Optical Techniques for Low-Noise Microwave Frequency Sources

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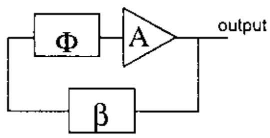
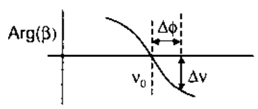
Outline

- Why Optical Techniques
  - What does a high performance oscillator require
  - Shortcomings of conventional techniques
  - Advantages of optical techniques
- Wavemixing: Advantages and Disadvantages
- Wavemixing with Feedback: The OEO
- Feedback in both loops: COEO
- Sate of the Art and Future Prospects

Oscillator Theory (Leeson Model)



A: noiseless amplifier
b: resonator with $Q = \nu_0/\Delta\nu_c$



Frequency shift due to a phase deviation Δφ:

$$\frac{\Delta\nu}{\nu_0} = \frac{\Delta\phi}{2Q}$$

Loop phase noise spectrum $S_\phi(f)$

Within the resonator bandwidth, the oscillator phase noise spectrum

$$S_\phi^{osc}(f) = \frac{1}{f^2}\left(\frac{\nu_0}{2Q}\right)^2 S_\phi(f)$$

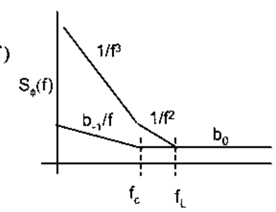
Outside the resonator bandwidth:

$$S_\phi^{osc}(f) = S_\phi(f)$$

Leeson model

$$S_\phi^{osc}(f) = \left[1 + \frac{1}{f^2}\left(\frac{\nu_0}{2Q}\right)^2\right] S_\phi(f)$$

Leeson frequency $f_L = \frac{\nu_0}{2Q}$



Conventional Approaches for High performance Microwave Oscillators

- Start with a good quartz oscillator at ~ 100 MHz and multiply up
  - Noise also multiplies at 20 logN with N the multiplication factor
  - Usually complex chains, requiring low noise amplifiers, mixers, etc.
- Use a high-Q microwave cavity
  - Q degrades with frequency (QF~ a constant)
  - High Q cavities sensitive to environmental perturbations
- Highest spectral purity at f > 10 GHz obtained only sapphire or air-gap cavities: large power consumption, and large size (shoe-box and larger)
- Susceptible to EMI
- Can't meet high end applications' requirements for temperature stability, acceleration sensitivity, etc.without adding to mass/size

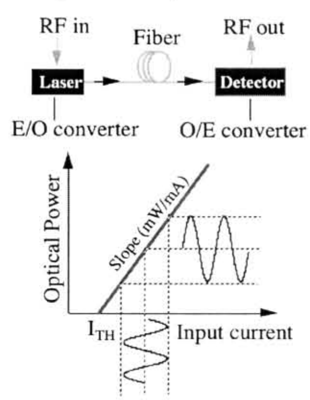
Why Optical Techniques

- Microwave signal is generated by photomixing of two or more optical frequencies, or sidebands
  - Not limited by RF components (except amplifiers)
  - Can be made at any microwave frequency
  - Approaches available for tuning with high performance optical filters
- Loss for these sidebands is about the same regardless of the sideband frequency, thus Q does not degrade
- Optical guides, cavities and filters have intrinsically lower loss than microwave counterparts
- Because of the small optical wavelengths, optical devices are intrinsically small

Basic Photonic RF links

Directly modulated Link

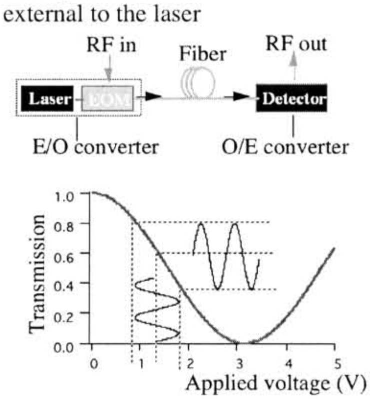
RF signal directly drives the laser



Lower dynamic range
most CATV systems

Externally modulated link

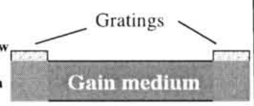
RF signal drives an E/O modulator external to the laser



High dynamic range
High performance systems

Commonly used lasers for RF systems

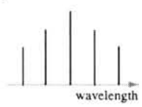
Distributed Bragg Reflector (DBR) Laser



* Bragg gratings are narrow band reflectors
* Optical feedback through grating reflection
* single/multimodes operation

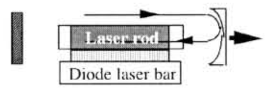
Fabry-Perot laser (F-P laser)

* Optical feedback provided by the end mirrors
* multi-longitudinal modes
* higher noise due to mode competition



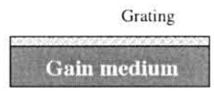
Diode-pumped solid-state laser

* Solid state gain medium pumped by diode lasers
* Narrowest spectral width
* Lowest noise
* Most expensive
* Less reliable



Distributed feedback laser (DFB laser)

* Optical feedback provided by the grating on top of the gain medium
* single longitudinal mode
* lower noise

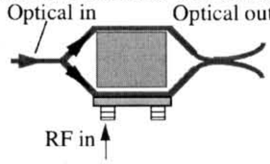


Commonly used Photodetectors

- InGaAs PIN photodiodes (0.8 - 1.7 um)
  - High responsivity: up to 0.95 A/W commercially available
  - High saturation power: up to 15 mW commercially available
  - High speed: up to 25 GHz commercially available
  - Lowest dark current: >0.1 nA (intrinsic noise)
- **InGaAs Schottky photodiodes (0.95 - 1.65 um)**
  - Lower responsivity: ~ 0.4A/W
  - Highest speed: 60 GHz commercially available
  - Low saturation power: ~ 2 mW
- Ge PIN photodiodes (0.8 - 1.8 um)
  - High responsivity: ~0.9 A/W
  - Higher dark current: ~ 1 nA

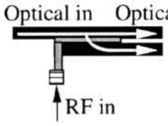
Common Modulators

Mach-Zehnder modulator



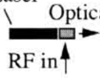
* Wide Bandwidth: up to 100 GHz
* Good linearity
* No chirp (good)
* Well developed, widely used
* High drive voltage ==>
High RF insertion loss

Directional coupler modulator



* Potential large Bandwidth
* Not well developed
* Not as good linearity
* Modulation chirp
* High drive voltage ==>
High RF insertion loss

Electro-absorption modulator



* Wideband width: > 60 GHz
* Easy integration with diode lasers
* Extremely compact
* Low drive voltage * Modulation chirp (not good)

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Other photonic devices

- Directional couplers (ratio: 1 - 50%, backreflection < -65 dBo)
- Isolators (insertion loss: < 0.6 dBo, isolation > 40 dBo)
- Circulators (insertion loss: < 0.8 dB, isolation > 40 dBo)
- Polarizers (insertion loss: < 0. 4 dB, backreflection < -60 dB)
- Polarization controllers (no loss, no backreflection)
- Filters (insertion loss < 0.5 dB, BW: 0.8 nm and up)
- Faraday polarization rotator and mirror
- connectors: Physical contact (PC) and angled physical contact(APC)
  - loss < 0. 25 dB, backreflection: PC < -40 dB, APC < -65 dB
- Fiber optic amplifiers: doped fiber & semiconductor

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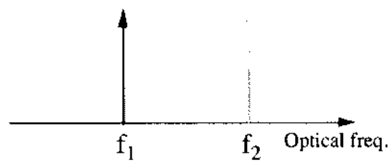
Photodetector as a mixer

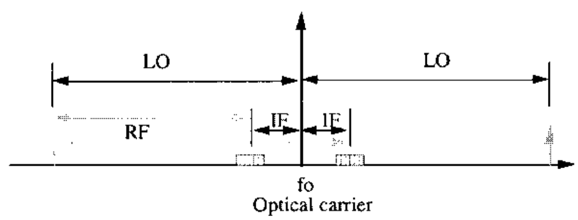
Power Law Photodetector ==> acts as a mixer



Photocurrent $I \sim |E|^2$

$(A\sin 2\pi f_1 + B\sin 2\pi f_2)^2$

==> $(f_1 + f_2)$ and $(f_1 - f_2)$



Modulator & photodector combination ==> signal up or down conversion

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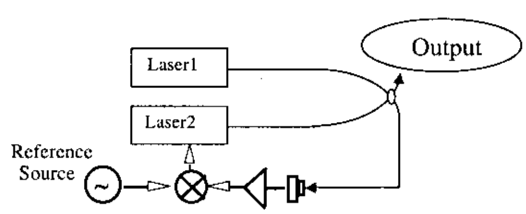
Features of Signals Generated by Photo-mixing of Lasers

- Simple approach requiring two lasers with narrow linewidth
- Can be used with lasers that are phase, frequency, or injection locked
- Highly tunable over a long range
- The microwave beat signal limited by laser linewidth, set by lasers or by lock oscillators



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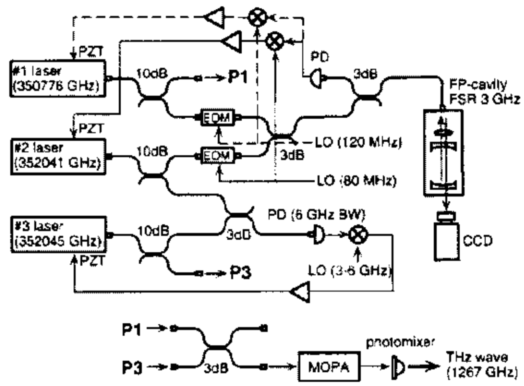
Example of a High Frequency Beat Note generqator

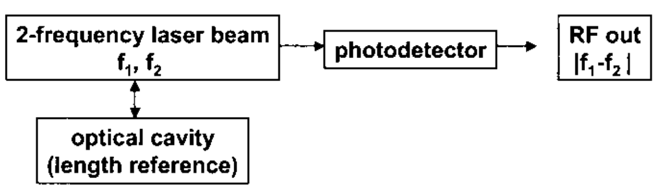


Three-laser synthesizer for THz, *Matsuura, et al., IEEE Trans. Microwave Theory and Technique, 2000*

- Spontaneous emission is a noise with white frequency character, and a linewidth “Schalow-Townes” that is:

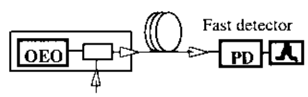
$$\Delta \nu_{ST} = \left(\frac{ahc^2}{4\pi} \right) \frac{T^2 \nu}{L^2 P_{out}}$$

$\Delta \nu = \pi S_f^2$, so that we have: $\longrightarrow$ $L(f) = \dfrac{S_f^2}{2f^2}$

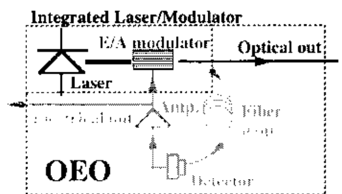


Opto-Electronic Feedback

- Start with a Photonic link



- Close the loop with gain and in phase



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OEO

- OEO is a generic device: various configurations of lasers, modulators, optical delays can be implemented
- OEO lends itself to diverse architectures (dual loop, Coupled OEO, etc) to support diverse applications
- OEO's performance will improve with improved components (amplifiers, lasers, modulators, detectors, optical delays)
- OEO is ideal for opto-electronic integration
- The OEO signal is available both electrically, and on an optical carrier
- The COEO version generates short (sub-picosecond) optical pulses with lowest jitter
- OEO cab be phase locked, frequency locked, self locked, and used as a VCO
- The microresonator based OEO has a small size, low power consumption and intrinsically low acceleration sensitivity
- Unique microresonator based optical filter enables widely tunable oscillator

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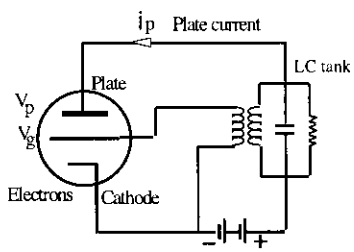
OEO vs. van der Pol Oscillator

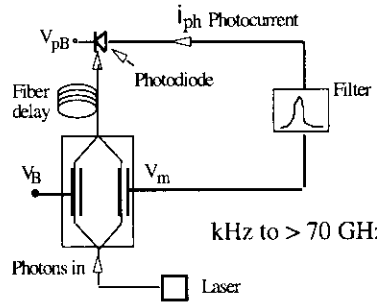
van der Pol Oscillator



kHz

Low Q & Low Frequency

Opto-electronic Oscillator



kHz to > 70 GHz

High Q & High Frequency

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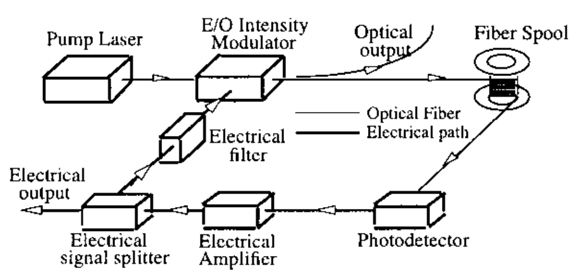
OEO Features



- High Q resulting from the low loss fiber ==> Low phase noise
- High frequency resulting from fast photonic devices
- Widely tunable
- Both electrical & optical outputs ==>No E/O & O/E conversion required
- Can be locked to a master reference either optically or electrically
- Meets the requirements of RF photonics systems

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Important characteristics of the OEO

- **High spectral purity** due to long optical storage time provided by the fiber in a closed loop.
- The quality factor (RF $Q \sim 10^5$-10^6) is proportional to the oscillation frequency, leading to **noise level performance that is *independent* of frequency**.
- The **mode spacing** is related to the inverse of loop trip time: $\approx \frac{c}{n \cdot L}$

where c is the speed of light, n is the fiber refractive index and L is the fiber length.

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OEO

Some significant features

- OEO is a generic device: various configurations of lasers, modulators, optical delays can be implemented
- OEO lends itself to various architectures (dual loop, Coupled OEO, etc) to support diverse applications
- OEO's performance will improve with improved components (lasers, modulators, detectors, optical delays)
- OEO is ideal for opto-electronic integration
- The OEO signal is available both electrically, and on an optical carrier
- The COEO version generates short (sub-picosecond) mode locked optical pulses with lowest jitter

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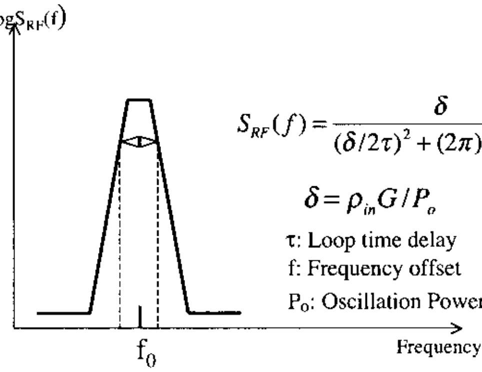
$$\Delta f = \frac{1}{2\pi}\frac{\delta}{\tau^2}$$

$$Q = \frac{f_0}{\Delta f} = \frac{2\pi f_0 \tau^2}{\delta}$$



$$S_{RF}(f) = \frac{\delta}{(\delta/2\tau)^2 + (2\pi)^2 (f\tau)^2}$$

$$\delta = \rho_{in} G / P_o$$

τ: Loop time delay

f: Frequency offset

P_0: Oscillation Power

ρ_i ==> Input noise power density

ρ_{in} = Thermal noise + Shot noise + Laser RIN noise

* Noise decays with f: 20 dB/Decade

* Noise decays with τ: 20 dB/decade

* Noise is independent of oscillation frequency f_0.

* Q increases with f_0.

Typical δ ~ 5 x 10^{-17}/Hz

For τ = 6 μs (1 km fiber)

Q ~ 4 x 10^{-5} f_0 (Hz)

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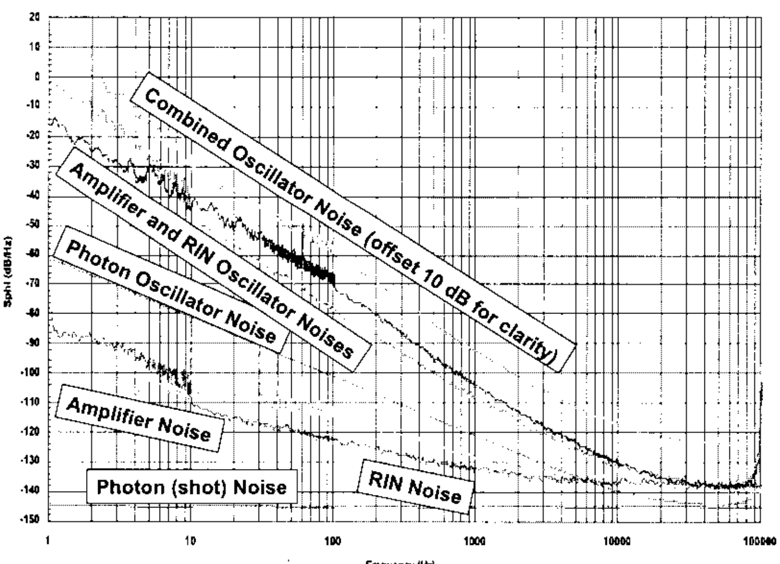
Noise Sources and Effect on Phase Noise

For OEO with 2km Fiber Length



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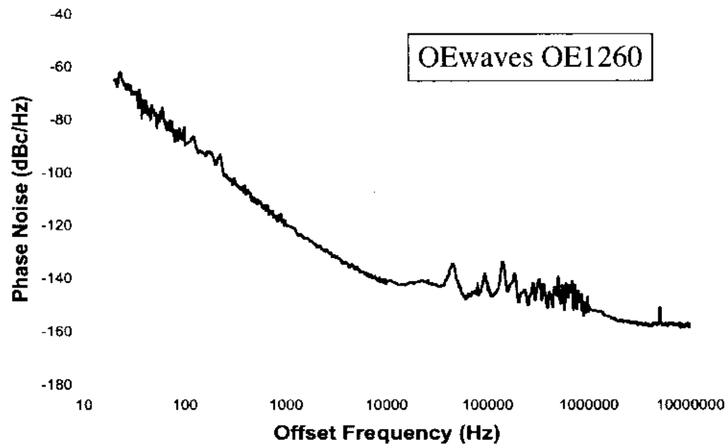
Typical phase noise of an OEO (10GHz)



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Other performance characteristics of the OEO

- Fixed frequency from MHz to 40GHz and beyond.
- Harmonics –40dBc.
- Frequency vs. temperature slope of –0.1ppm/°C.
- Allan deviation of $2 \cdot 10^{-11}$ at 1sec.
- Frequency stability of 0.02ppm over 1 hour.
- Phase locking achievable through VCP.
- Vibration and acceleration sensitivity at 10^{-10}/g.

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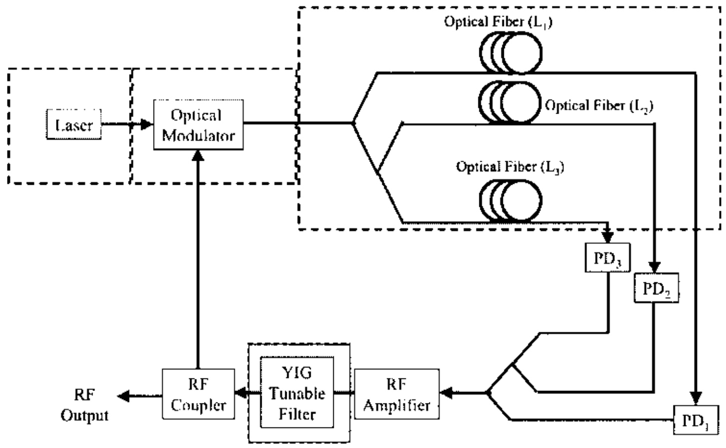
Multi-loop tunable OEO



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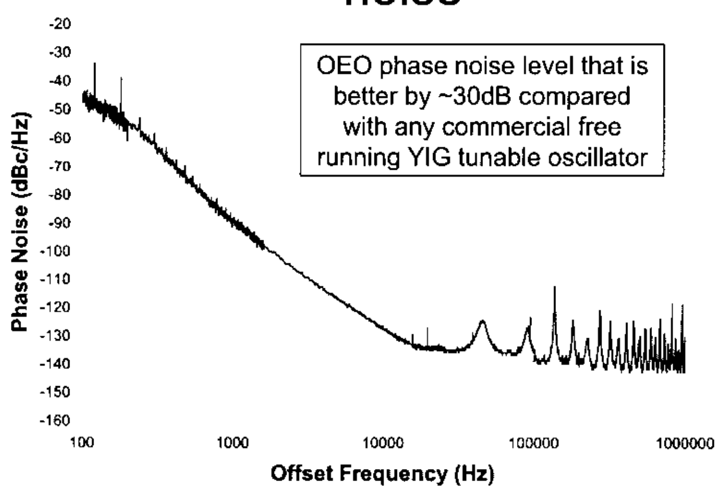
YIG tunable OEO – phase noise



OEO phase noise level that is better by ~30dB compared with any commercial free running YIG tunable oscillator

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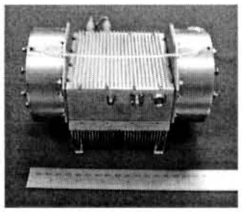
Packaged OEO with Vibration Compensation



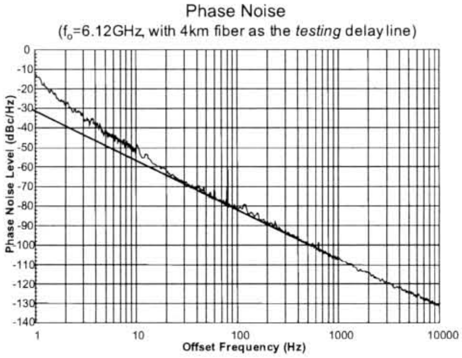
- Packaged OEO with vibration compensation (reduced the acceleration sensitivity).

Vibration Test Results (without fiber delay line compensation)
OEO-2, Fc=11.763 GHz, Fv=40 Hz, Value in 10^{-10}/G

Number of Test	Γx	Γy	Γz	ΓT
1	0.713	0.650	32.259	32.273
2	0.465	0.900	32.146	32.162
3	0.453	1.124	30.870	30.894
4	0.584	0.982	31.484	31.505
5	0.556	0.485	33.886	33.894
Average	**0.554**	**0.828**	**32.129**	**32.144**

Vibration Test Results (with fiber delay line compensation)
OEO-2, Fc=11.763 GHz, Fv=40 Hz, Value in 10^{-10}/G

Number of Test	Γx	Γy	Γz	ΓT
1	0.713	0.650	0.970	1.368
2	0.465	0.900	1.140	1.525
3	0.453	1.124	0.460	1.296
4	0.584	0.982	0.820	1.406
5	0.556	0.485	0.740	1.045
Average	**0.554**	**0.828**	**0.826**	**1.294**



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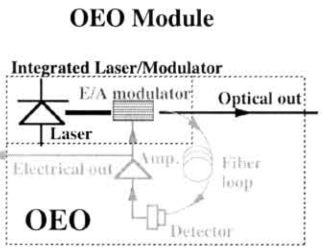
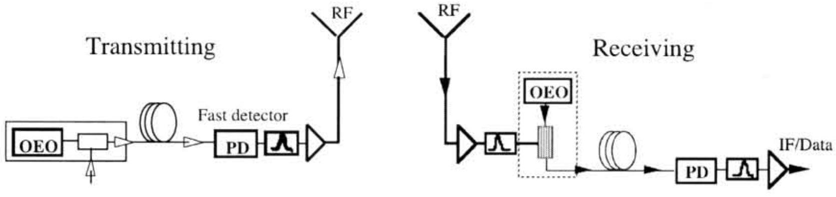
OEO and Optical distribution of Reference Signal



Advantages:

- * Dual electrical & optical outputs
- * High spectral purity, low phase noise
- * Frequency up to 100 GHz
- * Compact & potentially low cost
- * Tunable & VCO
- * Eliminate external LO ==> lower cost

No external LO needed



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Microsphere -- a low-loss photon trap, novel optical (micro)cavity

Whispering-gallery modes - closed circular waves under total internal reflection

(Term by J.W.S.Rayleigh, analogy to acoustic modes in the gallery of St Paul cathedral)

Sustained in any axisymmetric dielectric body with $R \geq \lambda$

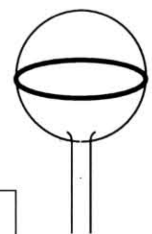
low material loss (transparent material, e.g fiber grade silica)

low bending loss ($R >> \lambda$)

low scattering loss (TIR always under grazing incidence

+ molecular-size surface roughness)

Quality-factor $Q = \lambda/\Delta\lambda_{RES}$	-	up to $\sim 10^{10}$
Photon lifetime $\tau = \lambda Q/2\pi c$ (cavity ringdown time)	-	up to $\sim 3\mu s$
visible and near-infrared band:	*Opt.Lett. 21, p.453 (1996)* *Opt.Lett. 23, p.247 (1998)*	



Visualization of WG mode field by residual scattering in silica microsphere, *V.S.Ilchenko et al, Opt.Commun. 113, p.133(1994)*

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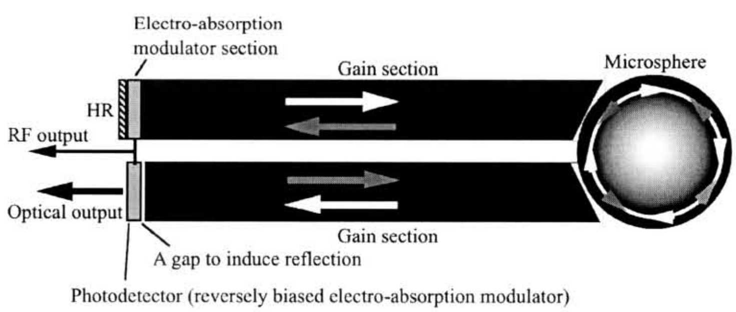
Opto-electronic Oscillator on Chip



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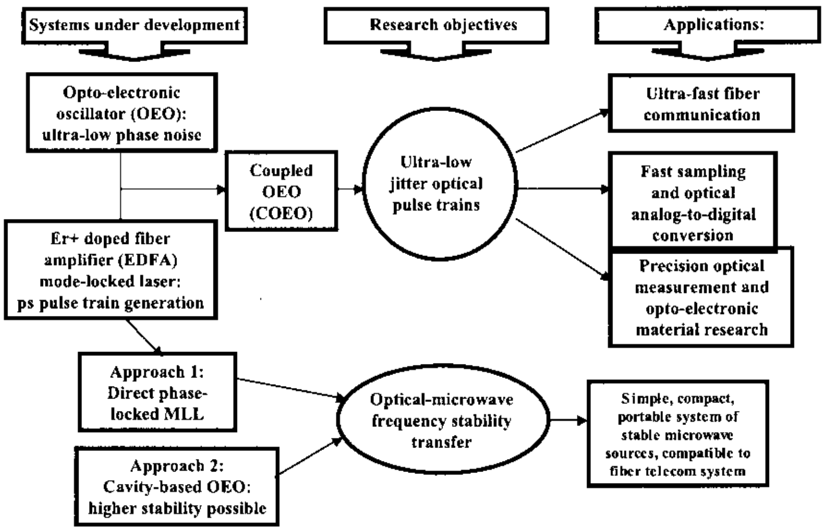
COEO



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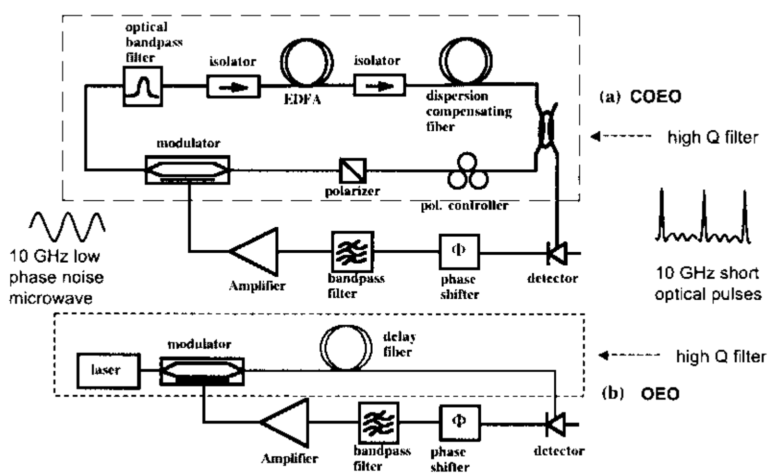
Mode-locked Laser (MLL), Opto-electronic Oscillator (OEO) and Coupled Opto-electronic Oscillator (COEO)



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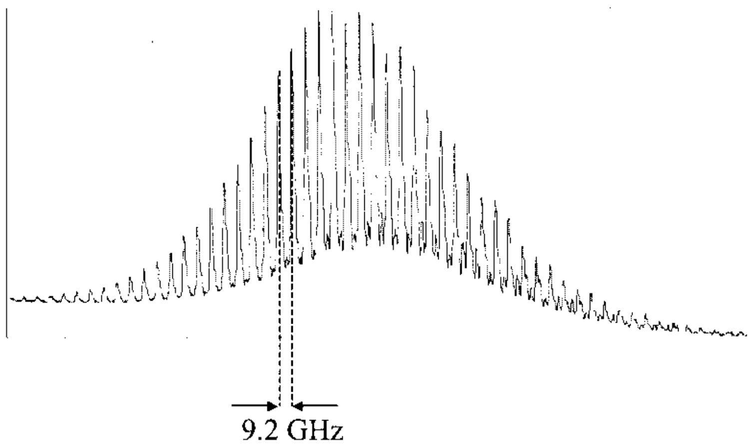
Locking modes



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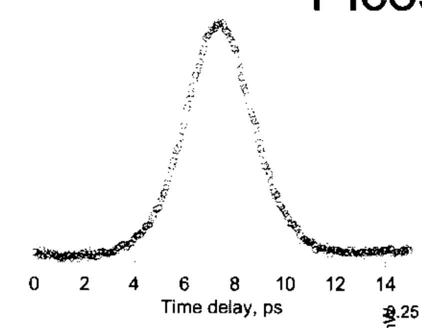
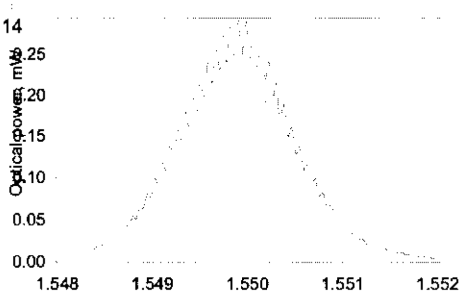
Picosecond pulse



2 ps pulse every ~100 ps



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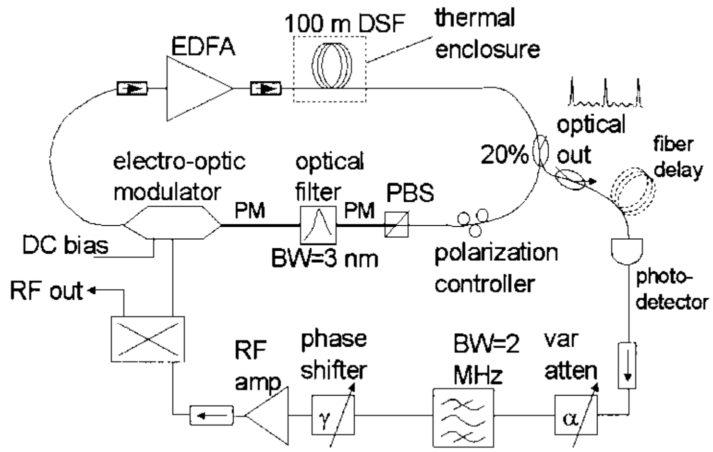
Coupled opto-electronic oscillator



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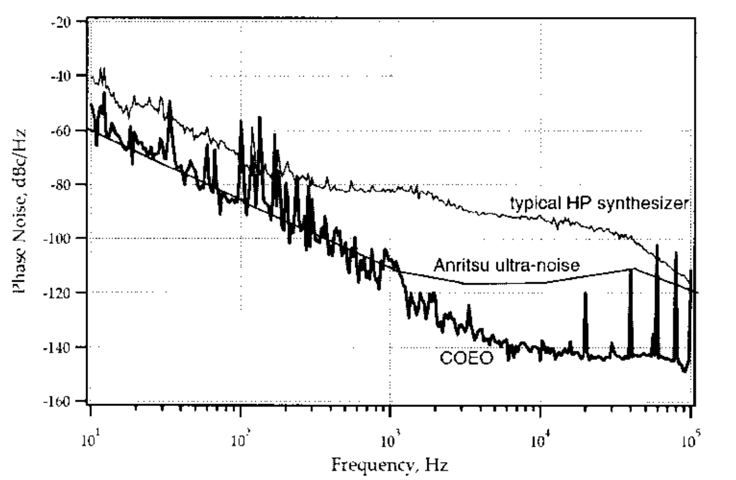
Measured Phase Noise of the COEO



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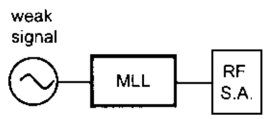
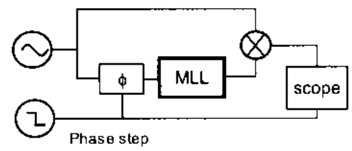
Small Signal and off-Resonance Responses





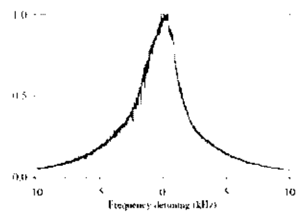
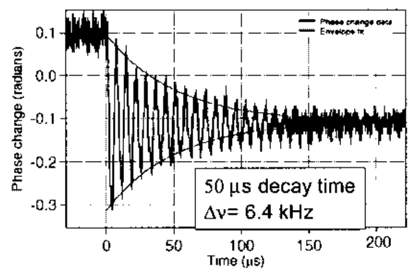
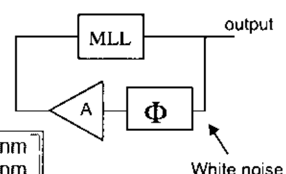
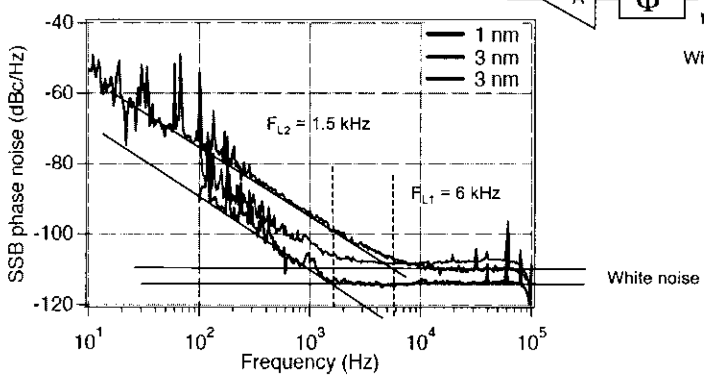


Figure 2. The measured microwave frequency response of the laser loop. A Lorentzian fit gives 3.5 kHz FWHM.



Experimental Verification of Leeson Frequency





Noises in the Mode-locked Laser As Filter

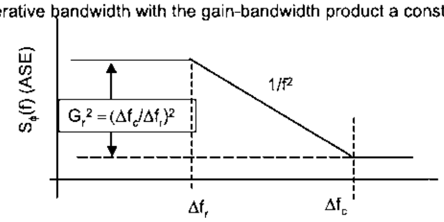
Noise source in the rf detector: laser quantum noise, photon shot noise, all white noise. No flicker that exists in electronic amplifier.

1) Photon shot noise power $S_\phi(f) = 1/N$. Typical optical power at detector 1 mW, $N=10^{16}$, $S_\phi(f) = -160$ dBc.

2) Spontaneous emission, one photon per cycle/Hz per second, $h\nu_0 = 1.3\times10^{15}$ W/Hz = -160 dBm/Hz.

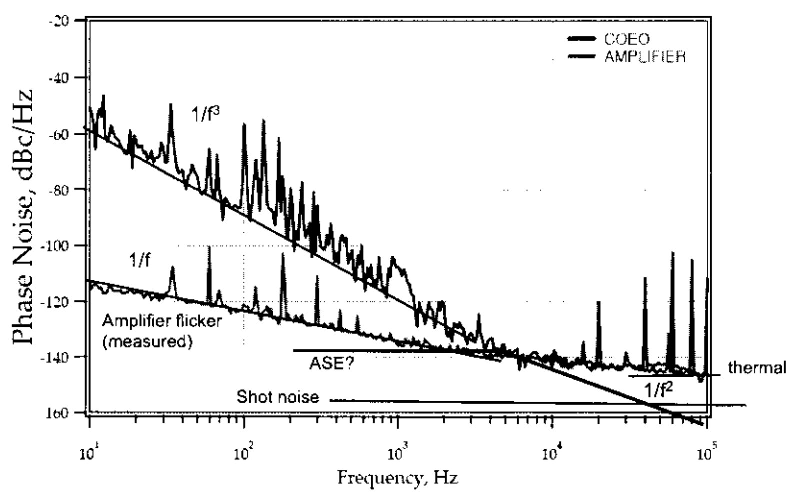
3) For comparison, amplifier thermal noise KT = -174 dBm/Hz.

Equivalent phase noise of the MLL laser as an rf filter:
The regenerative process in the loop amplifies the spontaneous emission by G_r within the regenerative bandwidth with the gain-bandwidth product a constant Δf_c.



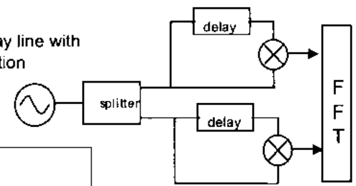
Relative high circulating optical power and free of flicker noise.

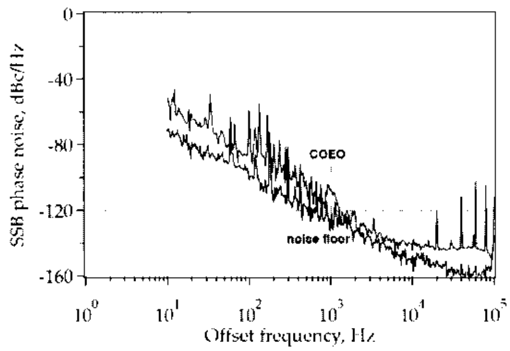
Analysis of the Measured Oscillator Phase Noise



Oscillator Noise Measurement Technique

Photonic delay line with cross correlation





Please come to two talks FC1 H-4 and FC1 H-5 on Friday on PN measurements with photonic delay lines.

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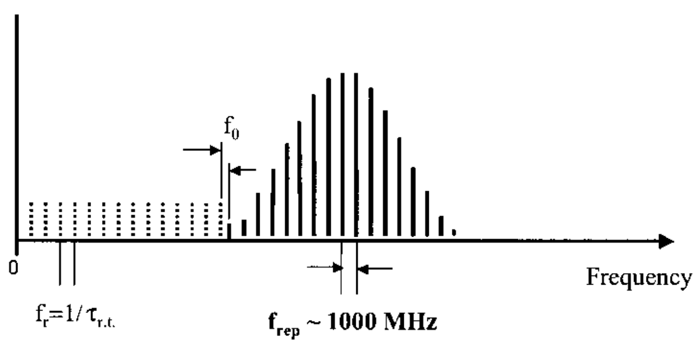
The frequency of a mode is simply $\mathbf{F_N} = N * \mathbf{f_{rep}} - \mathbf{f_0}$ → 0

Where N is and integer ~ 10^6



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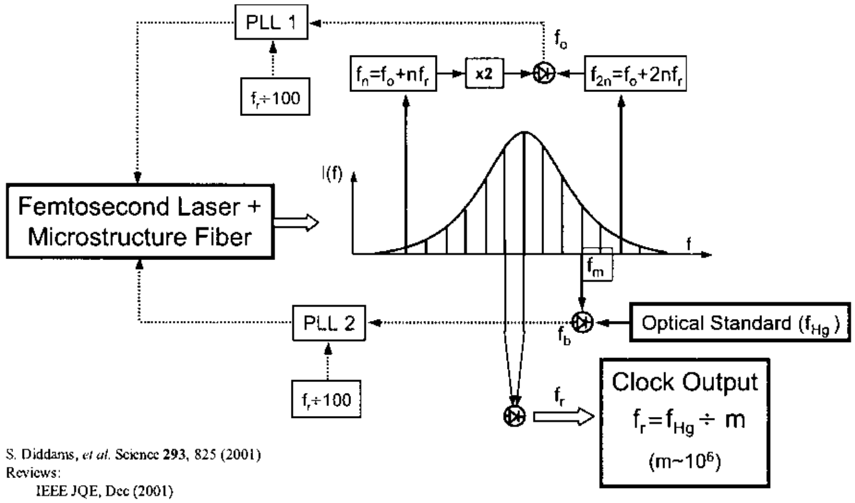
Optical Clock with a Femtosecond Synthesizer



S. Diddams, *et al.* Science **293**, 825 (2001)
Reviews:
IEEE JQE, Dec (2001)
IEEE JSTQE tbp (2003)

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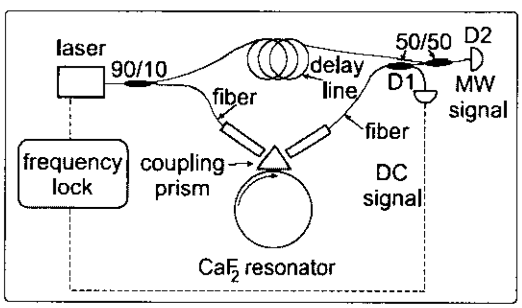
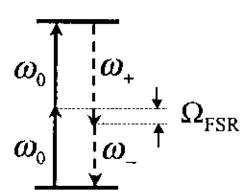
Hyper-parametric oscillations in fluorite resonators



Transition diagram



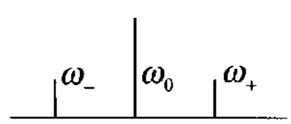
$Q = 2\times10^{10}$ *at* $\lambda = 1310\,nm$

Selection rules

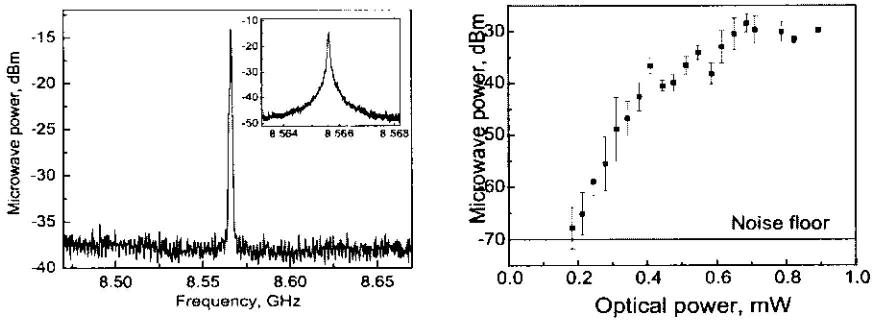
FWM: TE-TE

SRS: TE-TM

Optical spectrum



Microwave beat note observed



- Second-order ($2\Omega_{FSR}$) beat note is insignificant
- Raman scattering is not observed (expected at 322 cm^{-1})

A.A.Savchenkov et al., Submitted to PRL (2004)

Noise sources in photonic systems

- Thermal noise: kT
- Shot noise: 2eIR
- Laser RIN (relative intensity noise): <DP2>/P2
- 1/f RIN (at < 10 kHz)
- Relaxation oscillation RIN peak
- Interferometric noise
- Double Rayleigh scattering noise
- Brillouin scattering caused noise
- Fiber dispersion mediated noise
- Fiber thermal noise

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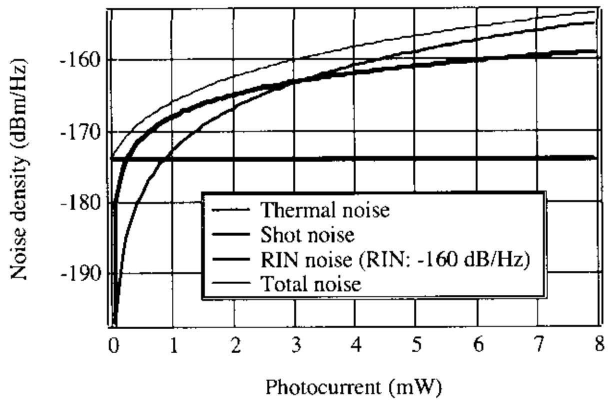
White Noise



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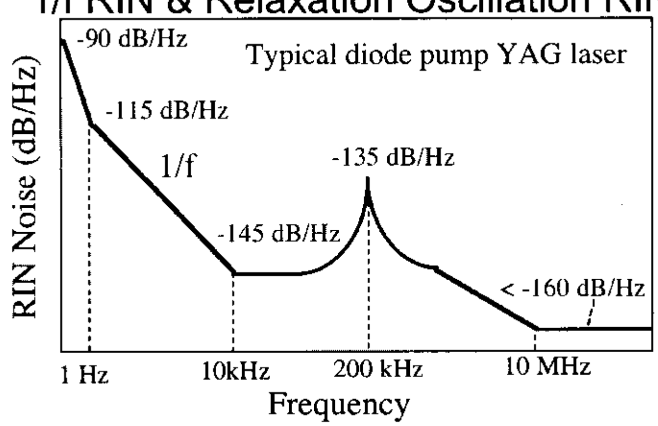
1/f RIN & Relaxation Oscillation RIN



* The low frequency 1/f noise & relaxation oscillation peak will be multiplied up by the modulator & affect the signal

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Fiber thermal fluctuation noise

Just like Johnson's noise, fiber's refractive index fluctuates with kT

First studied by fiber gyro researchers

For 9/125 um fiber @ 1.3 um

$\langle \Delta f \rangle / f = \langle \Delta L \rangle / L \sim 10^{-12} / L^{1/2}$

$L = 100$ m $\Longrightarrow \langle \Delta f \rangle / f \sim 10^{-13}$

$L = 10$ km $\Longrightarrow \langle \Delta f \rangle / f \sim 10^{-14}$

Fiber dispersion mediated noise

Dispersion: different light frequency "see" different fiber lengths

Optical frequency fluctuation
==> RF phase fluctuation

For standard single mode fiber,
1 nm away from zero dispersion:

$\langle \Delta f \rangle / f = \langle \Delta L \rangle / L \sim 0.6 \times 10^{-5}\, \Delta \upsilon / \upsilon$

$\Delta \upsilon / \upsilon$: laser frequency stability

$\Delta \upsilon / \upsilon = 10^{-10} \Longrightarrow \langle \Delta f \rangle / f = 6 \times 10^{-15}$

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APPENDIX

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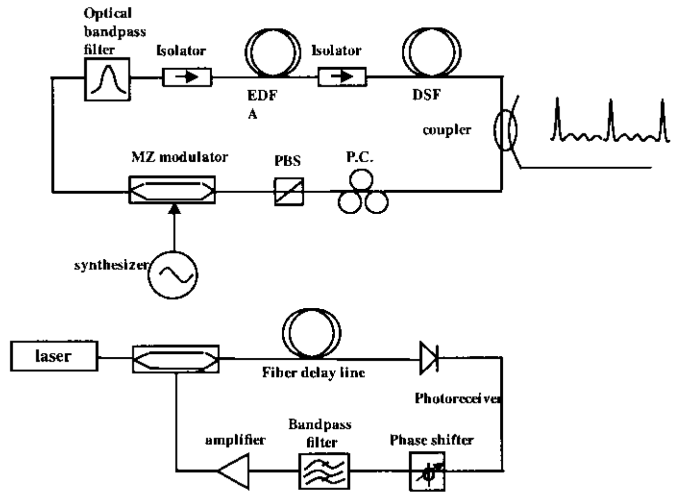
Ref Carruthers et al., Opt. Lett., v23 (1996);
Yoshida et al., Electron. Lett., v32 (1996);
Li et al., IEEE Photon. Technol. Lett., v12 (2000).



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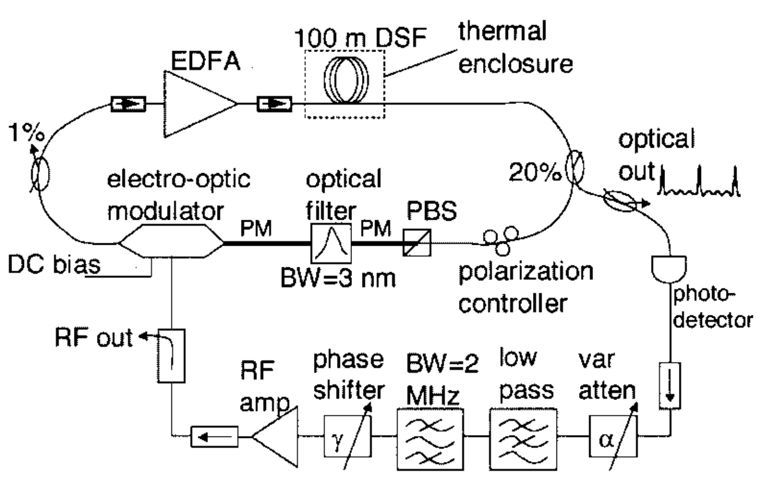
Experimental Setup Details



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Advantages of Optical Fiber

- Wide Bandwidth ==> High frequency
  - 20 MHz-km (multimode) to > 100 GHz-km (single mode)
  - With wavelength division multiplexing, > 1Tb/s over 600 km demonstrated.
- Low Loss ==> High Q delay line for low phase noise
  - ~0.5 dB/km @ 1300 nm, 0.2 dB/km @ 1550 nm
- Low thermal-induced delay change ==> High stability
  - Single mode fiber: 7 ppm/°C, Special fiber: < 0.1 ppm/°C
- No RFI or EMI problems ==> Immune to spurious noise sources
- Electrical isolation between ends
- No ground loops
- Small, lightweight, & corrosion resistant
- Material is plentiful & inexpensive
- Cost/capacity ratio is extremely low

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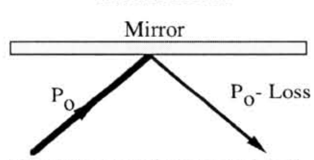
How Fiber Works

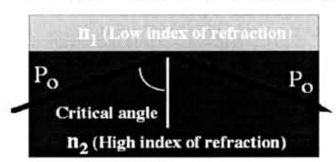
Snell Law

Reflection



All mirrored surfaces have loss!!

Total Internal Reflection



No Loss!!

* n = c/v

c = the speed of light in a vacuum (3 x 10^8 m/s)

v = the speed of light in the material (~ 2 x 10^8 m/s in glass)

* The index of refraction of glass can be changed by adding impurities (doping)

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Basics of Optical Fiber

History

- 1910: Concept conceived by Hondros & Debye
- 1915: Existence of a dielectrically guided wave demonstrated by Zahn, Ruter & Schriever
- 1959: Waveguide modes in optical fiber observed by Snitzer & Hicks.
- 1965: Fibers with a loss less than 20-dB/km for fiber optic communications proposed by Kao.
- 1970: Practical fiber with 20 dB/km loss announced by Kapron, Keck, & Maurer.
- 1972: 4 dB/km loss fiber developed by Corning.
- Today: Fiber has a loss of **0.2 dB/km** @ 1550 nm