Phase-Lock Techniques for Phase and Frequency Control of Semiconductor Lasers

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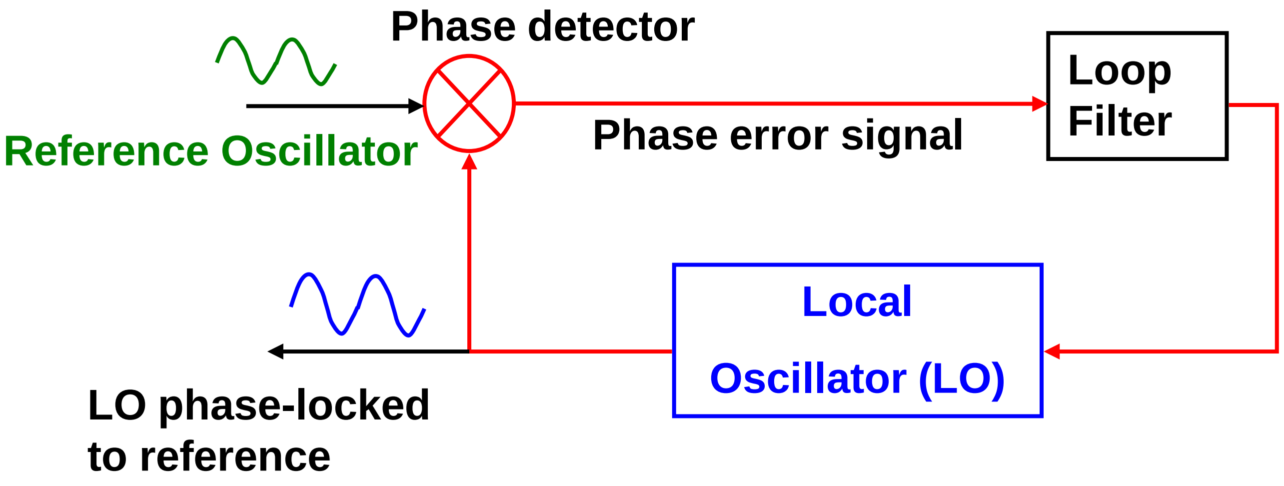
Outline

- Semiconductor Laser Optical Phase-Lock Loops
- Coherence Cloning
- Coherent Power Combination
- Broadband Swept-Frequency Sources
- Chirp Multiplication using Four-Wave Mixing

What is a Phase-Lock Loop?



Phase detector

Reference Oscillator

Phase error signal

Loop Filter

Local Oscillator (LO)

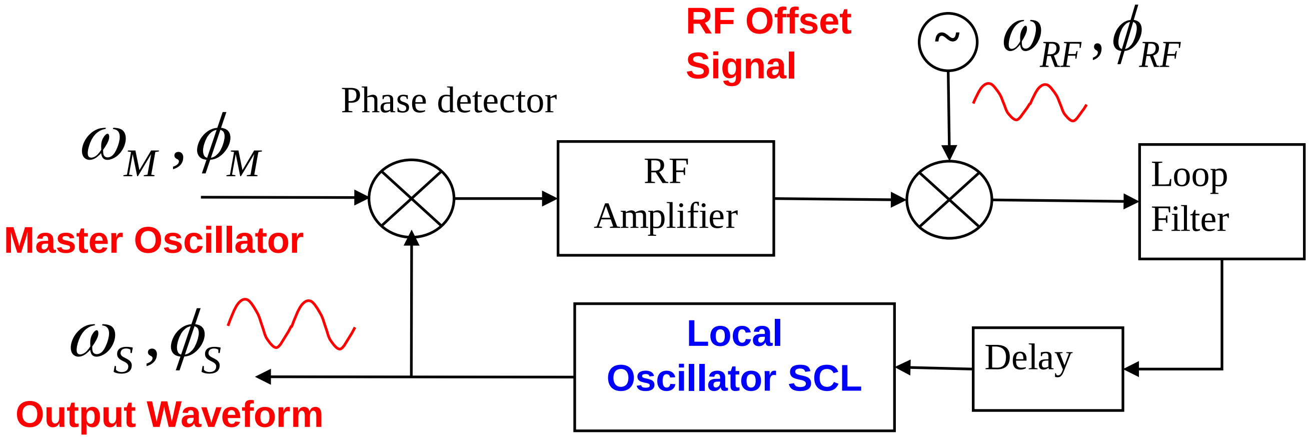
LO phase-locked to reference

A **PLL** is a negative feedback control system that forces the LO to track the frequency and phase of the reference signal when in lock

Key elements: Phase detector, voltage controlled oscillator

RF Offset in a heterodyne loop (not shown) can provide additional control over LO phase and frequency

OPLL basics



RF Offset Signal

ω_{RF}, ϕ_{RF}

Phase detector

ω_M, ϕ_M

RF Amplifier

Loop Filter

Master Oscillator

ω_S, ϕ_S

Local Oscillator SCL

Delay

Output Waveform

$$\omega_S = \omega_M + \omega_{RF} \qquad \phi_S = \phi_M + \phi_{RF}$$

PLL Building Blocks	
Electronic PLL	Optical PLL (OPLL)
Phase Detector (Mixer)	Photodetector
Voltage Controlled Oscillator (VCO)	Semiconductor Laser (Current Controlled Oscillator)

A. Yariv, Opt. Lett. 30, pp2191, 2006

RF Electronic PLLs are ubiquitous

PLL history

- Developed in 1930s
- PLL IC, 1965
- Digital PLL, 1970

Clock Recovery

- Data retrieval from disk drives

Clock Generation

- Up-conversion of low frequency clock to generate clock for high speed processors

Wireless communication systems

- Generation of LOs for frequency up/down conversion
- AM/FM demodulation

- Clock Distribution and jitter compensation in ICs
- Lock-in measurements for noisy environments

Phase-Lock Optics

Key applications enabled by phase-lock optics

Optical communication – utilize both phase and intensity of the optical wave

- **Superior utilization of available bandwidth in high speed networks**
- **Robust modulation formats**

Coherence Cloning – Sensor networks

Phase Controlled Apertures

- **Coherent power combination**
- **Optical phased arrays – rapid beam steering, adaptive optics**

Swept Frequency Lasers – electronically controllable chirp

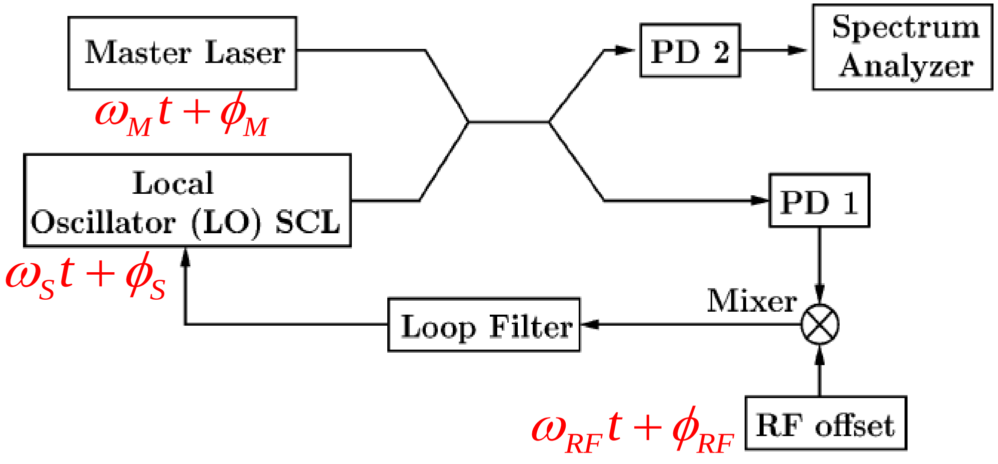
- **Optical Ranging and LIDAR**
- **3D imaging and biometrics**
- **Optical Coherence Tomography and biomedical imaging**
- **Arbitrary waveform generation**

RF and Terahertz Photonics

- **Generation and transmission of RF/THz signals on optical carriers**
- **Swept THz sources for imaging / detection / spectroscopy**

Phase locking of commercial SCLs

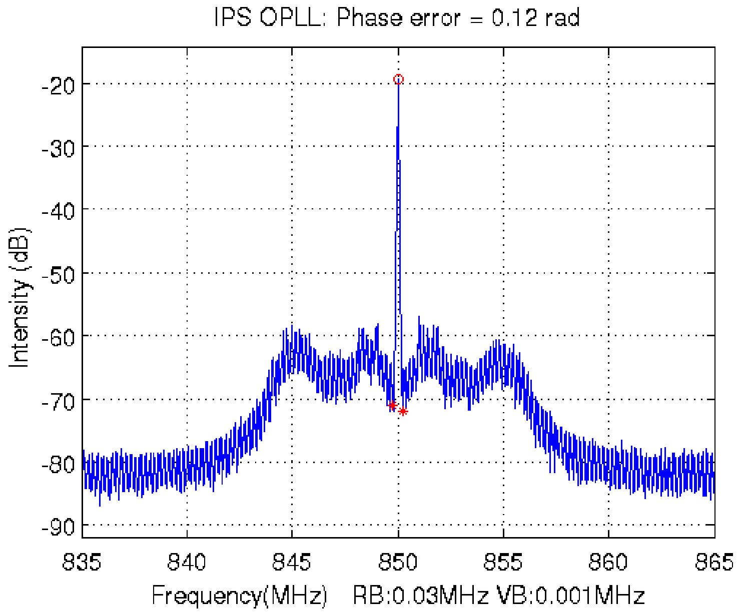
Heterodyne OPLL



$$\omega_S = \omega_M + \omega_{RF}\,,\;\; \phi_S = \phi_M + \phi_{RF}$$

Power spectrum of locked beat signal

Slave laser: Commercially available SCL
Master laser: High quality fiber laser



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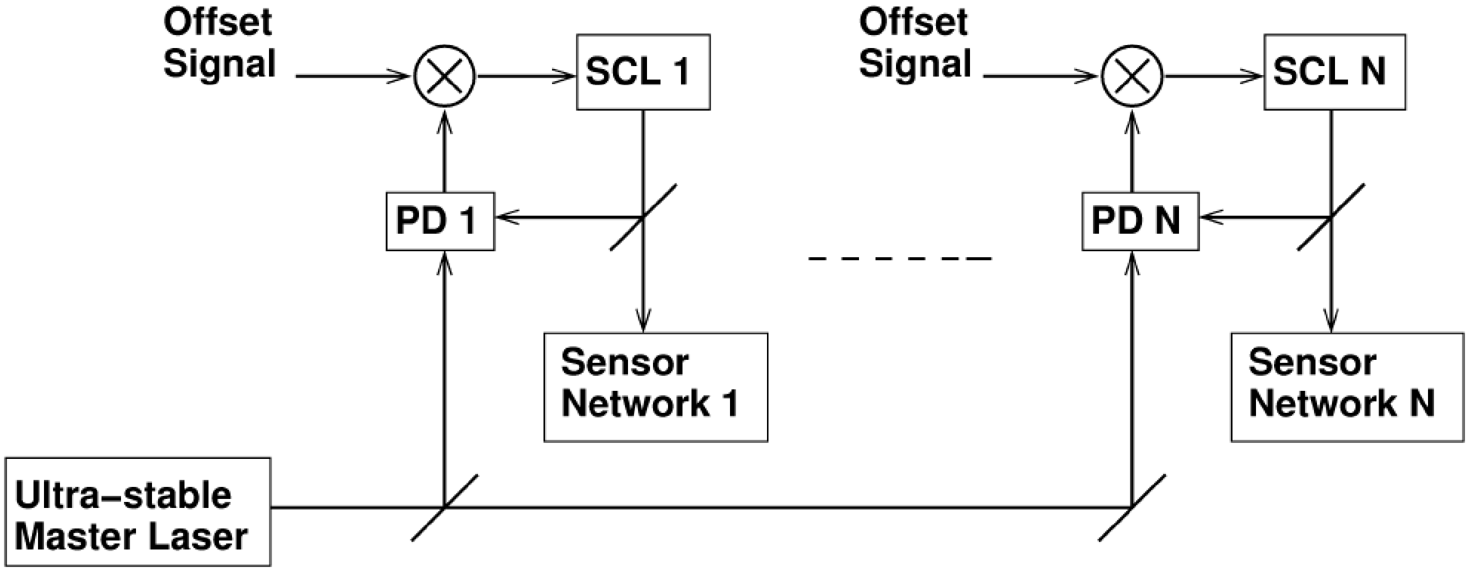
Coherence cloning with OPLLs

Transfer coherence from high quality expensive fiber laser/solid state laser to a number of inexpensive SCLs using OPLLs

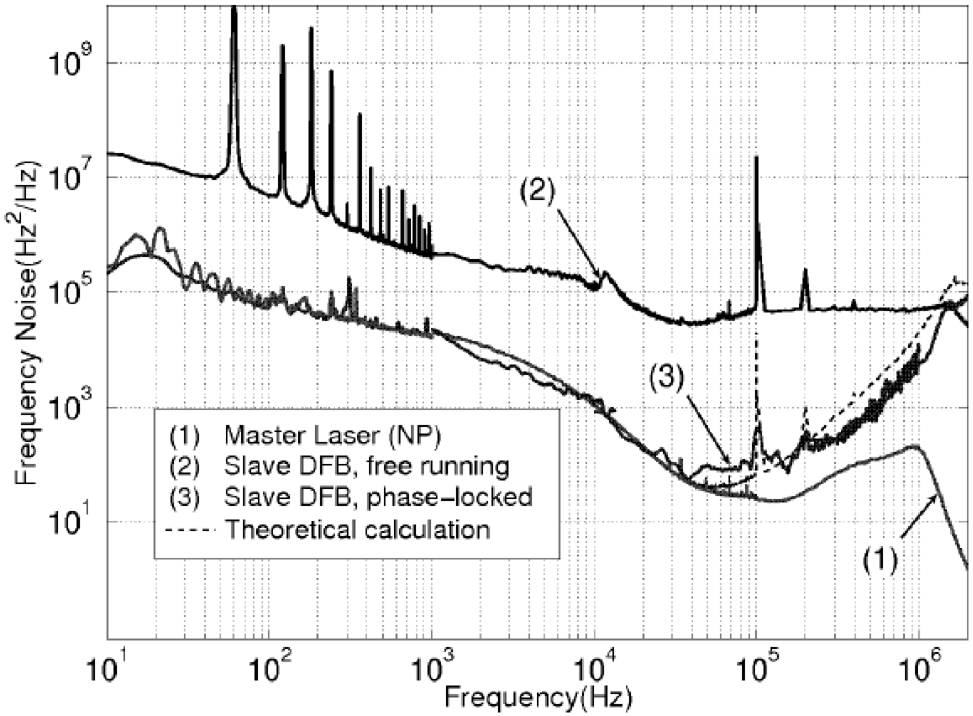


Slave laser frequency noise follows master laser within the loop bandwidth

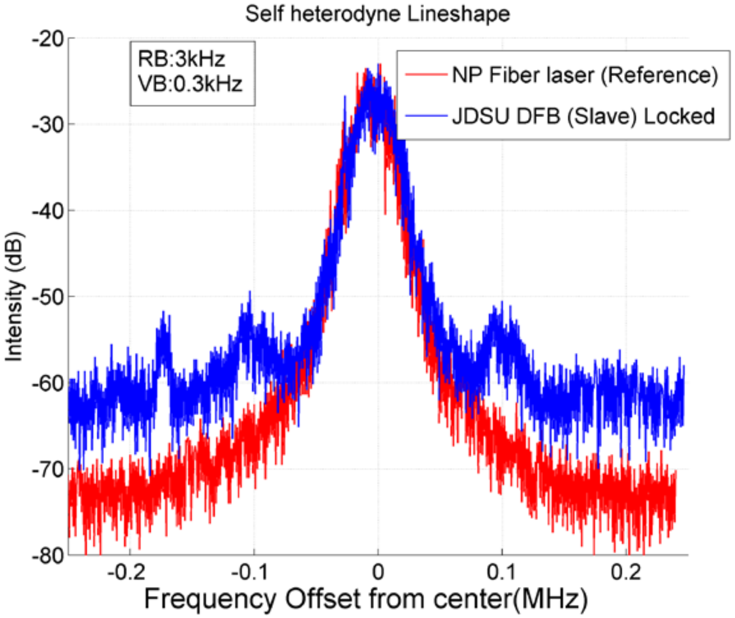
Signal to noise ratio in coherent interferometric experiments using the phase-locked SCL is determined by the phase noise of the master laser

N. Satyan et al, IEEE J. Quantum Elect. July 2009 (In press)

Coherence Cloning



Power spectral density of laser frequency noise



Coherence of the master laser is cloned within the loop bandwidth.

N. Satyan et al, IEEE J. Quantum Elect. July 2009 (In press)

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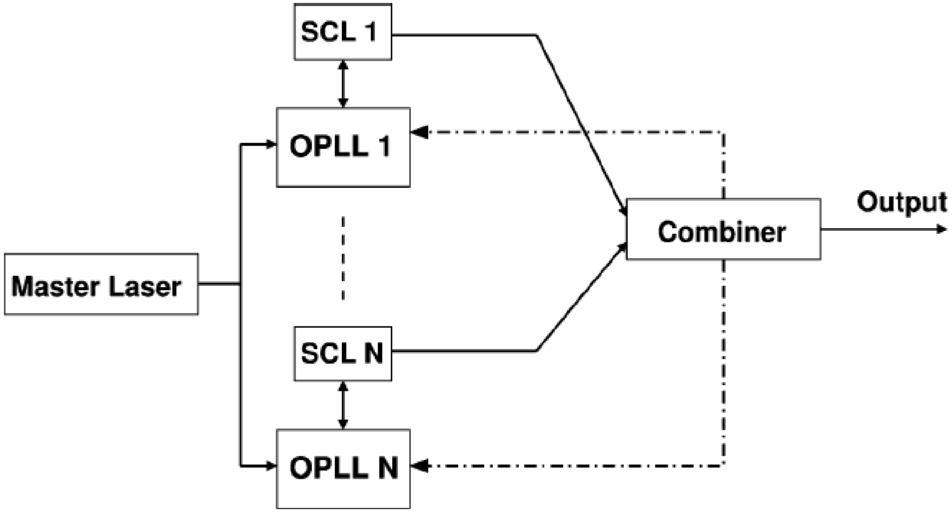
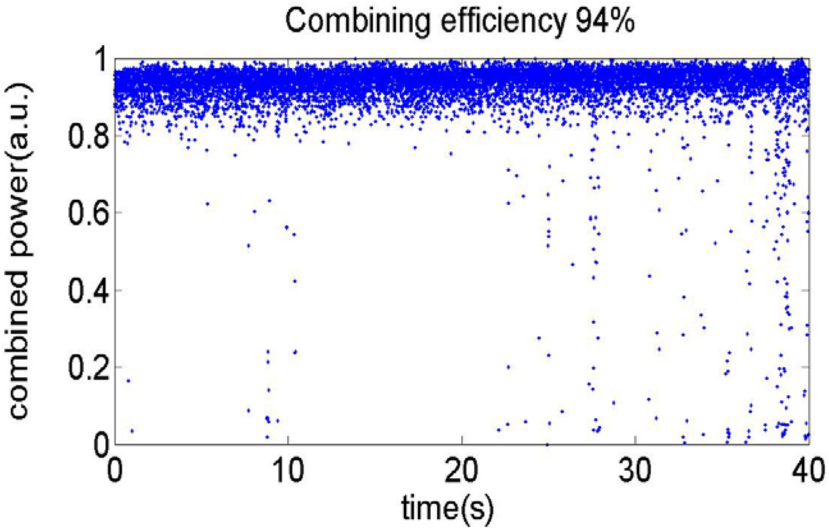
Coherent power combination





VCOs are used to provide RF offset signals to OPLLs

Combined Power, two OPLLs

94% combining efficiency

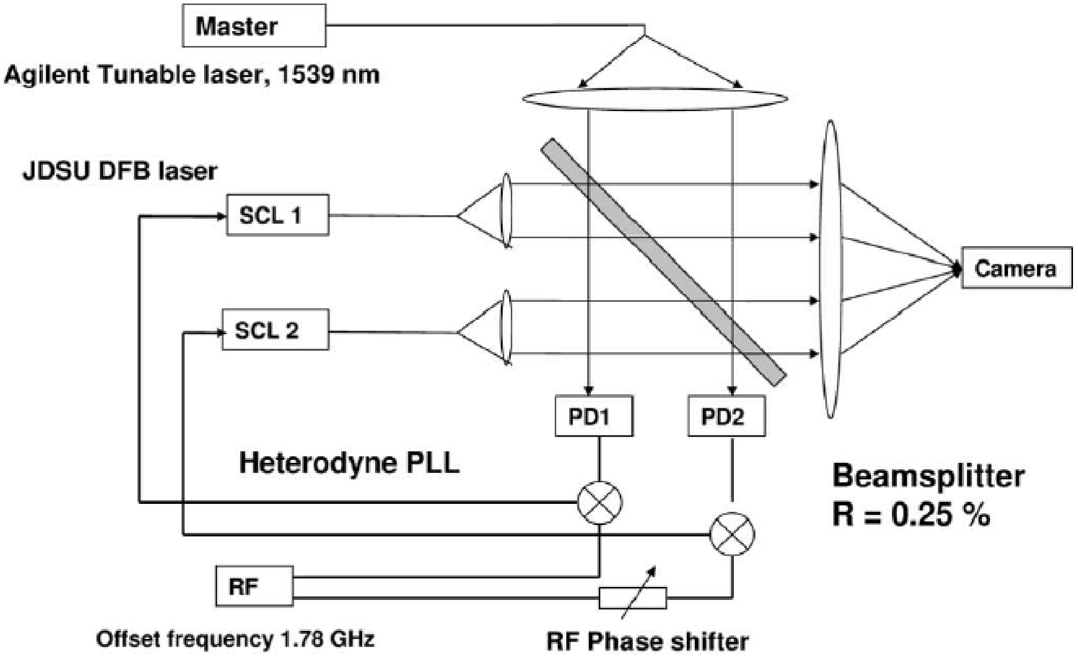
Advantages

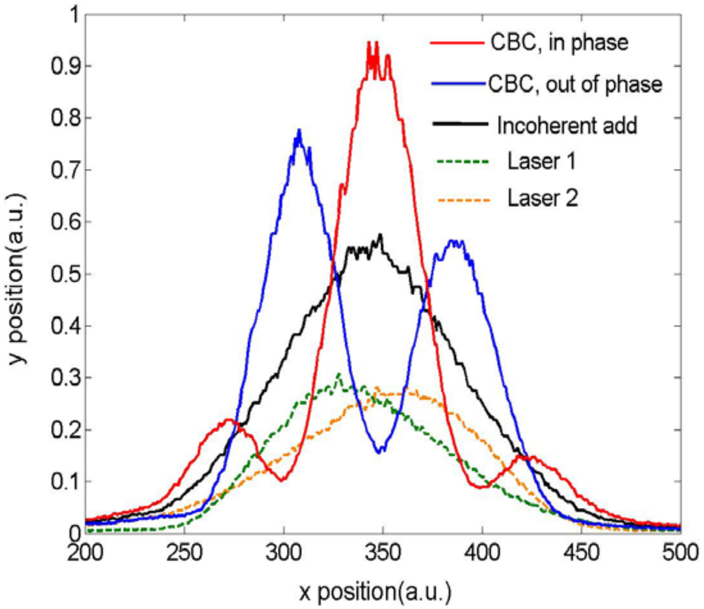
- Eliminate optical phase or frequency shifters
- Fully electronic servo system of low cost and compact size

We have demonstrated power combination of five fiber amplified SCLs with total combined power of 110 W at Telaris Inc.

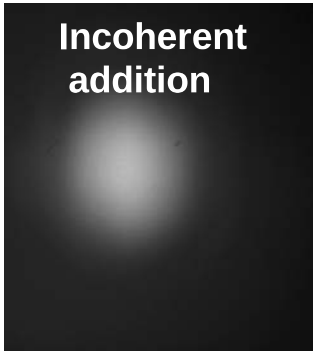
N. Satyan et al, IEEE J. Sel. Top. Quant. **15,** 240-247 (2009)

Beam steering with OPLLs

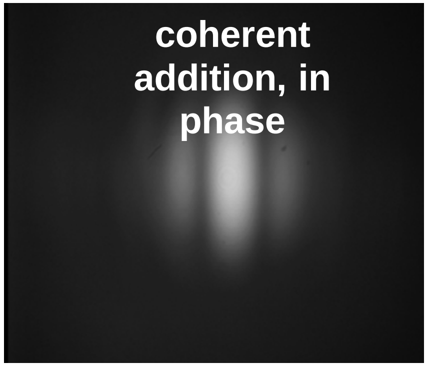




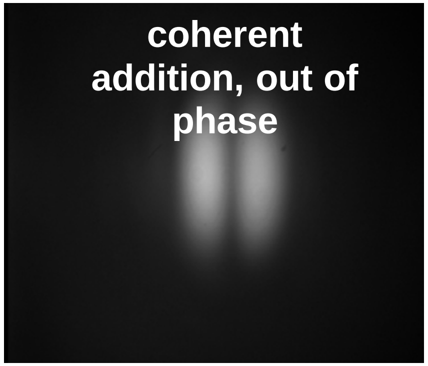
RF Phase shifter is used to steer the beam



Incoherent addition



coherent addition, in phase



coherent addition, out of phase

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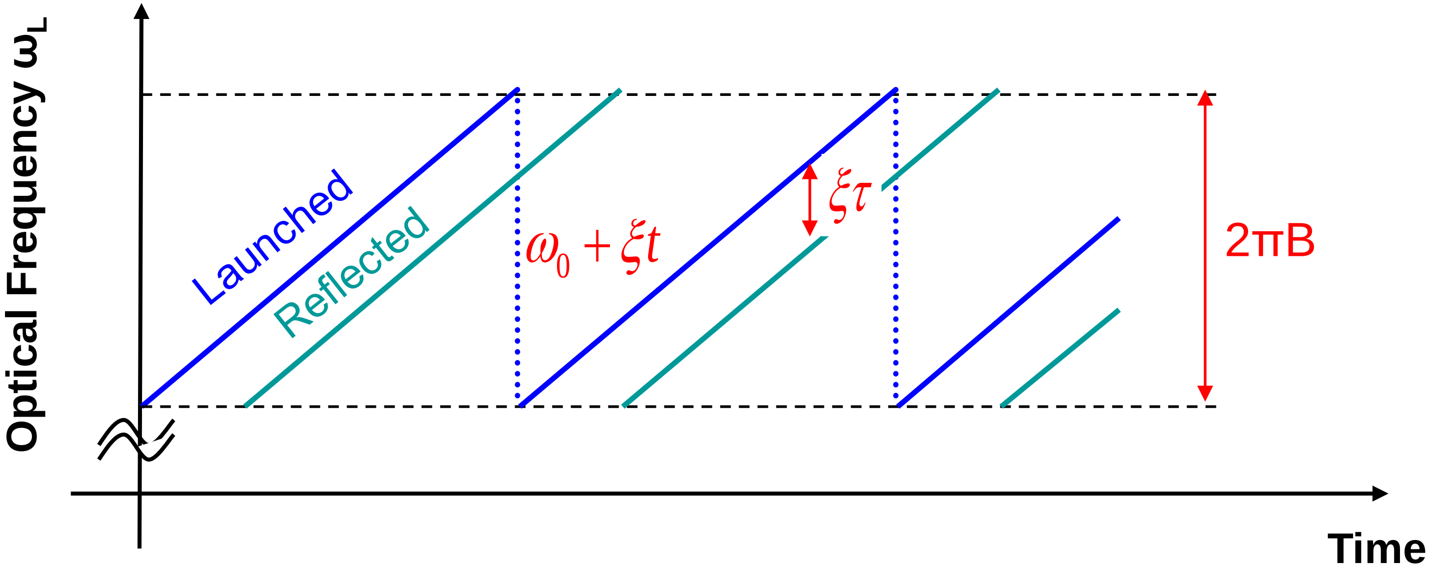
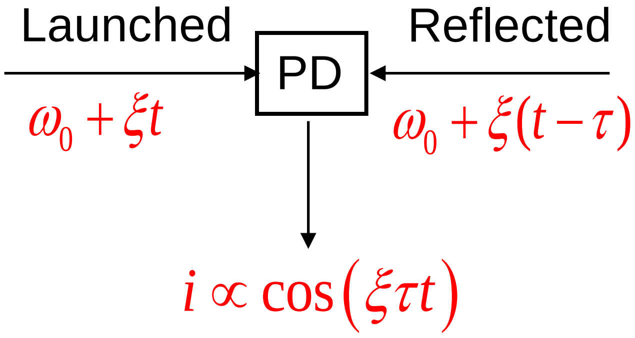
Ranging using chirped optical waves



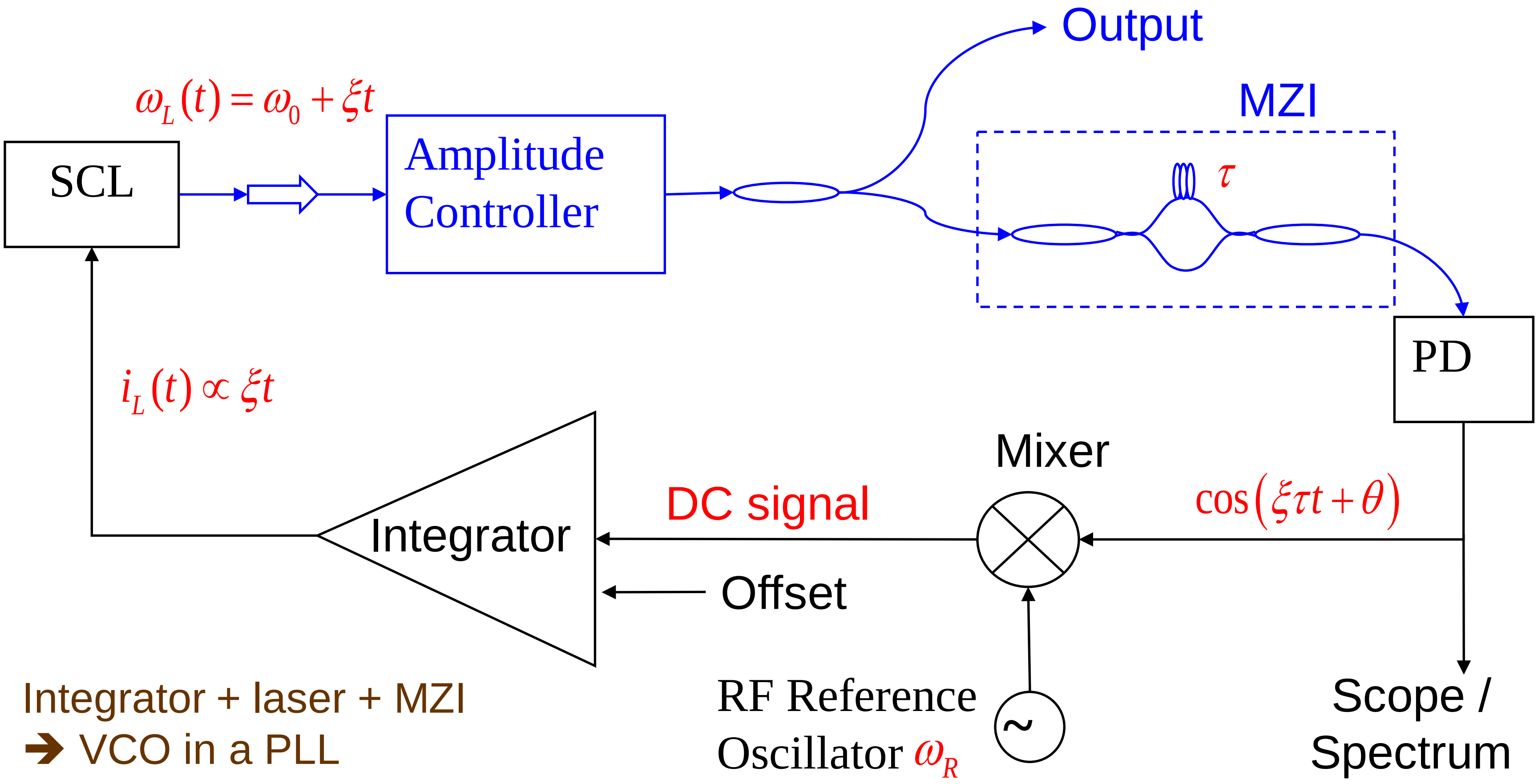


Resolution

$$\delta z\sim\frac{c}{2B}$$

$$B=10^{12}\,\mathrm{Hz},\quad \delta z=150\,\mu\mathrm{m}$$

Linear chirp system



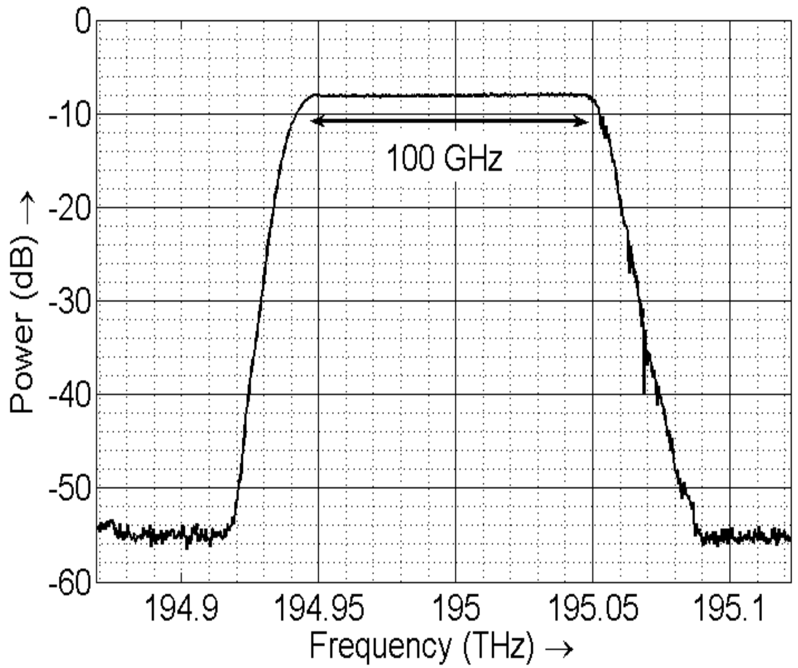
Integrator + laser + MZI
➔ VCO in a PLL

$$\omega_R = \xi\tau$$

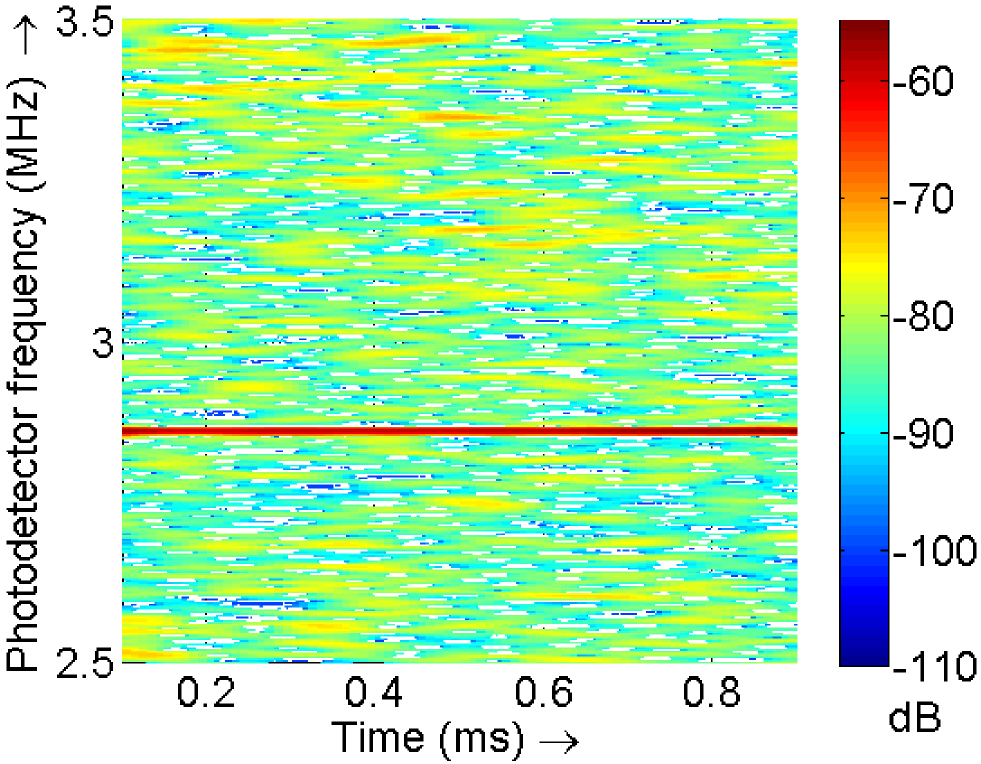
Can electronically control the slope of the frequency chirp

N. Satyan et al, Optics Express 2009 (submitted)

Linearly Chirped SCL



Optical spectrum

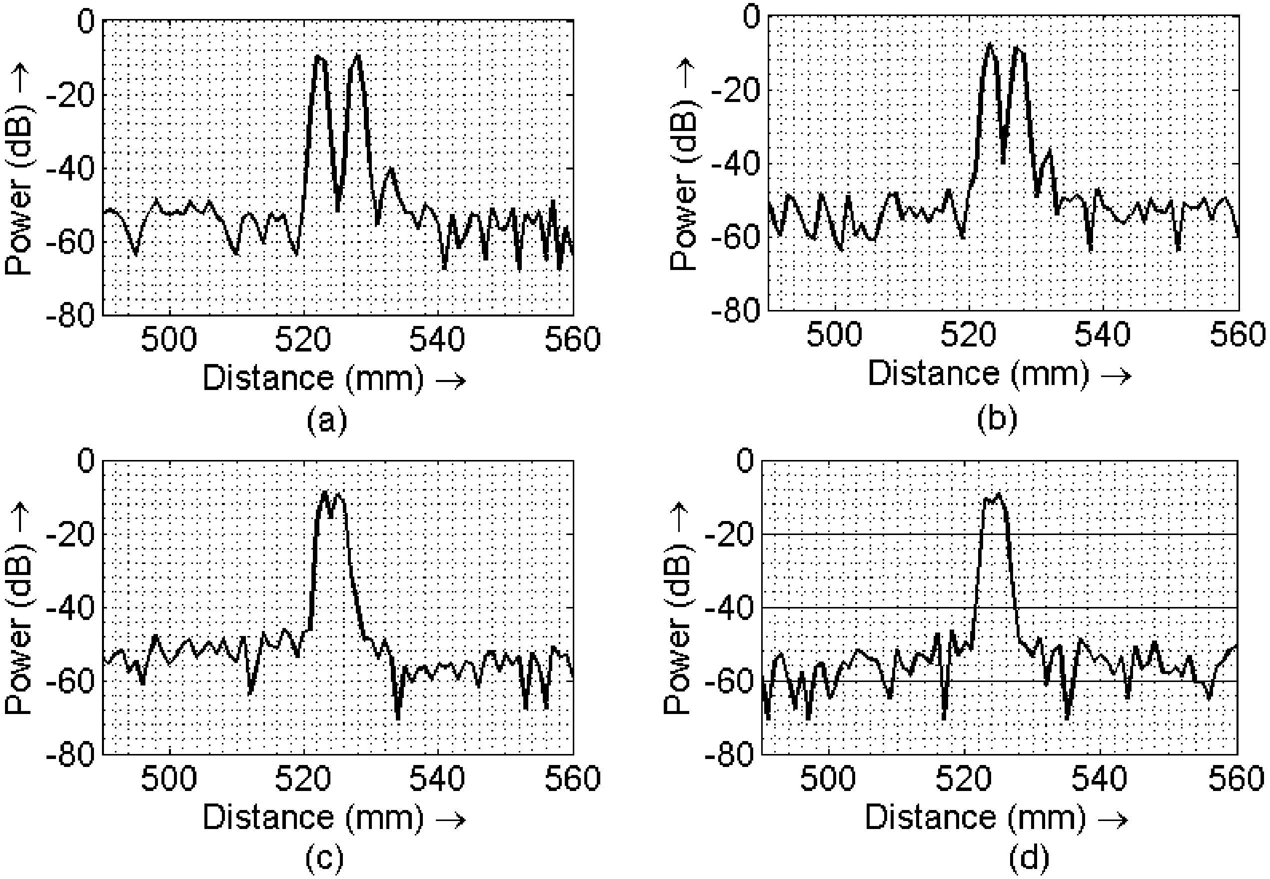


Variation of chirp slope with time

The feedback system generates a highly linear (transform limited) sweep. The phase noise of the laser within the loop bandwidth is also suppressed.

100 GHz in 1 ms   Range resolution = 1.5 mm (in air)

Range resolution measurements



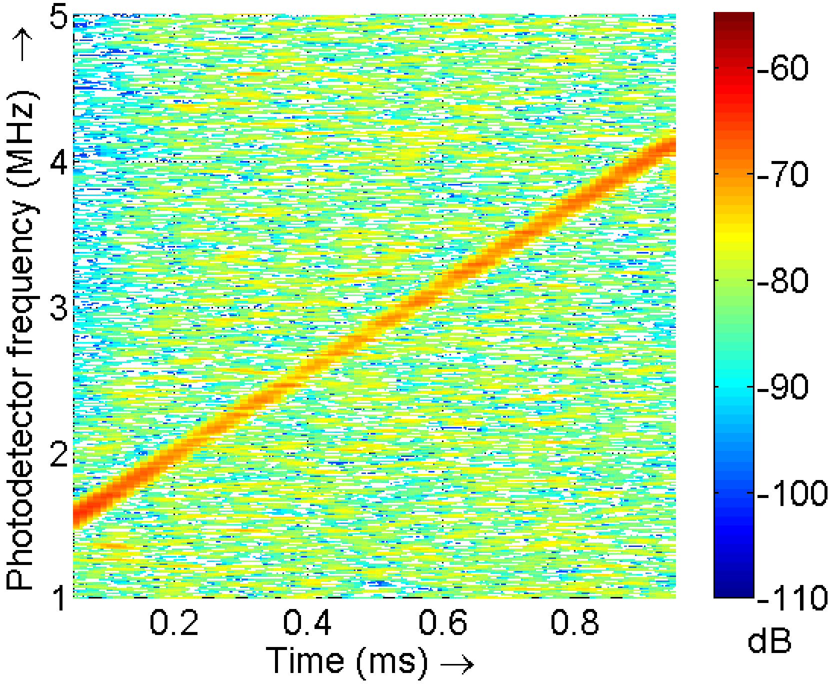
(a) (b) (c) (d)

Two targets: Reflections from front and back facet of acrylic plate
(a) 5.44 mm (b) 4.29 mm (c) 2.25 mm (d) 1.49 mm

Can resolve down to targets 1.5 mm thick (ref. index = 1.5)

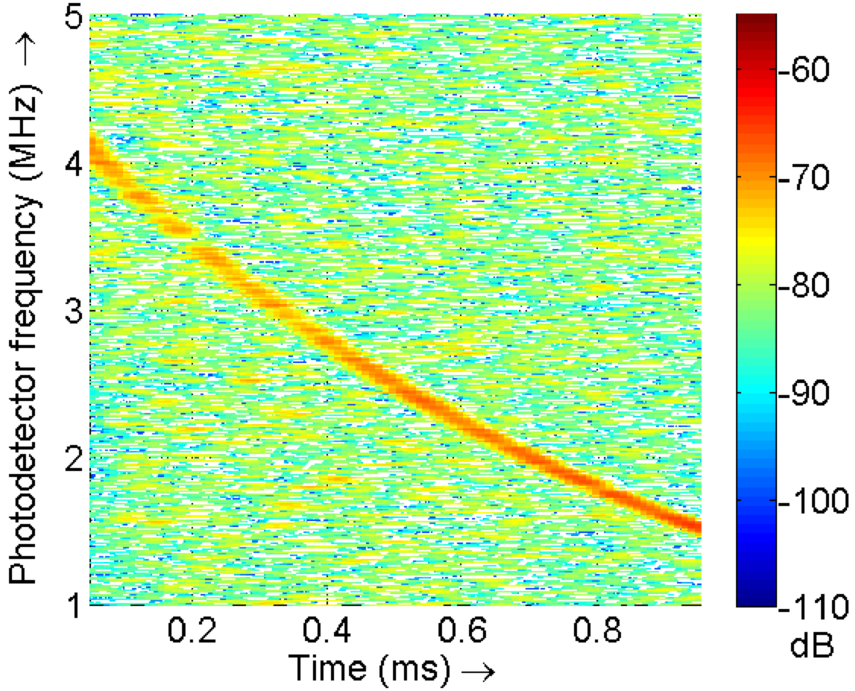
Arbitrary frequency sweeps

By changing the frequency of the reference signal (using a VCO), we obtain variable slopes of the optical frequency



(a)

Quadratic optical frequency sweep



(b)

Exponential optical frequency sweep

(Measurements correspond to slope of optical sweep; varies between 50 & 150 GHz/ms)

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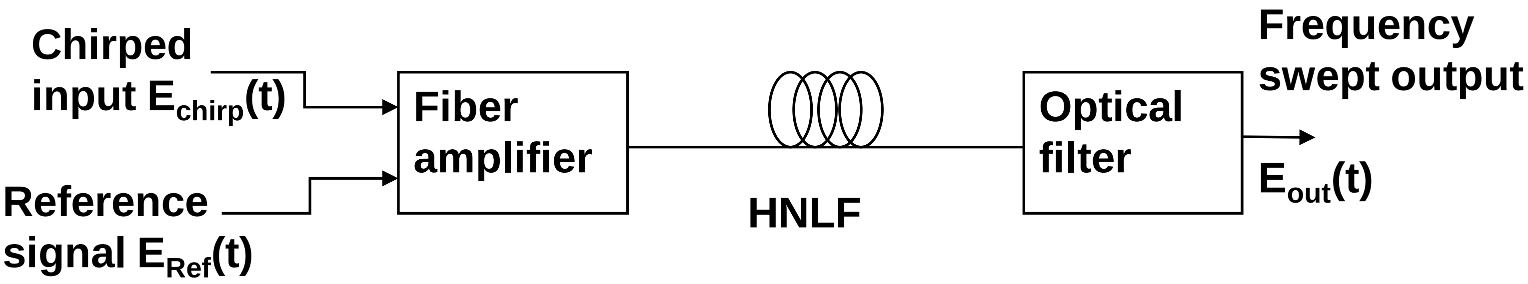
Chirp multiplication by Four Wave Mixing



Chirped input $E_{chirp}(t)$

Reference signal $E_{Ref}(t)$

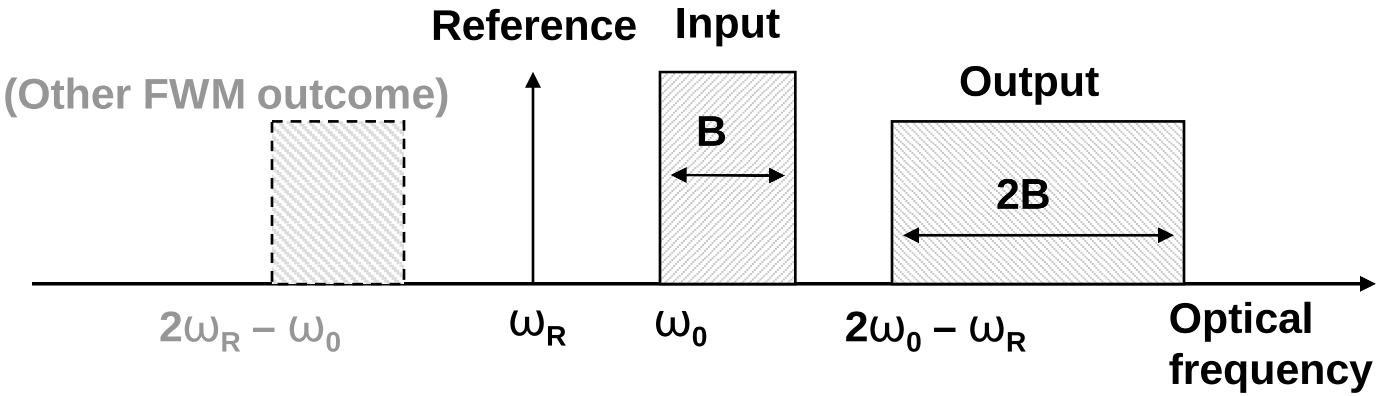
Fiber amplifier

HNLF

Optical filter

Frequency swept output

$E_{out}(t)$



Reference

Input

Output

(Other FWM outcome)

B

2B

$2\omega_R - \omega_0$

ω_R

ω_0

$2\omega_0 - \omega_R$

Optical frequency

Use the four wave mixing process which gives $\omega_{out} = 2\ \omega_{chirp} - \omega_{Ref}$ (next slide)

Optically filter out other FWM outcomes

HNLF: Highly Non-Linear Fiber. Can also use PCF, or silicon waveguides for FWM.

Theory

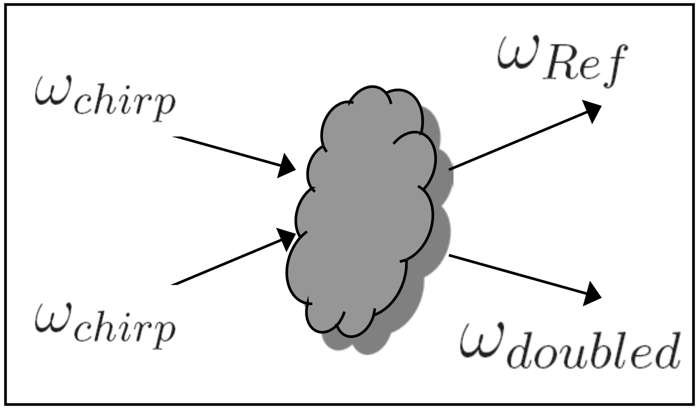
$$\vec{P}_{NL} = 4\chi^{(3)} \vdots \vec{E}\vec{E}\vec{E}$$

Use $\vec{P}_{NL} = 4\chi^{(3)} \vdots \vec{E}_{chirp}\vec{E}_{chirp}\vec{E}_{Ref}$

Chirp

$$\vec{E}_{chirp} = \frac{A_c}{2} e^{i[\omega_0 t + \phi(t)]}$$

$$\vec{E}_{Ref} = \frac{A_r}{2} e^{i\omega_r t}$$



$$P_{NL} \propto \chi^{(3)} A_c^2 A_r^* e^{i[(2\omega_0 - \omega_r)t + 2\phi(t)]}$$

Chirp doubling

(a) Chirp is doubled (b) FWM output is nominally at the same wavelength

Theory-II

1. Non linear wave equation $$\frac{\partial^2 E}{\partial z^2} = \frac{n^2}{c^2}\frac{\partial^2 E}{\partial t^2} + \frac{\alpha n}{c}\frac{\partial E}{\partial t} + \mu_0 \frac{\partial^2 P_{NL}}{\partial t^2}$$

2. Non linear polarization by FWM $$\vec{P}_{NL} = 4\chi^{(3)} \vdots \vec{E}\vec{E}\vec{E}$$

3. Define normalized field amplitudes $$E(z,t) \propto \frac{A(z)}{2} e^{i(\omega t - \beta z)} + \text{c.c}$$

4. Substitute the sum of input and reference E fields in (2), and look for the terms that correspond to frequency slope doubling: $\omega_{out} = 2\omega_{in} - \omega_R$

$$P_{NL}^{\omega_{out}}(z) \propto A_{in}^2 A_R^* e^{-i\Delta\beta z}; \qquad \Delta\beta = 2\beta_{in} - \beta_R - \beta_{out} = \frac{\lambda^2}{2\pi c} D_c \left(\omega_{in} - \omega_R\right)^2$$

5. Write down the growth equation for the generated field

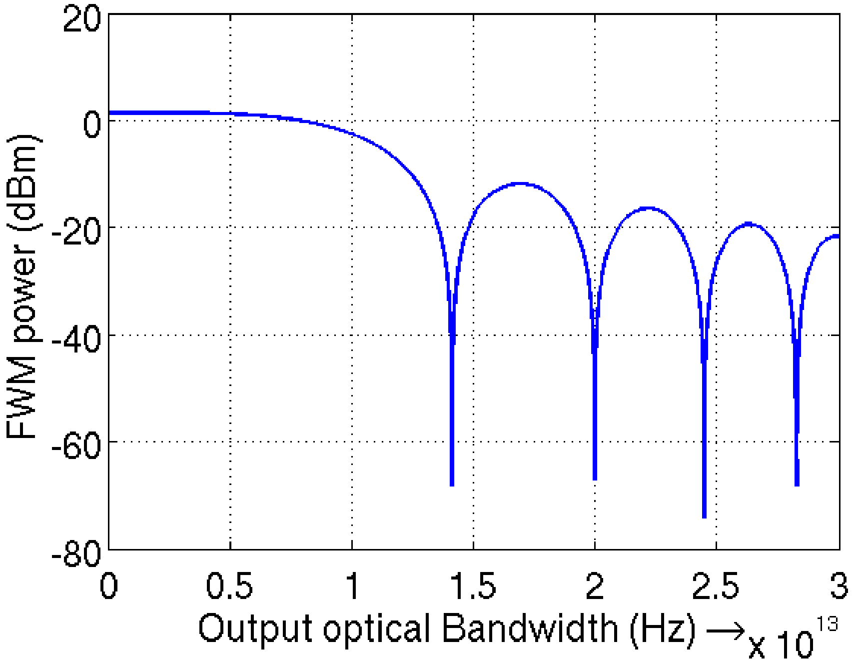
$$\frac{dA_{out}}{dz} = -\frac{\alpha}{2} A_{out} - j\gamma A_{in}^2(0) A_R^*(0) e^{-3\alpha z/2} e^{-j\Delta\beta z}$$

Dispersion limited bandwidth

$$P_{out}^{(\omega_{out})} = \gamma^2 P_{in}^2 P_R \left(\frac{1-e^{-\alpha L}}{\alpha}\right)^2 e^{-\alpha L} \cdot \frac{\alpha^2}{\alpha^2+\Delta\beta^2}\left(1+\frac{4e^{-\alpha L}\sin^2\frac{L\Delta\beta}{2}}{\left(1-e^{-\alpha L}\right)^2}\right)$$

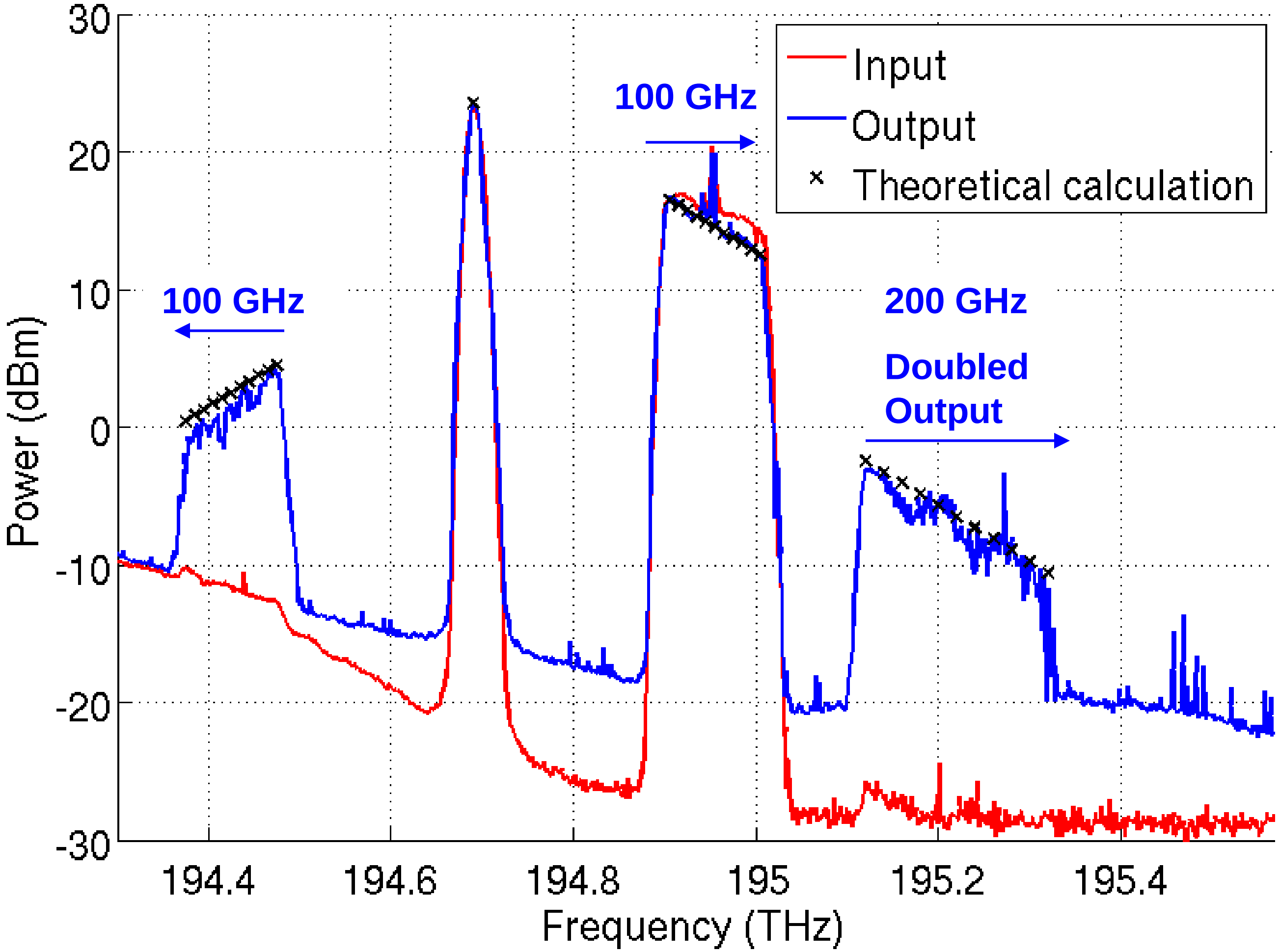
Limited bandwidth due to dispersion

Power generated as a function of output bandwidth →



Assuming a dispersion of 0.5 ps/nm.km
(pessimistic, but guaranteed in commercial fiber)
For 10 THz output BW, maximum fiber length = 1.25 m, $P_{in} = P_R = 1.9$ W

Experimental Demonstration

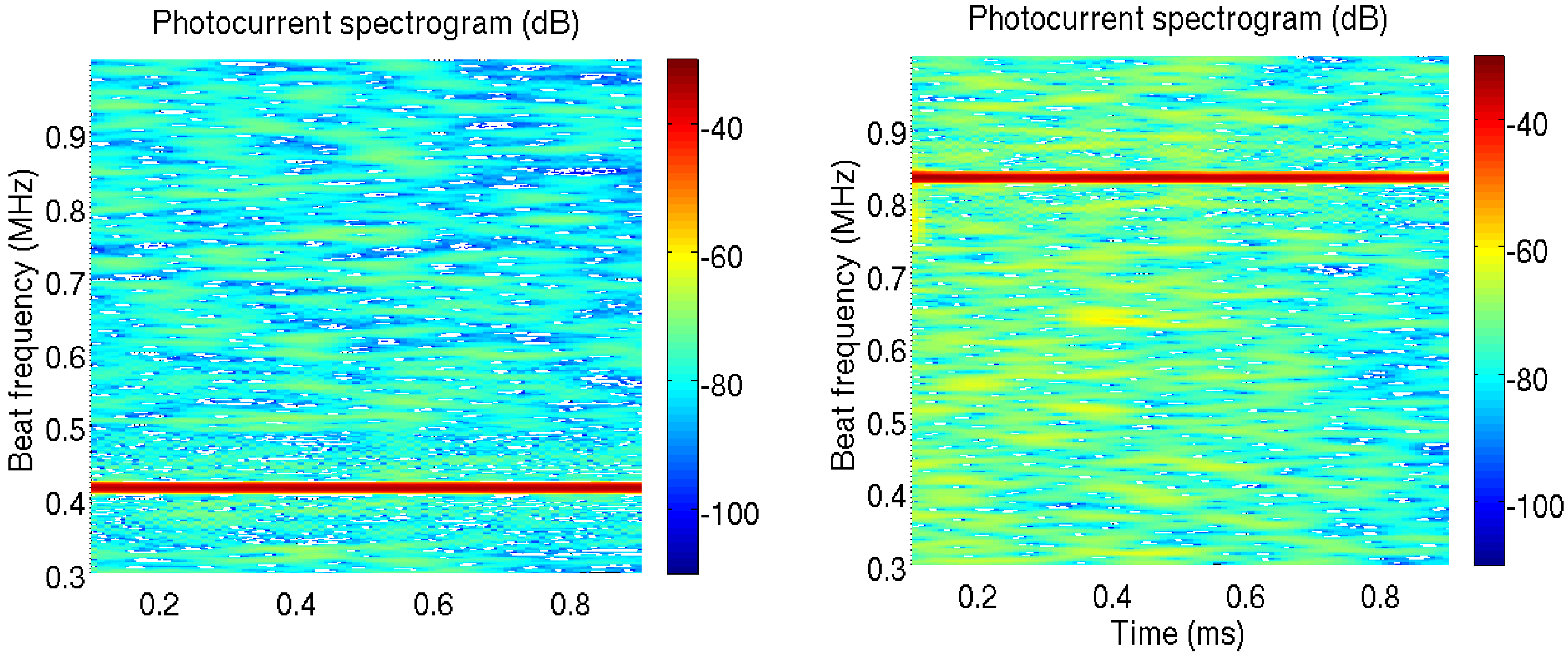


RBW = 0.2 nm (24 GHz)

Good agreement with theory

Experimental Demonstration II

Measurement of slope of optical sweep



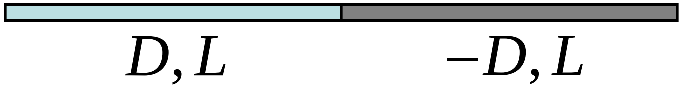
Original Sweep

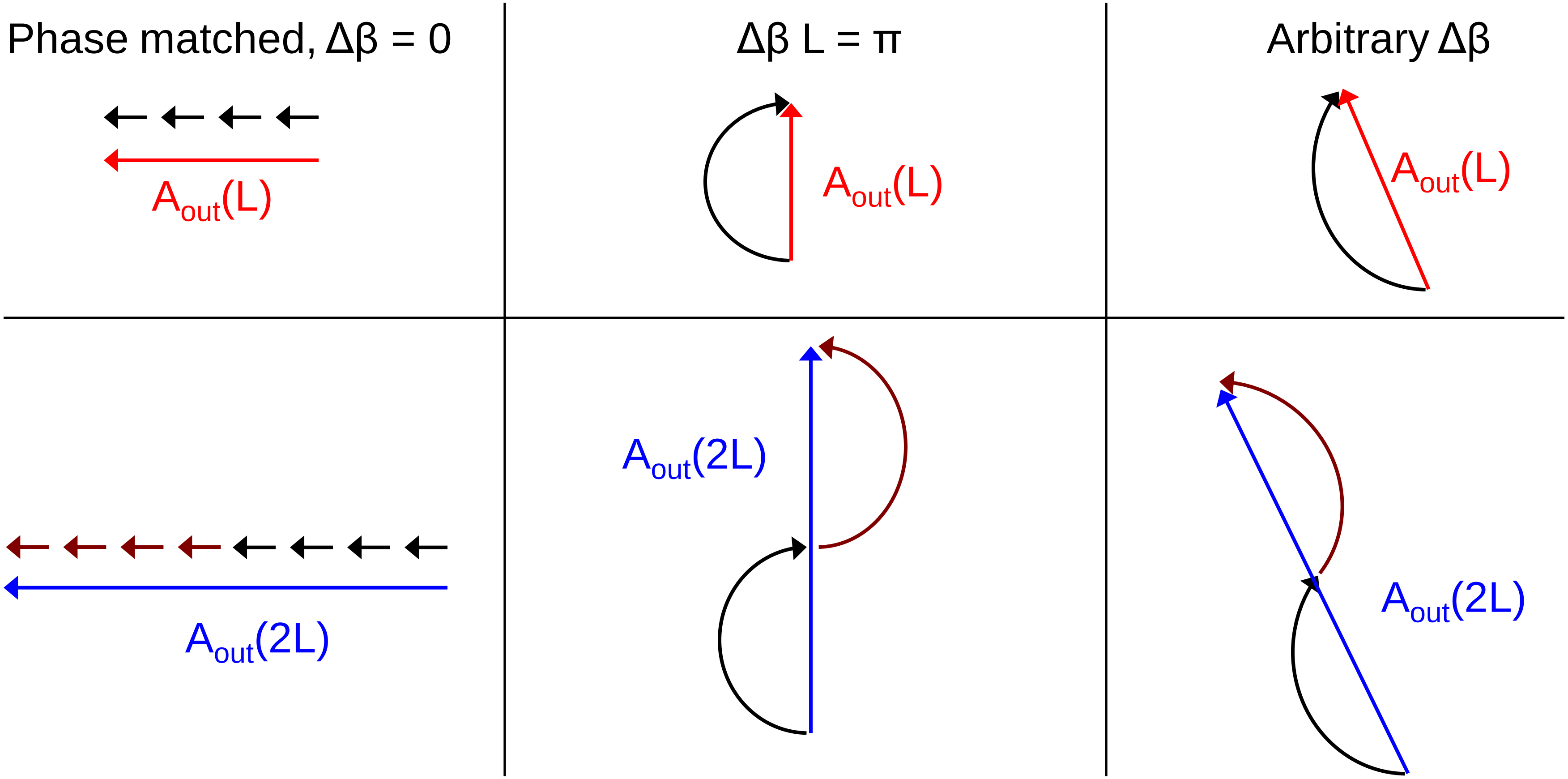
Doubled sweep

- Perfectly linear (transform-limited) doubled sweep
- Additional noise due to ASE in the amplification stage after filtering

Dispersion Compensation

Suppose we periodically invert the sign of the dispersion D, and hence the sign of Δβ





Phase matched, Δβ = 0

Δβ L = π

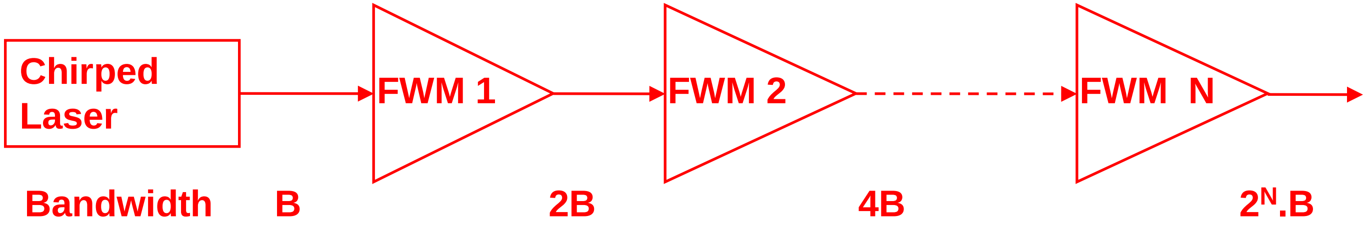
Arbitrary Δβ

$A_{out}(2L) = 2\,A_{out}(L)$ for ALL frequencies ➔ can use much lower powers

Towards 10 THz and beyond

One FWM stage doubles the slope, and the bandwidth of the chirp.

The FWM output is nominally at the same wavelength. Therefore, this process can be repeated recursively.



Chirped Laser

FWM 1

FWM 2

FWM N

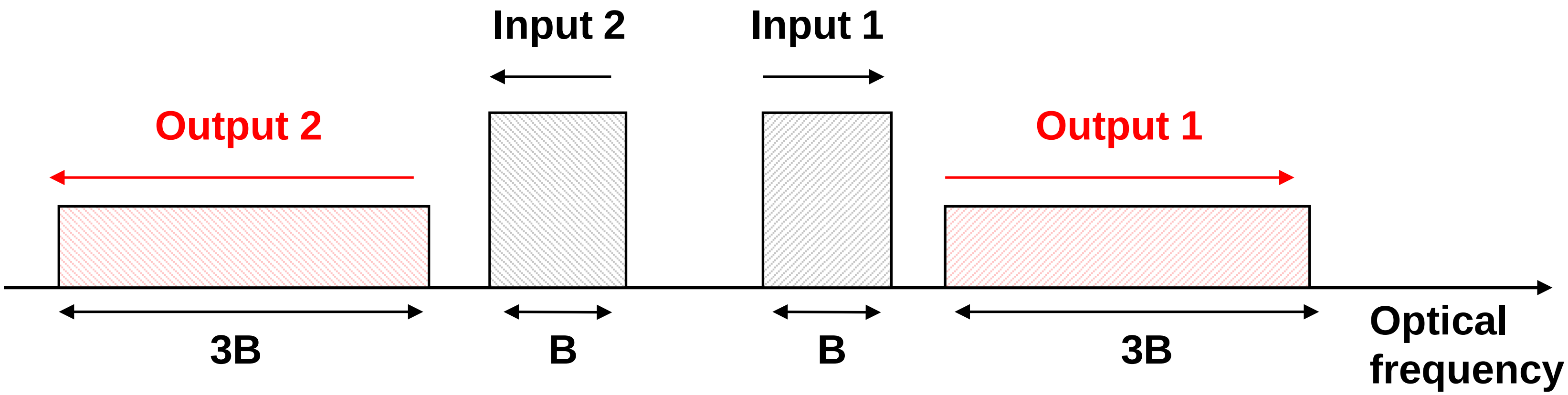
Bandwidth B

2B

4B

2^N.B

Suppose we start with TWO swept frequency sources going in opposite directions



Input 2

Input 1

Output 2

Output 1

3B

B

B

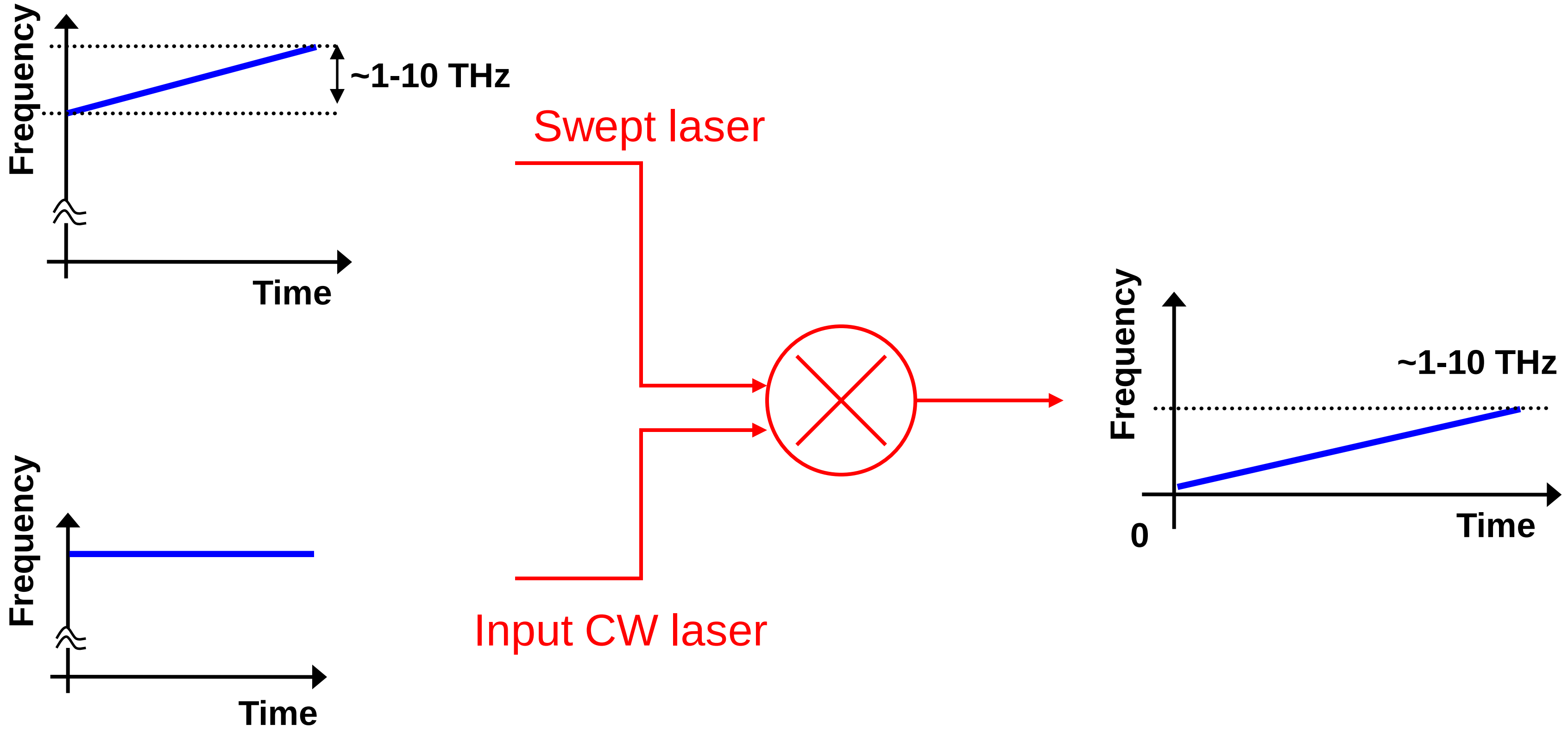
3B

Optical frequency

The two output FWM products have bandwidths of 3B each
If this is repeated N times, the resultant bandwidth is 3^N. B

Applications of chirped SCLs

Universal Terahertz source



Need a suitable Terahertz mixer

- Photoconductive mixers (Low Temperature Grown GaAs)
- Difference Frequency Generation in crystals

Applications of chirped SCLs

Tuning the frequency of a semiconductor laser over THz spans at high speeds

Laser ranging and biometrics
Long coherence length for imaging at a distance
Rapid frequency sweeps

Biological Imaging and OCT
Solid state laser source with no moving parts
Perfectly linear chirp for real time imaging

Tunable source for fast spectroscopy
Both Infrared and Terahertz spectroscopy
Narrow linewidth of SCL gives better spectral resolution

Terahertz imaging and detection
3D (depth resolved) THz imaging using swept THz source

Arbitrary Waveform Generation
Full control over frequency content of waveform
Possible to synthesize repetitive waveforms using cascaded OPLLs

Conclusion

Electronically controlled broadband swept-frequency (chirped) semiconductor laser sources and phase-controlled apertures have the potential of becoming new generic components;

Enabling a new spectrum of applications ranging from power combining and steerable optical beams to high resolution 3-D imaging, microscopy and Terahertz optics.

References

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