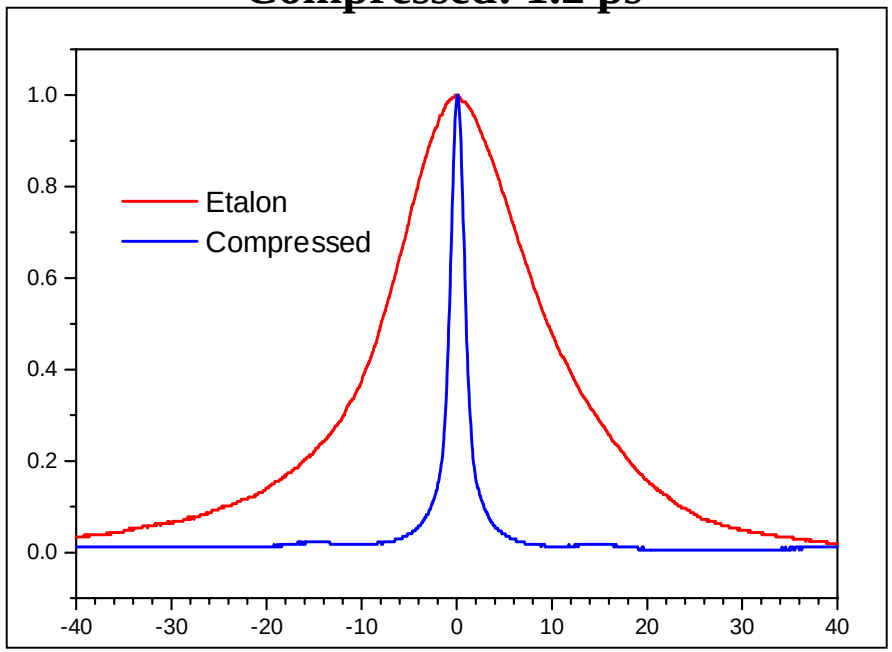
Low-Noise Modelocked Semiconductor Diode Laser

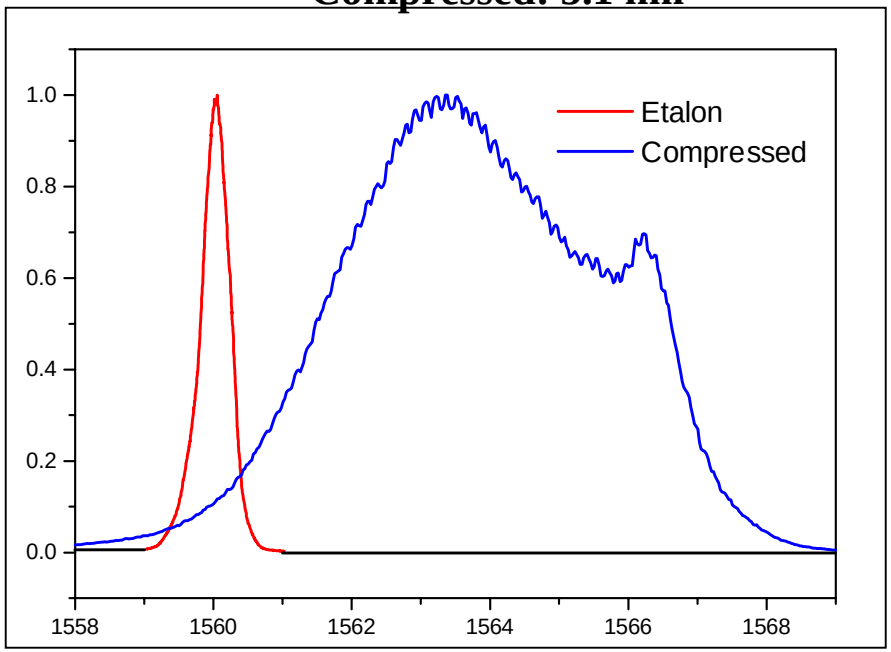
Output Characteristics

Autocorrelation
w/Etalon: 13 ps
Compressed: 1.2 ps



Delay (ps)

Output Spectra
w/Etalon: 0.47 nm
Compressed: 5.1 nm



Wavelength (nm)

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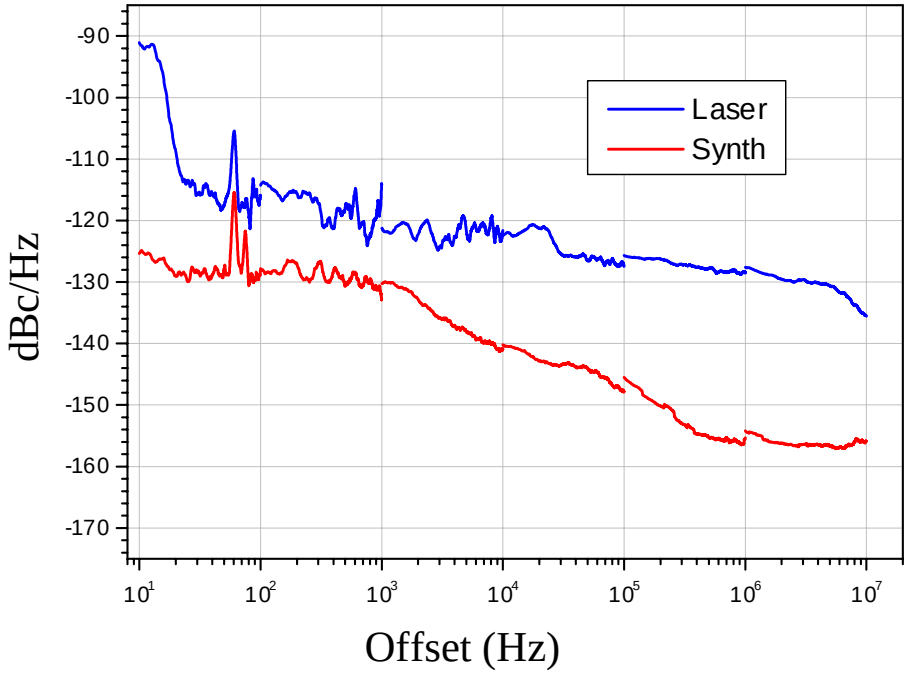
Low-Noise Modelocked Semiconductor Diode Laser

AM & PM Noise Measurements

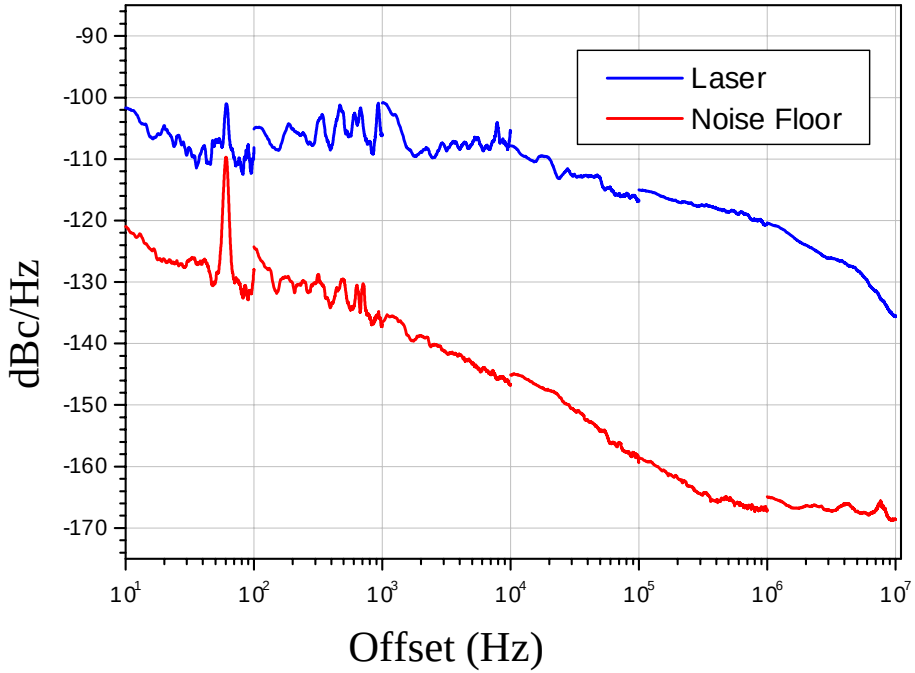
AM Noise Spectrum

(0.12% ; 10 Hz-10MHz)



Residual PM Noise Spectra

(43 fsec; 10 Hz -10 MHz)



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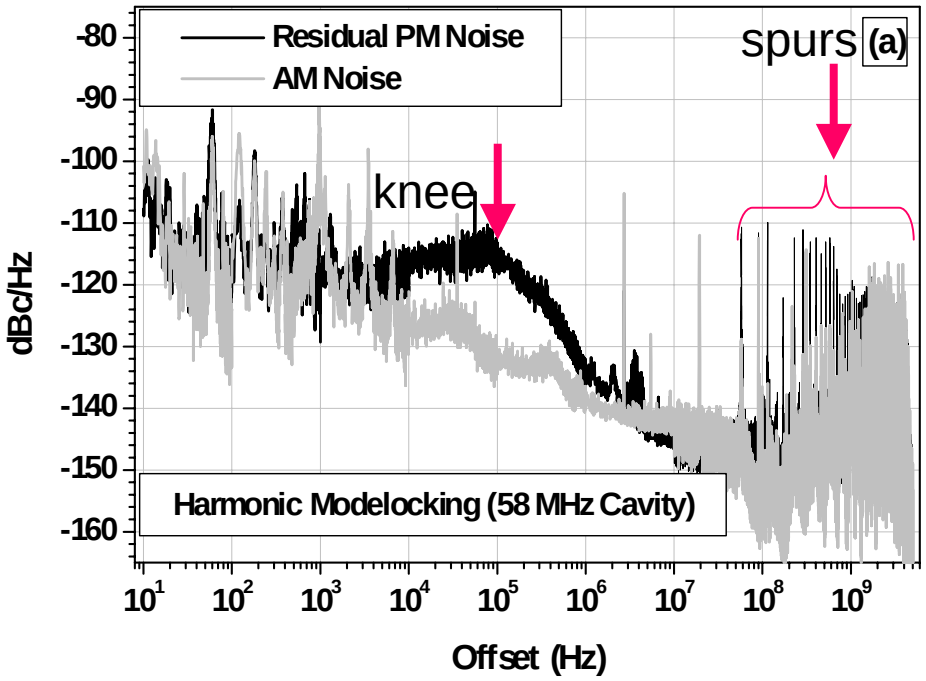
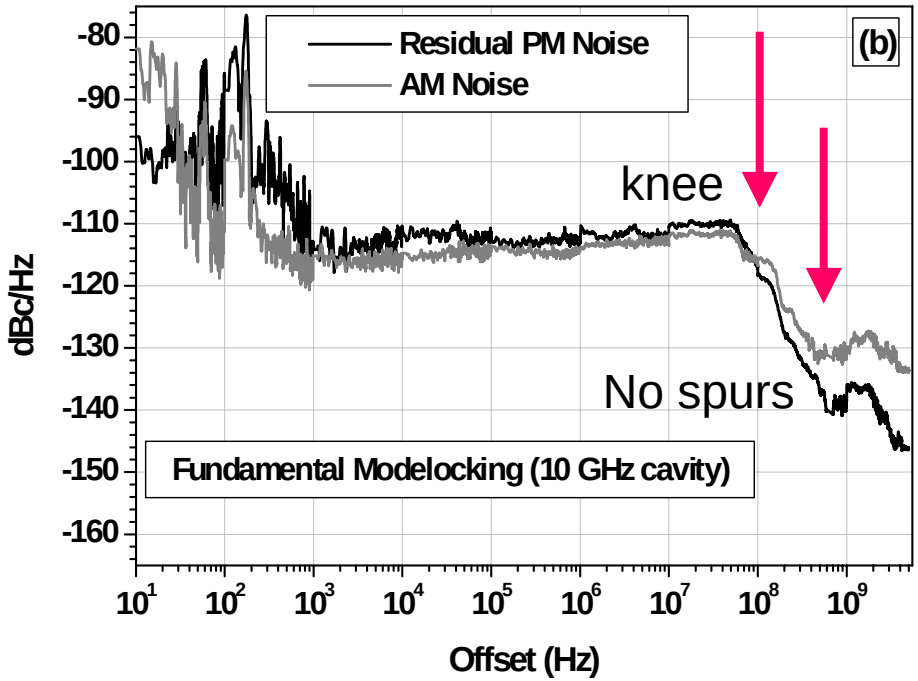
Low Noise Actively Modelocked Semiconductor Optical Clock

AM & PM Noise Spectra

Harmonic Modelocking



Fundamental Modelocking



The Trade-Off:

Close in 'knee' vs. supermode noise
(good) (bad)

Far out 'knee' vs. no supermode noise
(bad) (good)

Can we have the best of both?

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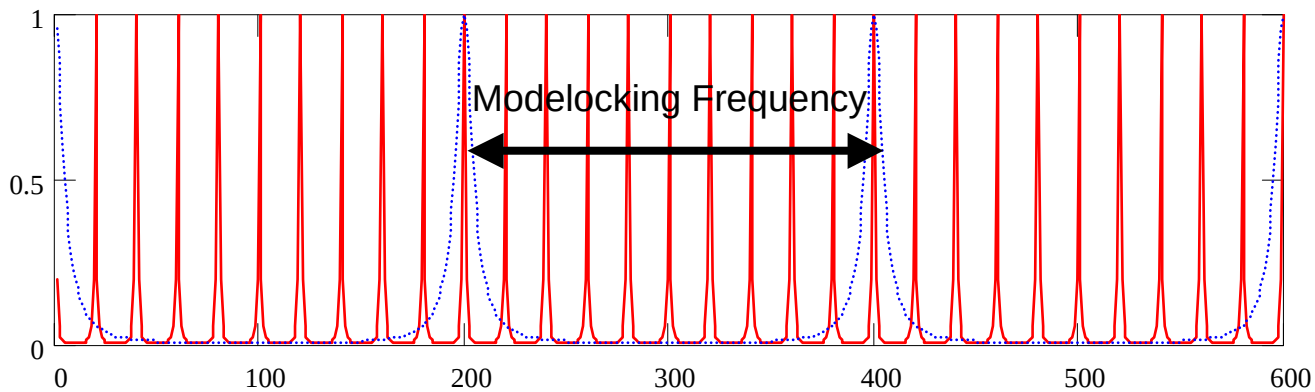
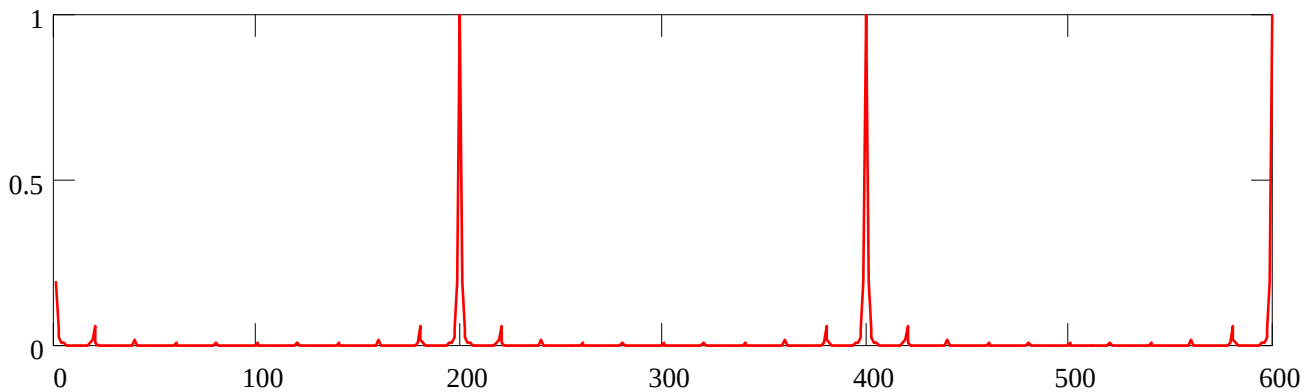
Supermode Noise Suppression

Intracavity Filtering

Cavity Mode Spectrum & Etalon Transmission Function



Cavity Mode Spectrum w FPE FIltering



⇒*Narrow Linewidth and Wide Mode Spacing*

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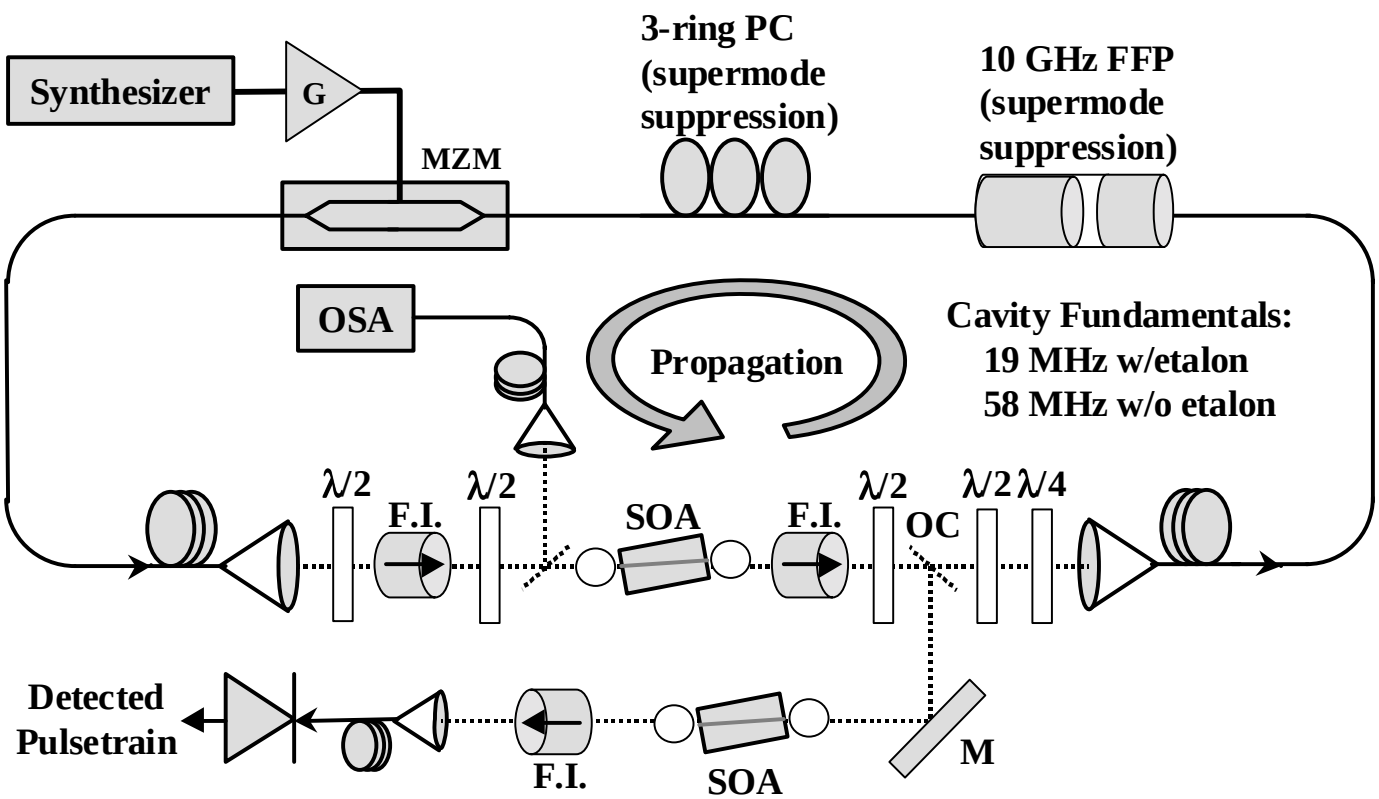
Low Noise Modelocked Semiconductor Optical Clock

Experimental Set-up



Incorporation a mode suppression filter

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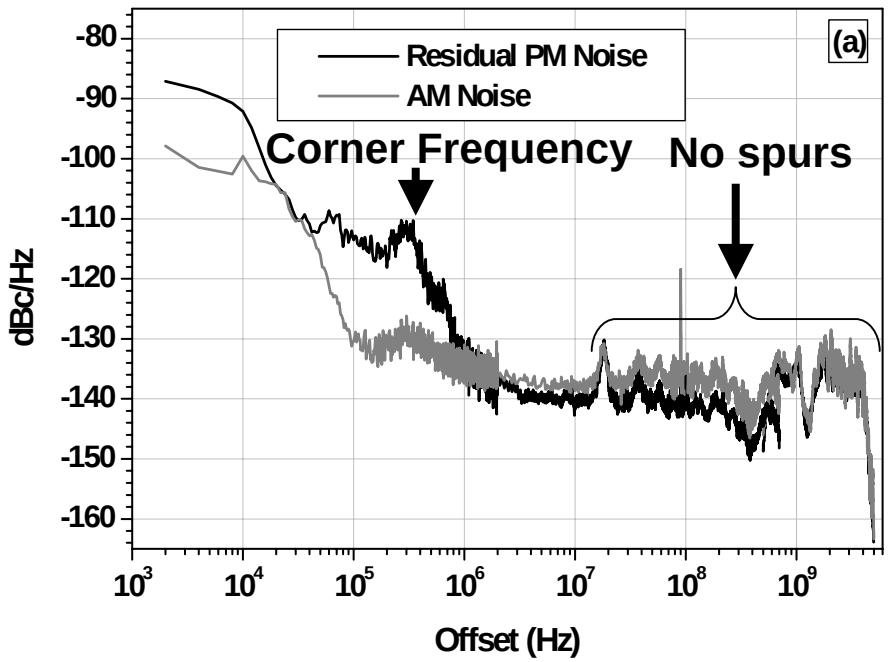
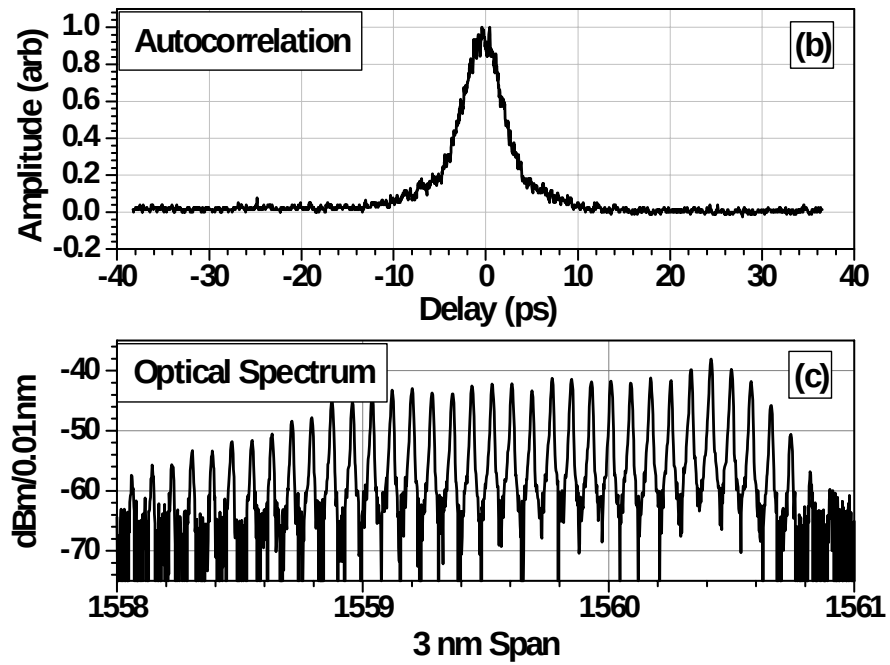
Low Noise Actively Modelocked Semiconductor Optical Clock

Harmonic Modelocking w/ Supermode Noise Suppression

AM & PM Noise



Optical Characteristics



YES!: Achieved Close in Knee AND no supermode noise spurs!

Jitter: 35 fsec AM Noise: 0.05% (10 Hz – 10 MHz)

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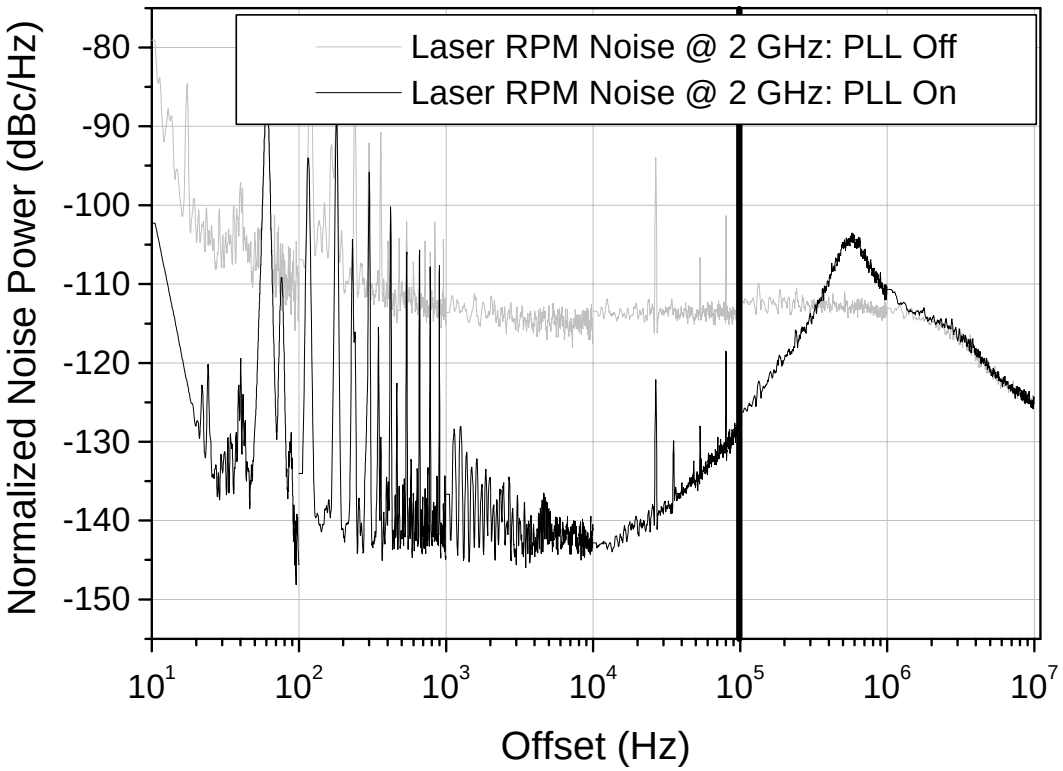
Timing Stabilization of Modelocked Diode Laser

Voltage Controlled Phase Shifter



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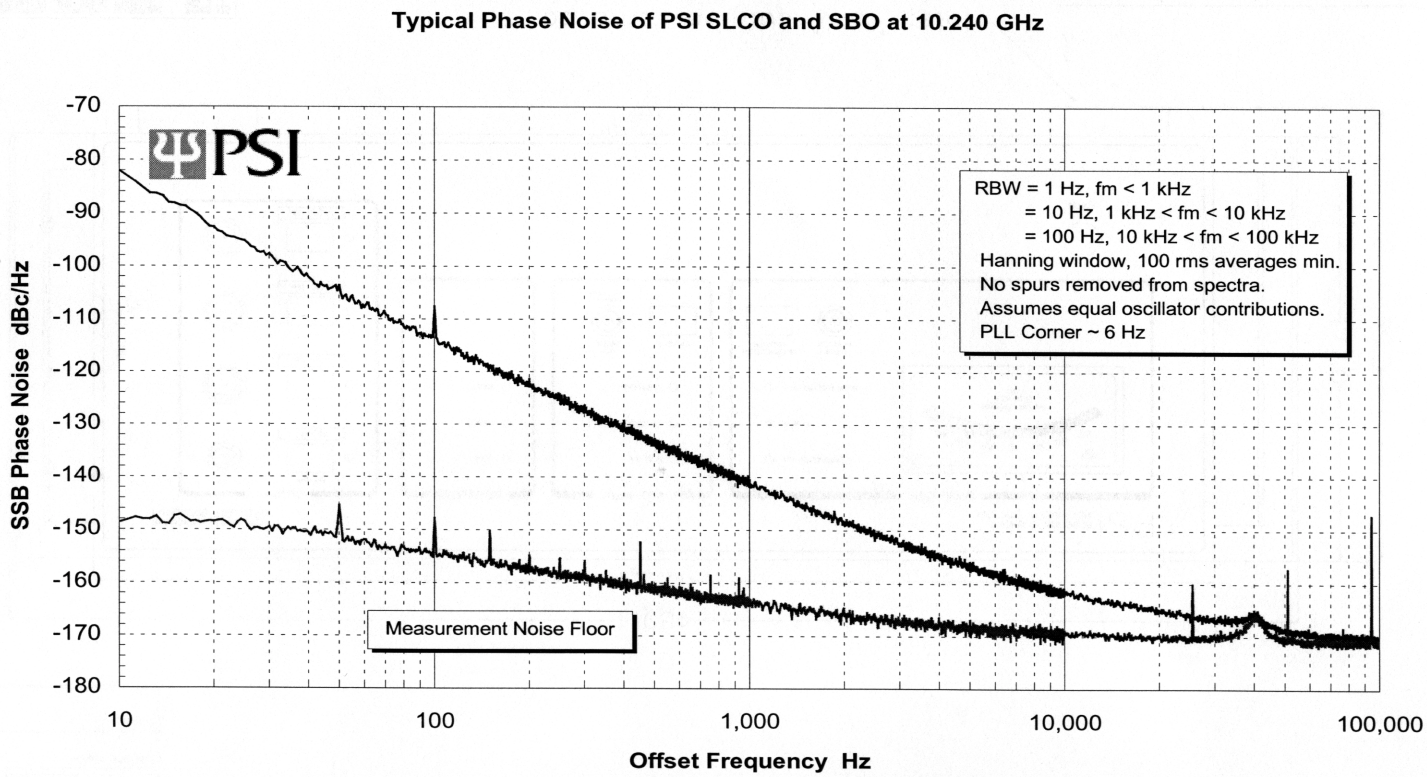
Low – Noise Frequency Oscillator

Poseidon Oscillator



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Filter Technology

Hyperfine WDM DeMux
Essex Corporation

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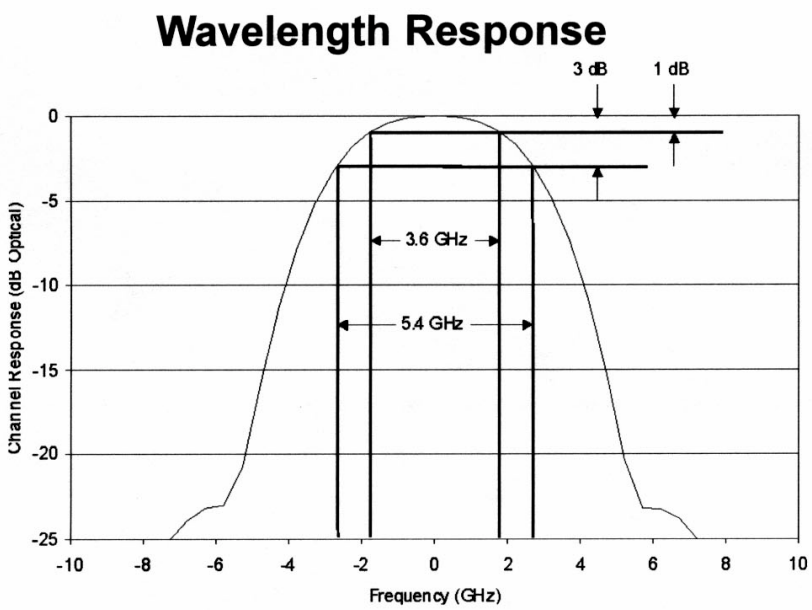
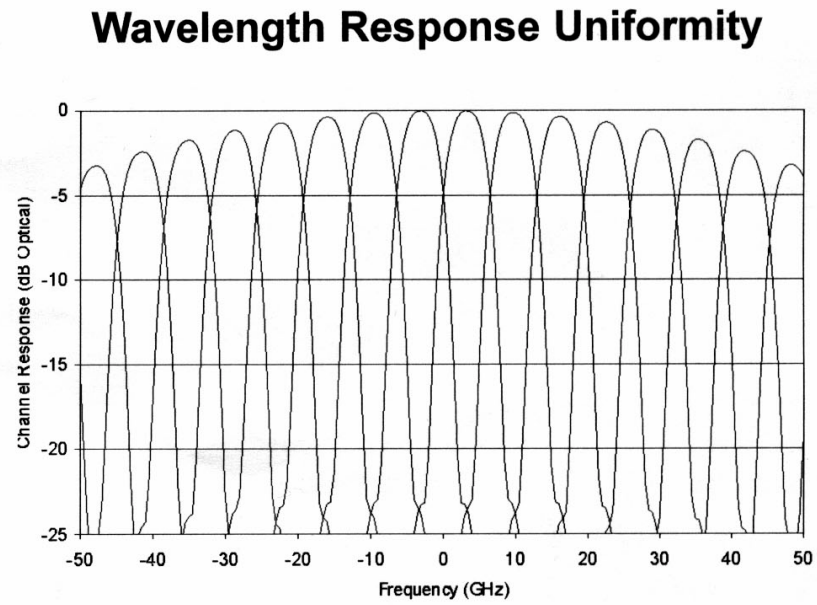
DWDM Filter Characteristics

Essex Corporation





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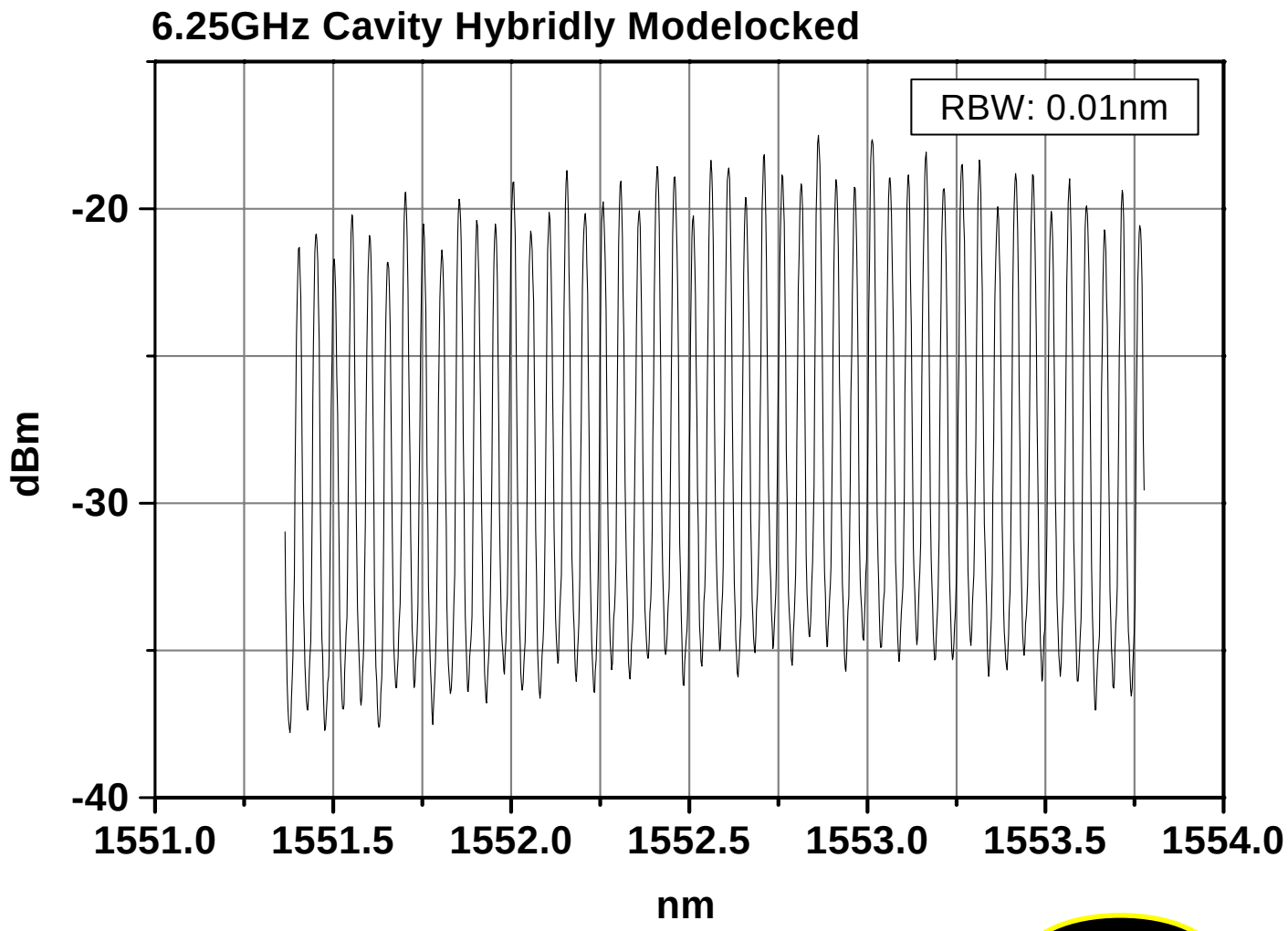
Coherent Comb Generator



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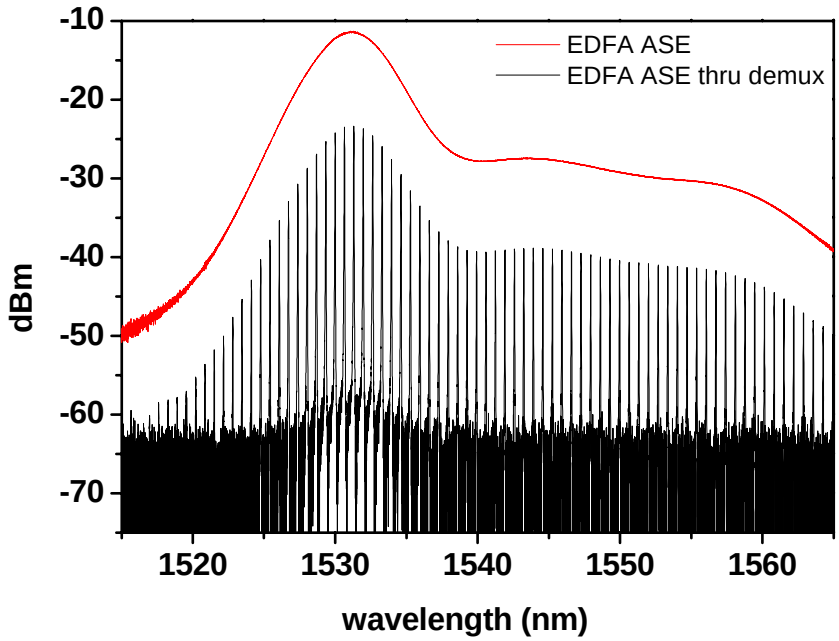
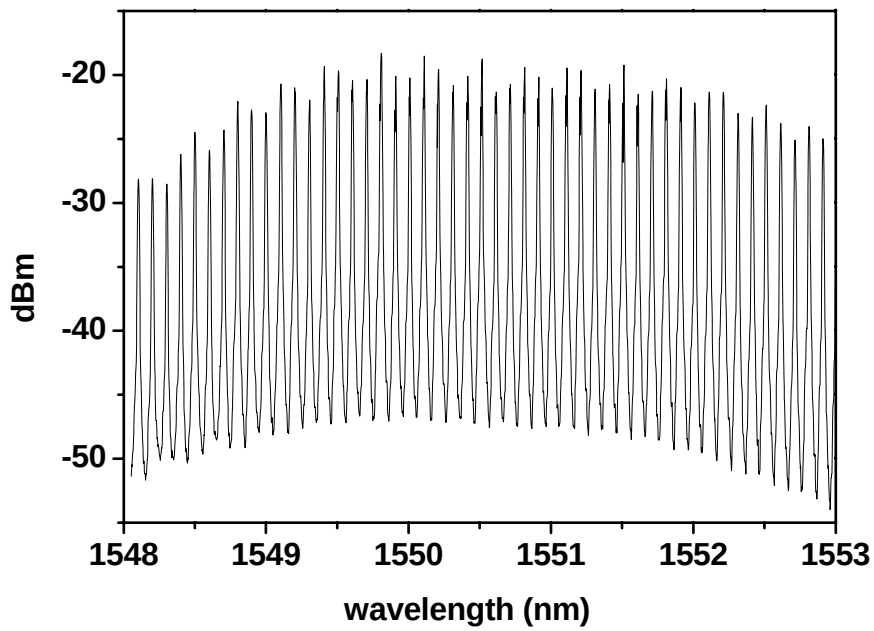
Demux Filter Characteristics

Essex Corp. Demux Single Channel Throughput



12.5GHz Fundamentally Modelocked Optical Spectrum



- **6.25GHz channel spacing**
- **12 channels**
- **foldover at 75GHz periodicity**

~40 longitudinal modes within 3dB bandwidth

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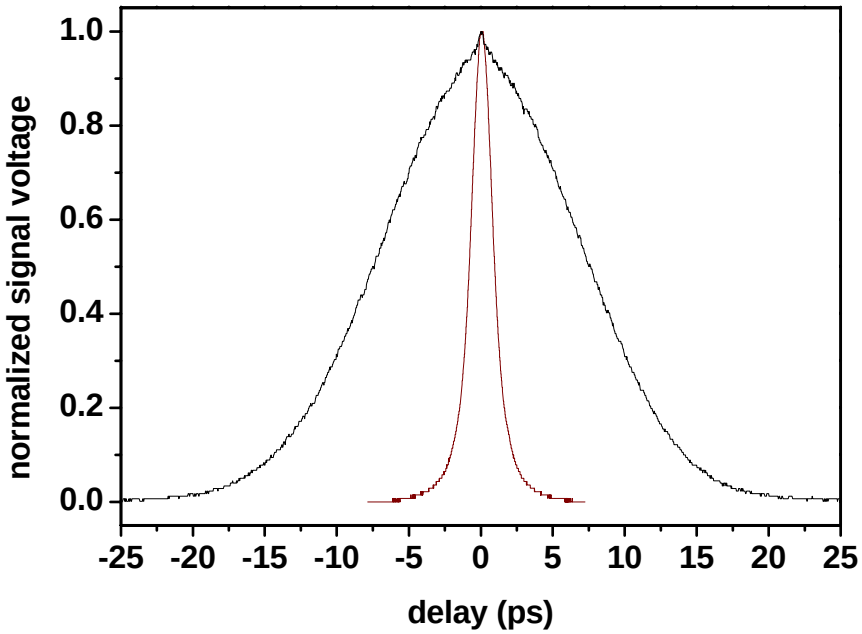
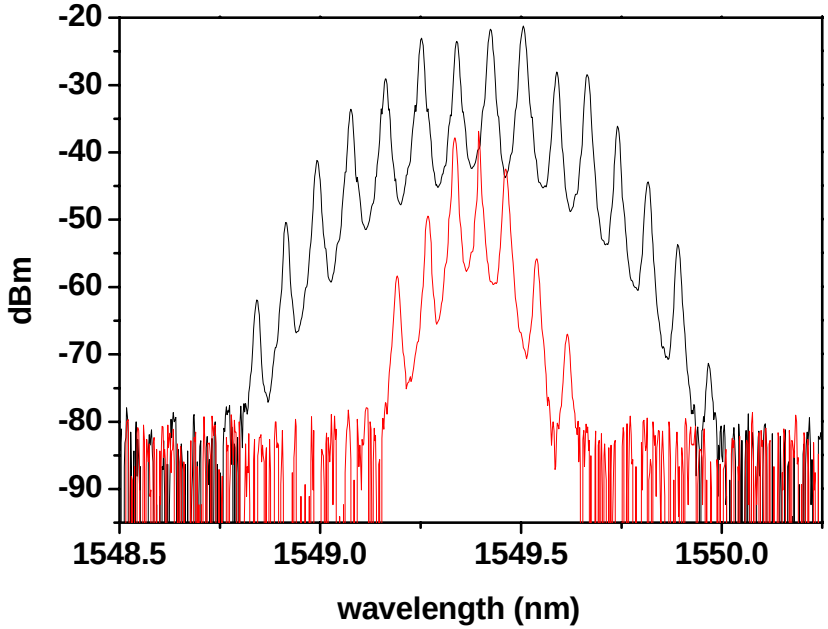
Dispersion Compensator/Pre-filter

Before and After Dispersion Compensation



pulsewidth: 11ps compressed to 1.25ps (deconvolved)

Changing Fourier Plane Slit Width



resolution spot ~50GHz

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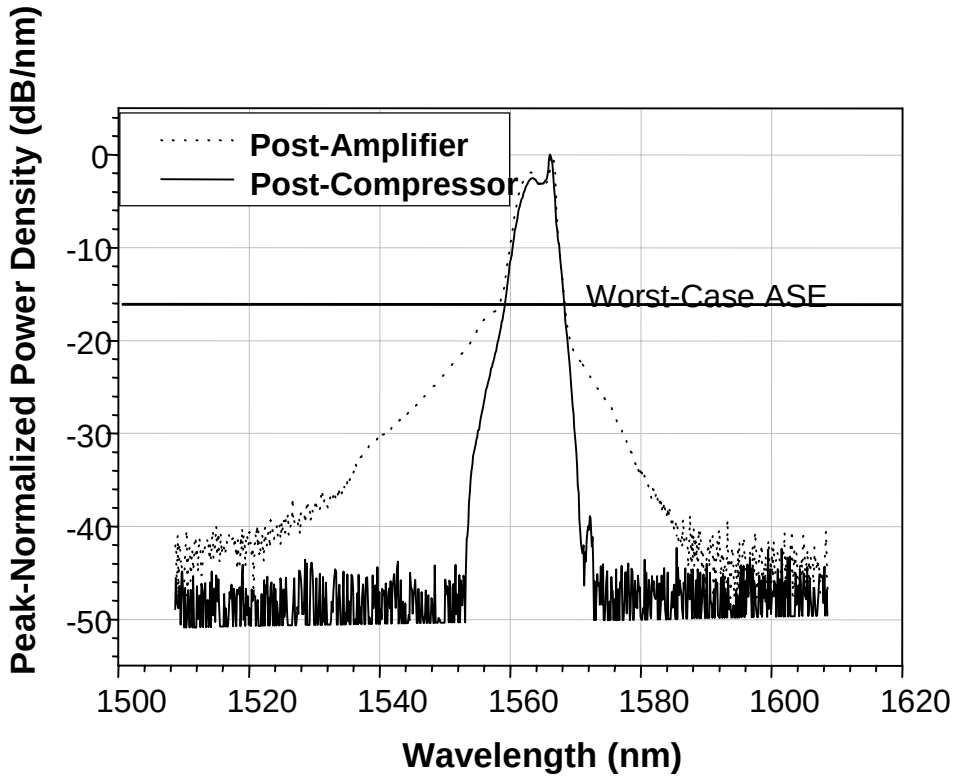
High Contrast Amplified Modelocked Diode Laser



Peak-normalized optical spectra of modelocked pulsetrain before and after ASE spectral filtering.

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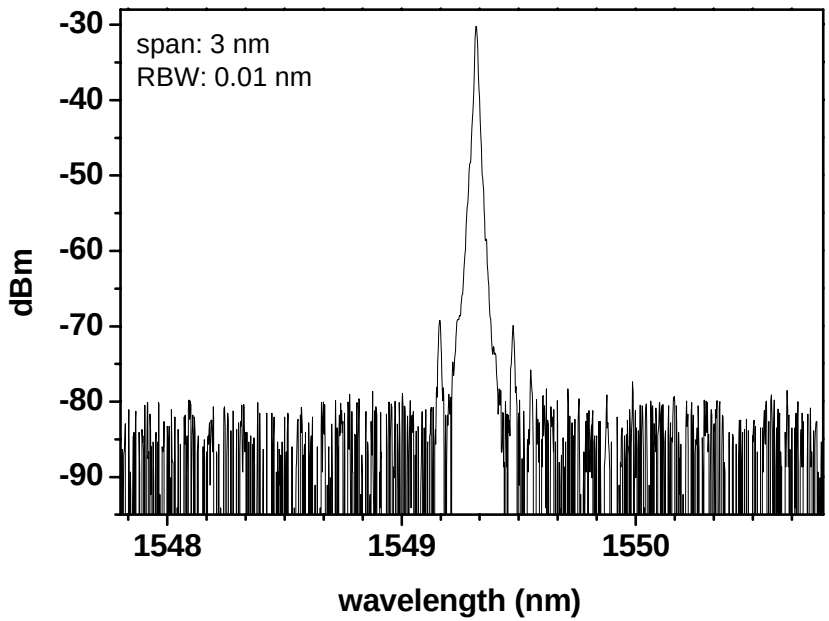
Optical Spectra After Filtering

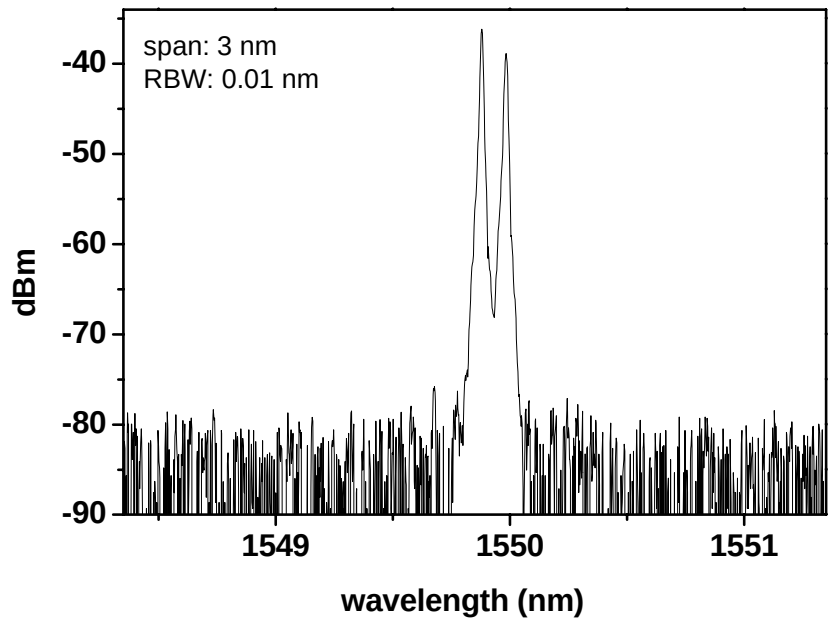
12.5GHz Fundamental Modelocking

Single Demux Channel



40dB SNR

2 Demux Channels Spaced at 12.5GHz



adjacent modelocked laser longitudinal modes

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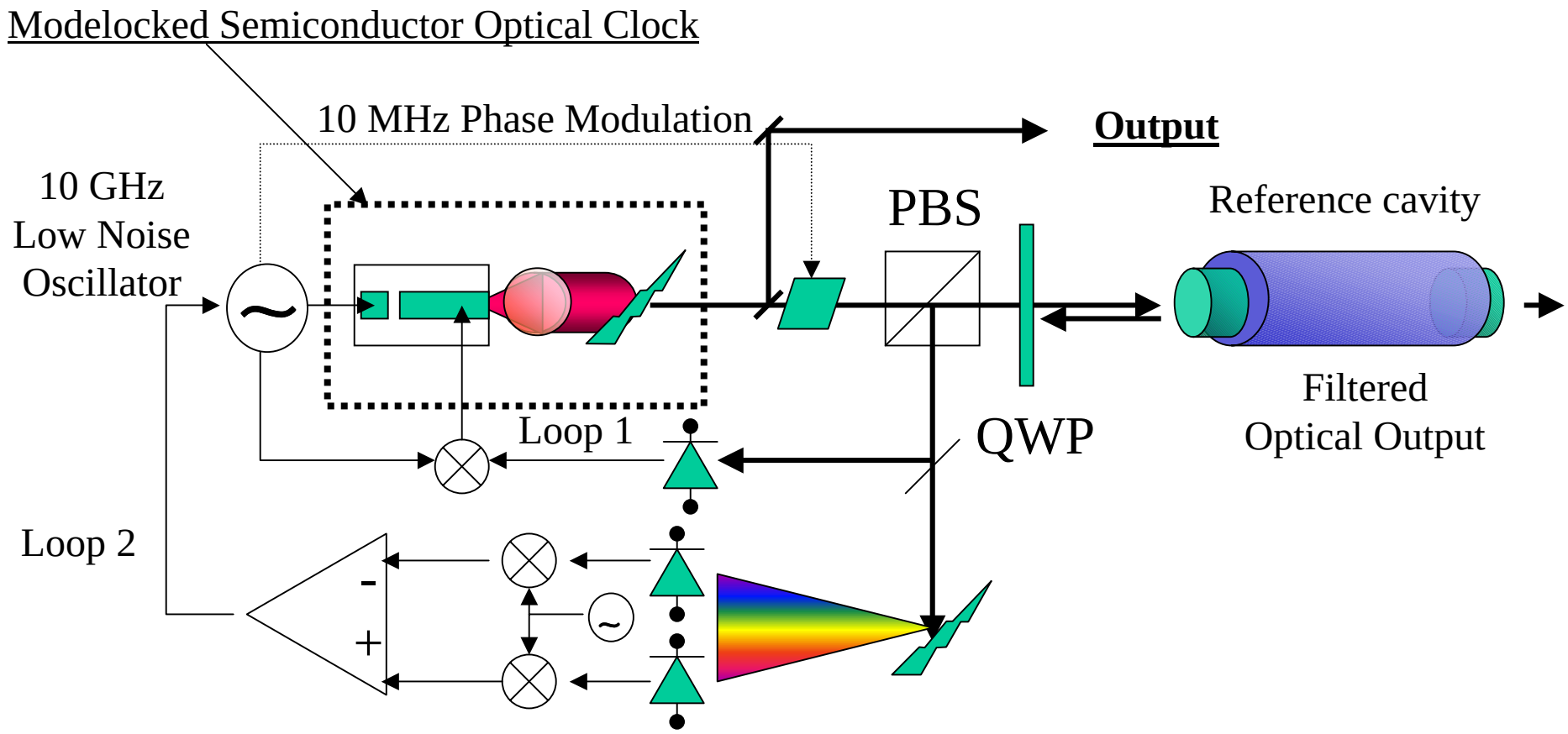
Stabilized Modelocked Optical Clock

PDH Technique



Control Loop 1 locks the average optical frequency to reference cavity via Pound-Drever Hall
Control Loop 2 locks the mode spacing to the reference cavity

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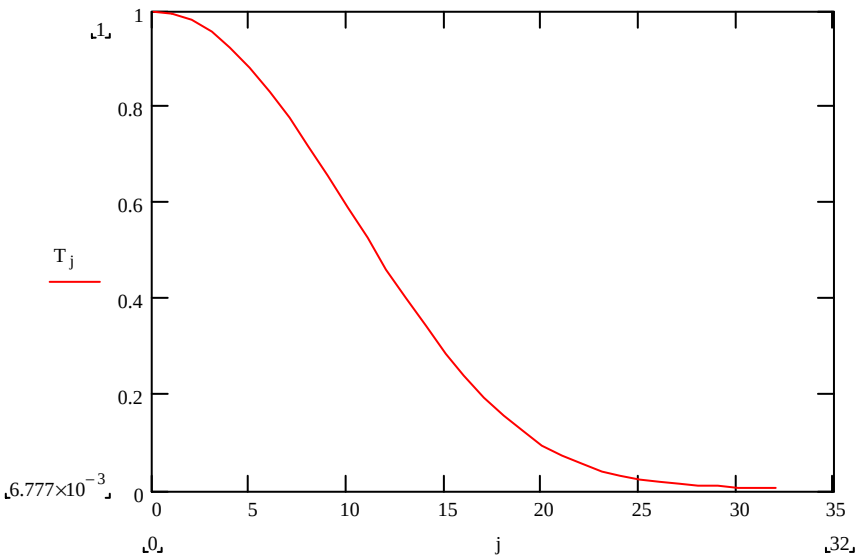
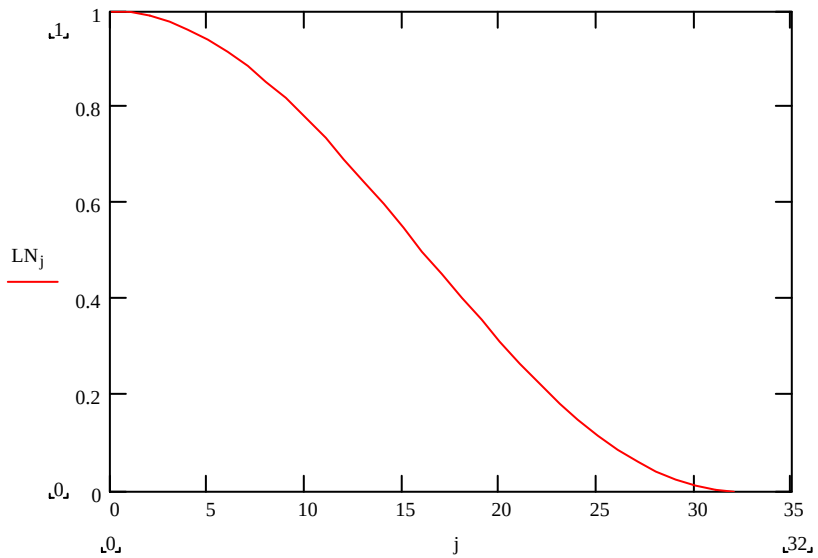
PAWG Modulator Technology

Semiconductor Electro-absorption



Mach-Zehnder $LiNbO_3$



Potential for full scale integration

Readily available

Linearity of EA modulation
Choose absorption edge to be Lorentzian
Absorption edge varies as applied voltage squared
Transmittance goes as exp(-aL)

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Modulator Technology

Electro-absorption & Electro-refractive Modulators
Sarnoff Corporation

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Preliminary Results

- Photonic arbitrary waveform generator (PAWG) setup
- 6.25 GHz channel spacing demultiplexer
- Photonic RF sine wave synthesis
- Arbitrary waveform generation
- Conclusions

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Photonic Arbitrary Waveform Generator

- Our photonic arbitrary waveform generator (PAWG) builds on our low timing jitter performance of modelocked semiconductor diode lasers

<u>The PAWG is capable of the following performance:</u>

- Photonically synthesized, low noise RF tones, from 12.5 GHz to 100 GHz, with a dynamic range of 50 dB at a resolution bandwidth of 100 Hz.

- The generation of complex arbitrarily generated modulation on optical carriers (converted to arbitrary RF waveforms via photodetection) with instantaneous bandwidths up to 100 GHz (total comb bandwidth: 625 GHz), using low frequency drive electronics at 12.5 GHz and lower.

- The complex waveforms can be updated every 80 ps (12.5 GHz)

- The capability of transform limited, ultralow timing jitter (~ 35 fs, 10 Hz-10 MHz), 1 ps pulse trains at 12.5 GHz repetition rate.

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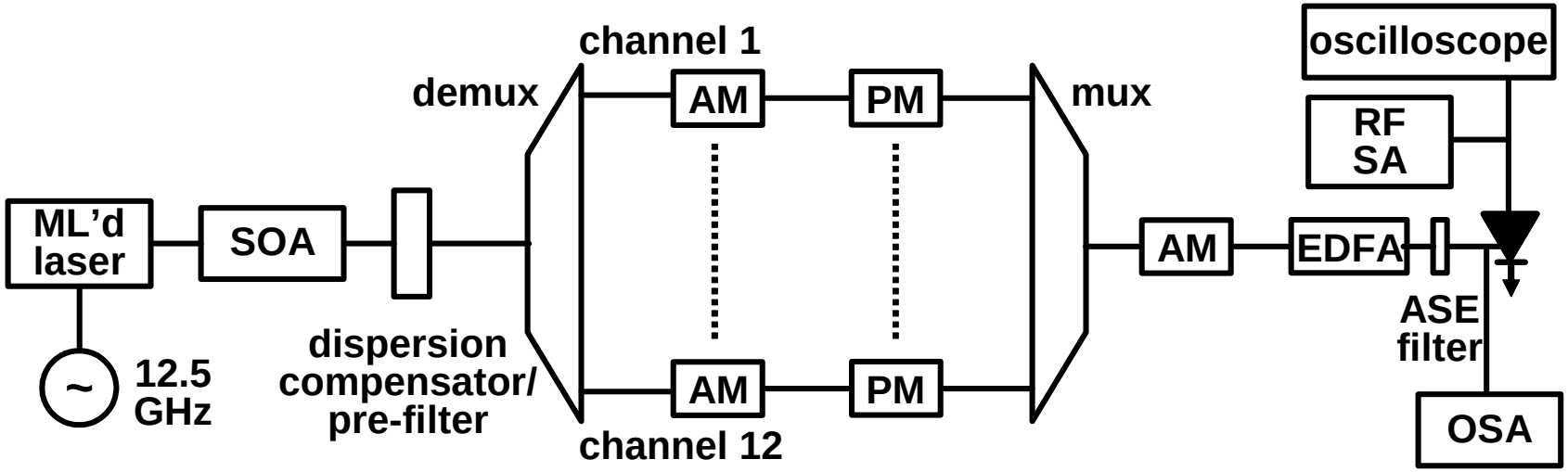
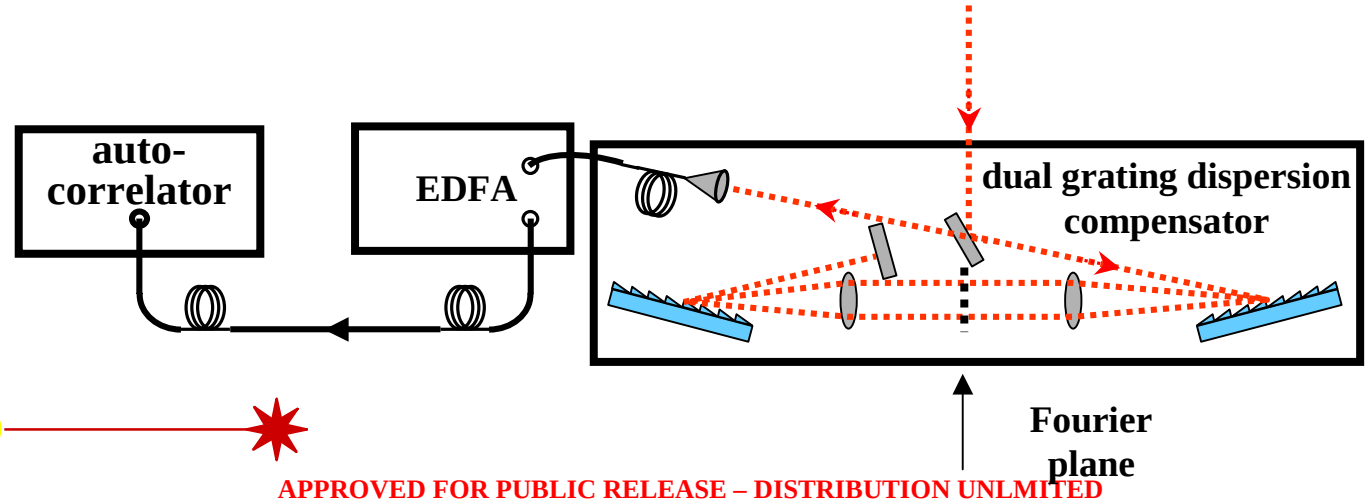
Photonic Arbitrary Waveform Generator

Experimental Setup



dispersion compensator/pre-filter



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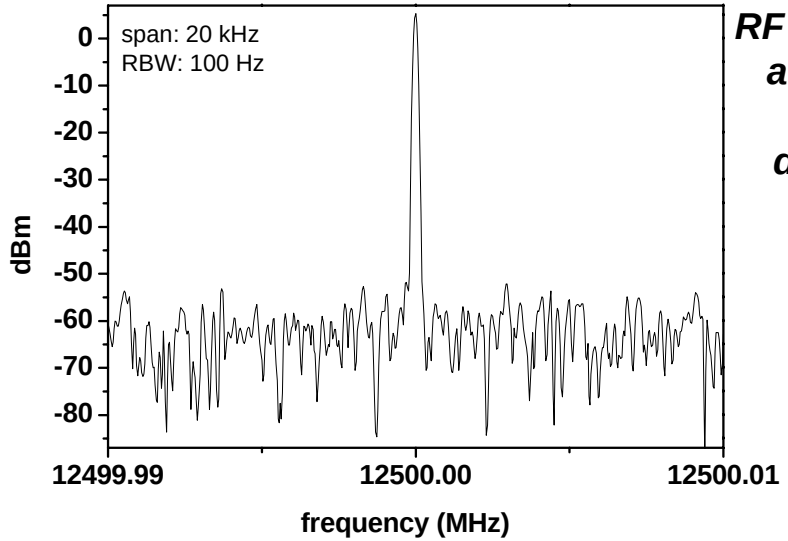
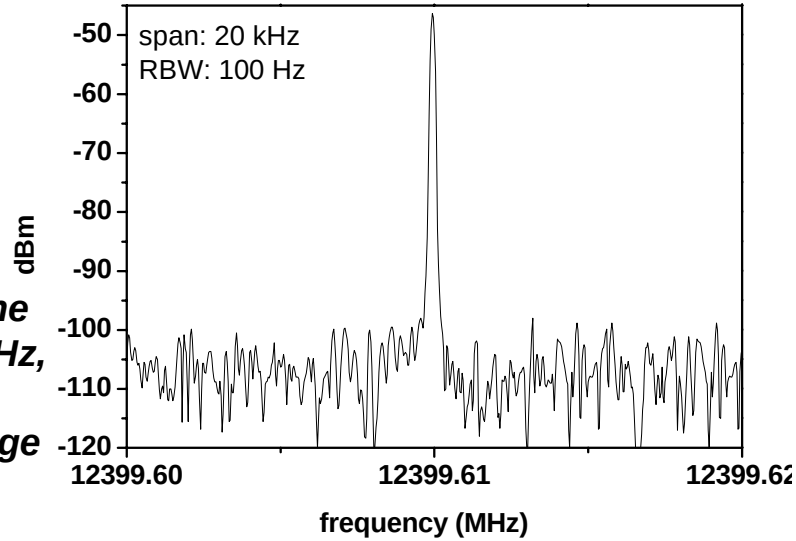
Photonic Synthesizer

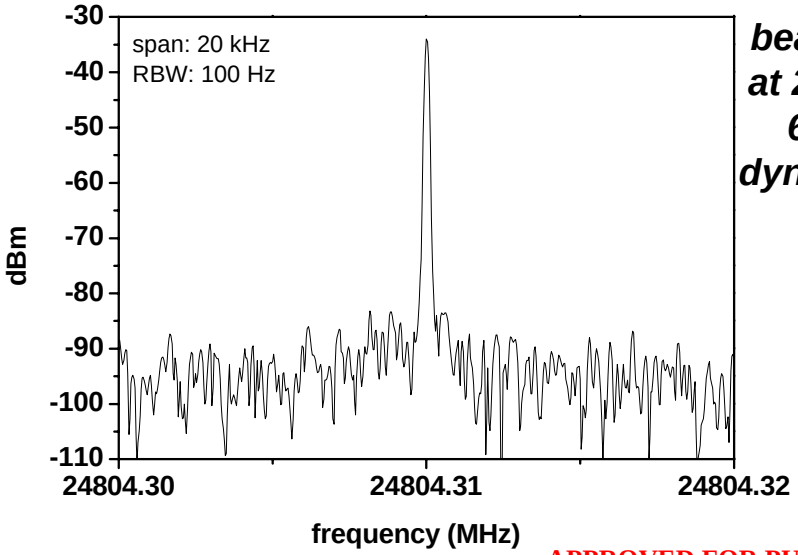
2-Channel-Beat RF Spectra



RF synthesizer at 12.5GHz, 65dB dyn. range

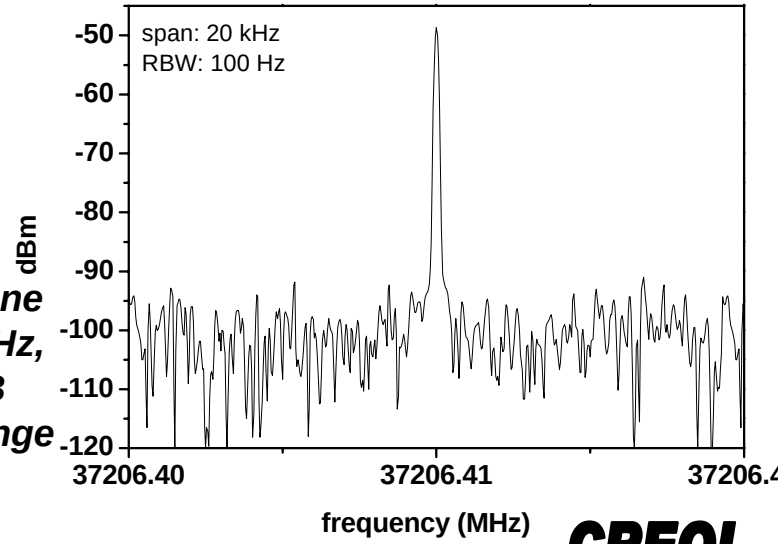
beat tone at 12.5GHz, 60dB dyn. range





beat tone at 25GHz, 60dB dyn. range

beat tone at 37GHz, 52dB dyn. range



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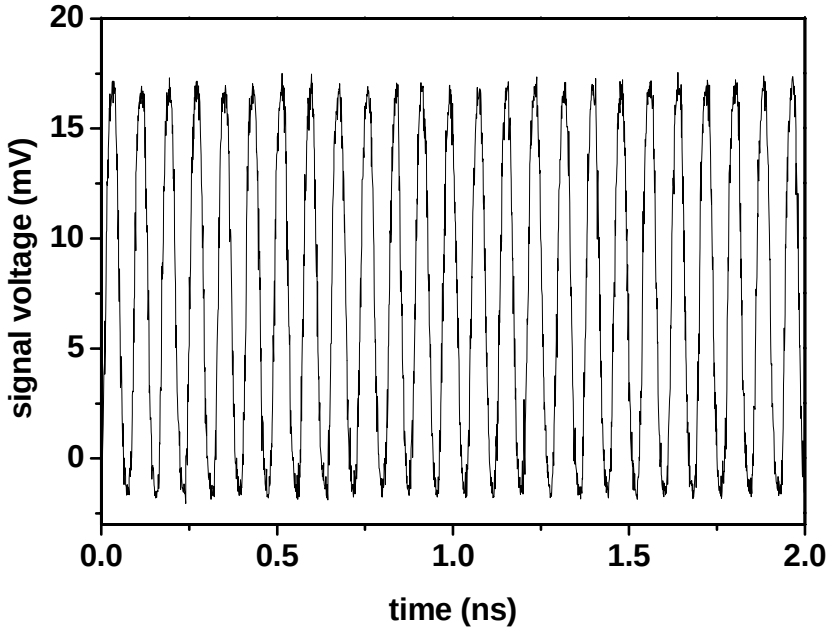
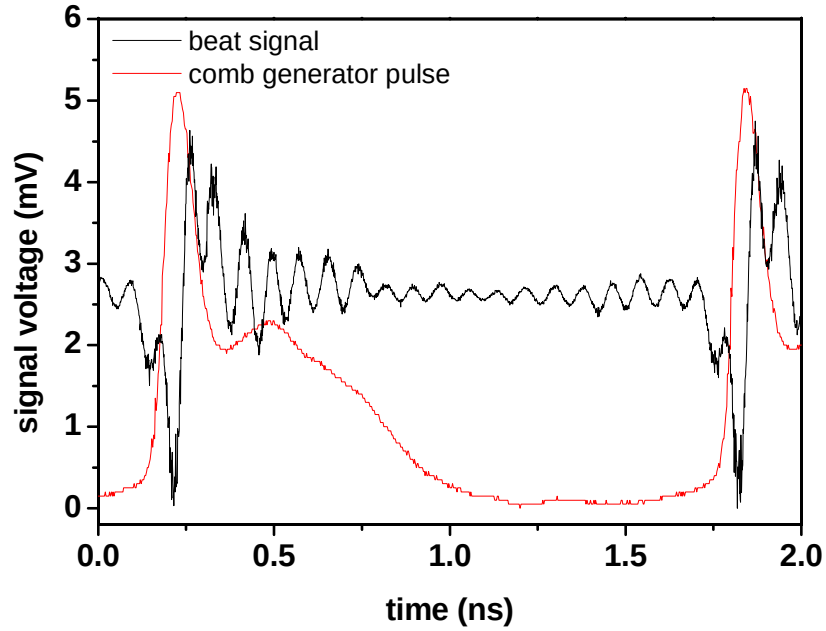
Photonic Synthesizer

2-Channel-Beat Time Domain Traces

12.5GHz Beat Note



12.5GHz Beat Note Modulated at 625 MHz with a Comb Generator Driving MZ Modulator



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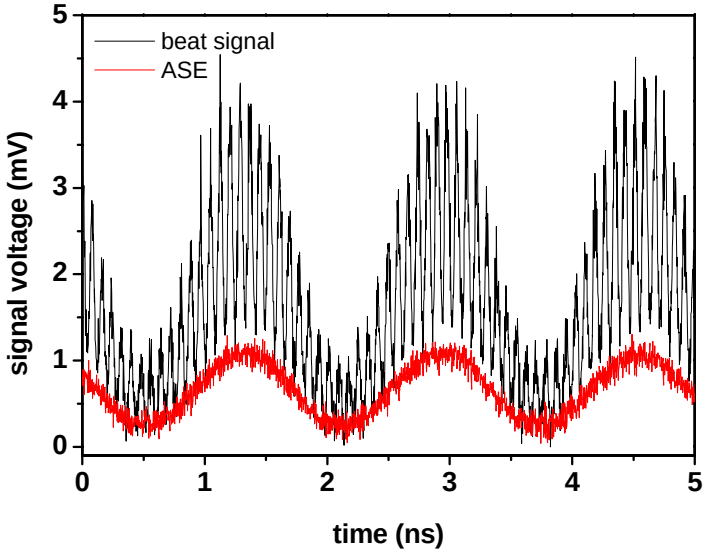
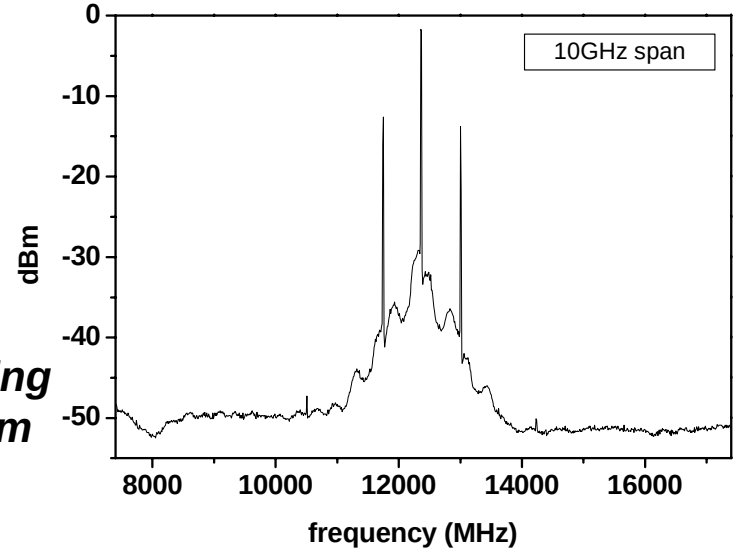
Photonic Arbitrary Waveform Generator

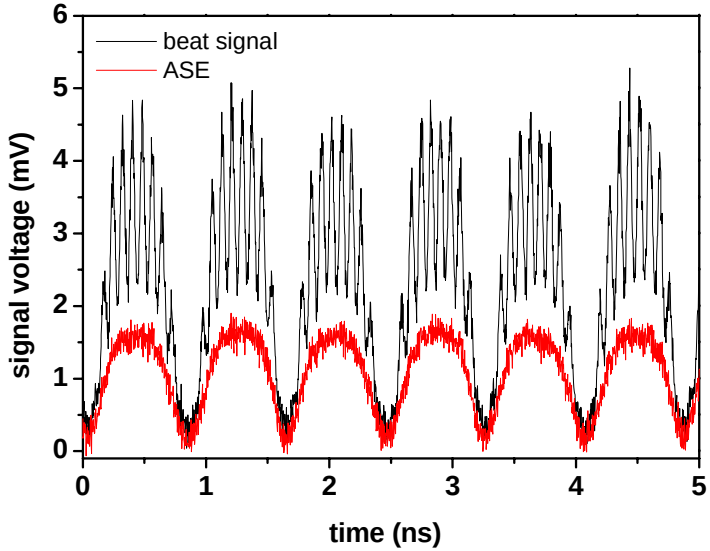
Modulated 2-Channel-Beat



12.5GHz Beat Note Modulated at 625 MHz at MZ Quad.

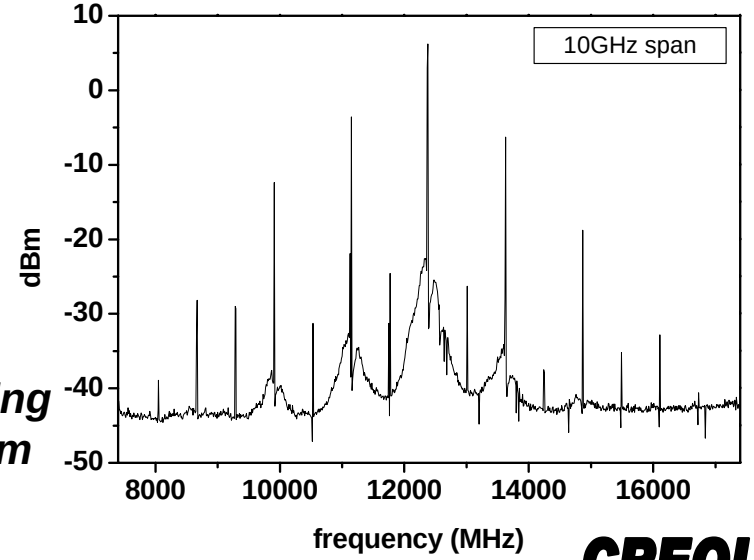
Corresponding RF Spectrum





12.5GHz Beat Note Modulated at 625 MHz at MZ Min.

Corresponding RF Spectrum



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Summary

- Extending low noise performance of modelocked diode laser to produce a comb of orthogonal Fourier components
- Control intensity and phase using electro-absorption & electro-refractive modulators → chip scale integration
- Modelocked laser longitudinal mode filtering with 40dB SNR
- Photonic RF sine wave synthesis with low noise (60 dB w/ 100 Hz RBW → > 80 dBc/Hz)
- Arbitrary waveform generation using intensity modulation

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