



Photonic Techniques for Frequency & Timing

A Tutorial

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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

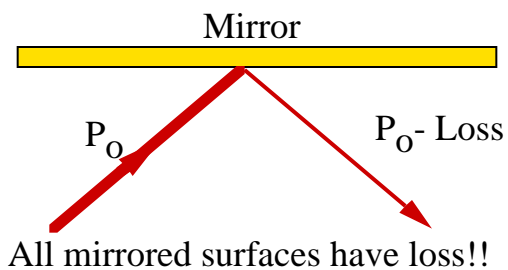
Advantages of Optical Fiber

- **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**

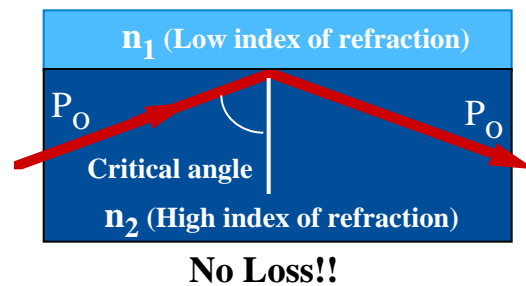
How Fiber Works

Snell Law

Reflection



Total Internal Reflection



* $n = c/v$

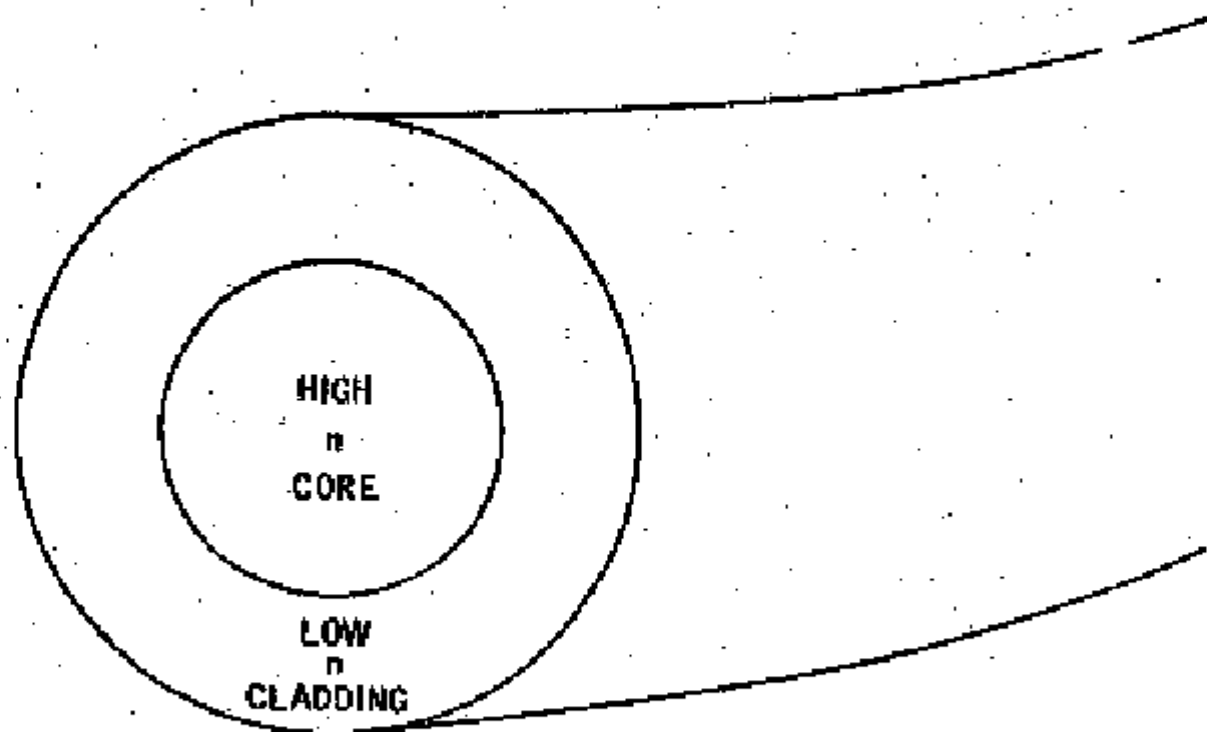
c = the speed of light in a vacuum (3×10^8 m/s)

v = the speed of light in the material ($\sim 2 \times 10^8$ m/s in glass)

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



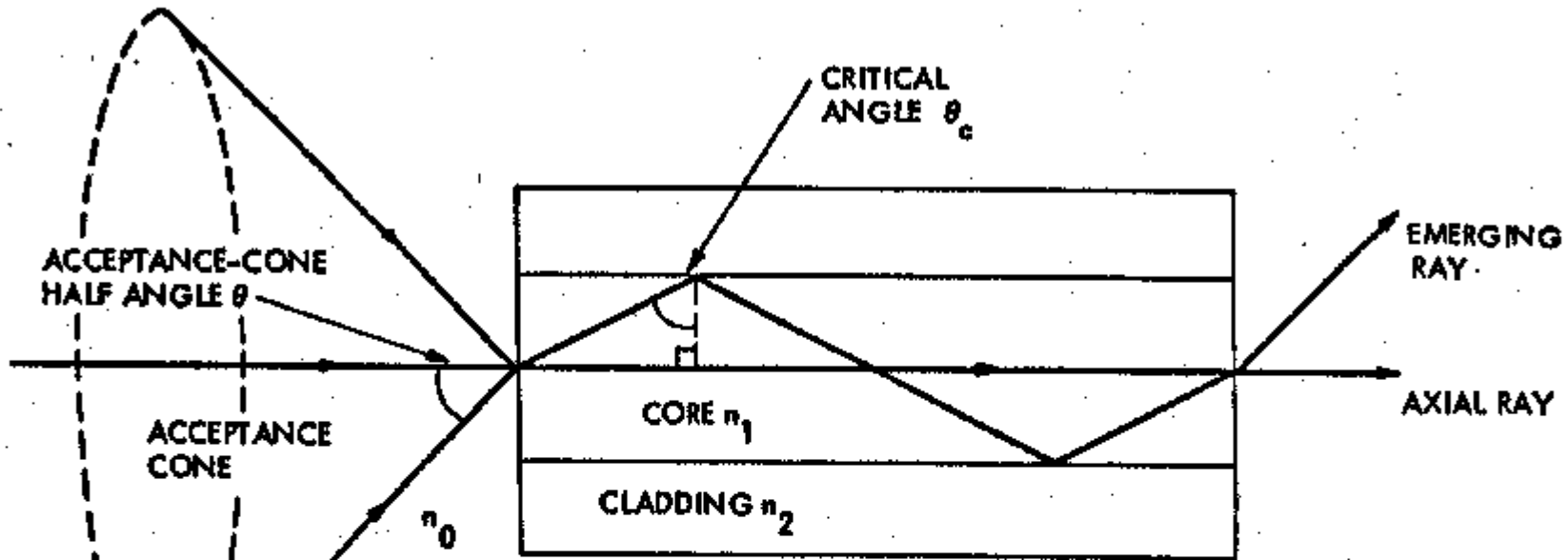
IMPLEMENTATION OF SNELL LAW



- LIGHT TRAVELING IN THE CORE AT GREATER THAN THE CRITICAL ANGLE IS TRAPPED. EACH TIME A RAY APPROACHES THE CLADDING, IT IS DEFLECTED BACK INTO THE CORE



OPTICAL FIBER PARAMETERS



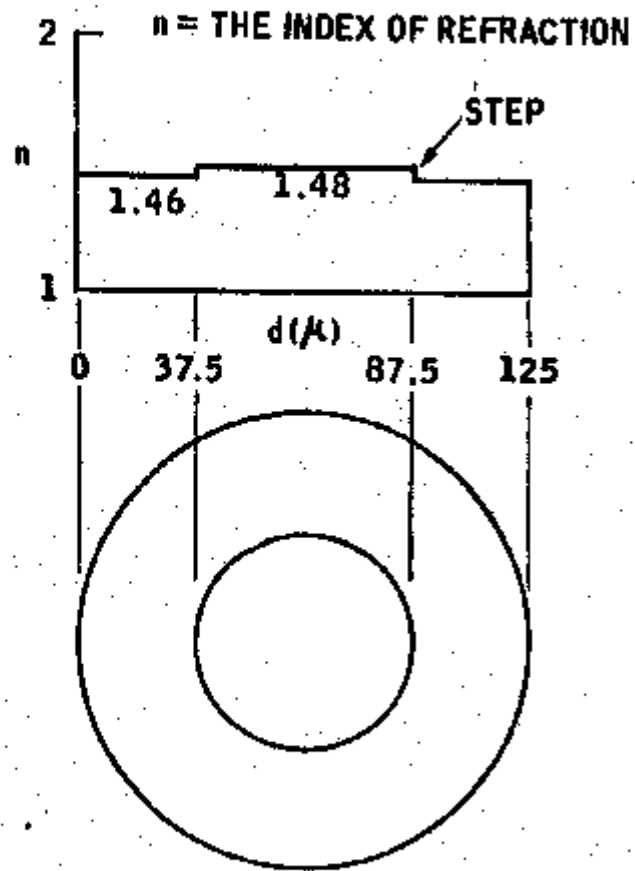
- n_0 = INDEX OF REFRACTION OF AIR
- n_1 = INDEX OF REFRACTION OF THE CORE
- n_2 = INDEX OF REFRACTION OF THE CLADDING

$$\theta = \text{ARC SIN} (n_2/n_1)$$
$$\theta = \text{ARC SIN} \left(\frac{1}{n_0} \sqrt{n_1^2 - n_2^2} \right) \text{ FOR STEP INDEX FIBER}$$

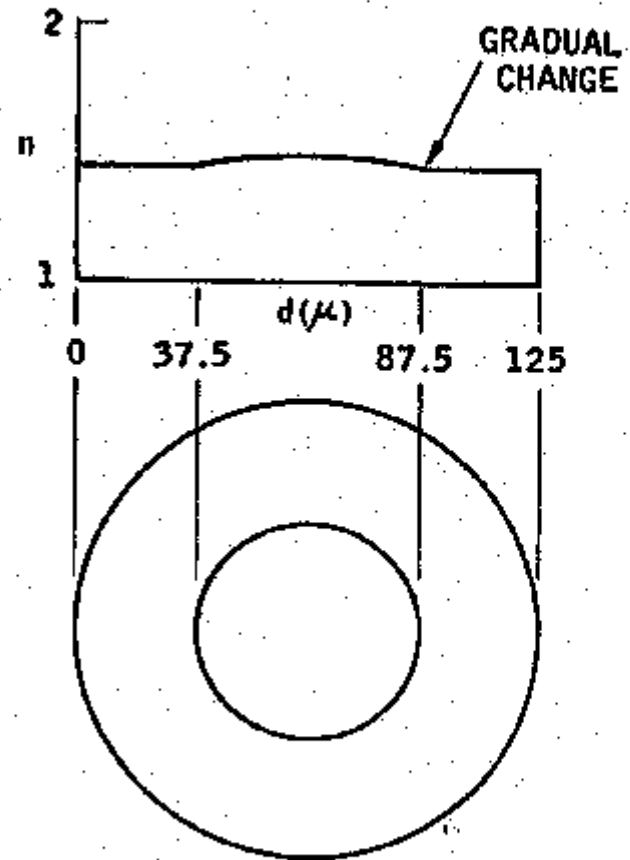
θ IS THE "NUMERICAL APERATURE" AND IS SPECIFIED BY THE MANUFACTURER



FIBER CONSTRUCTION



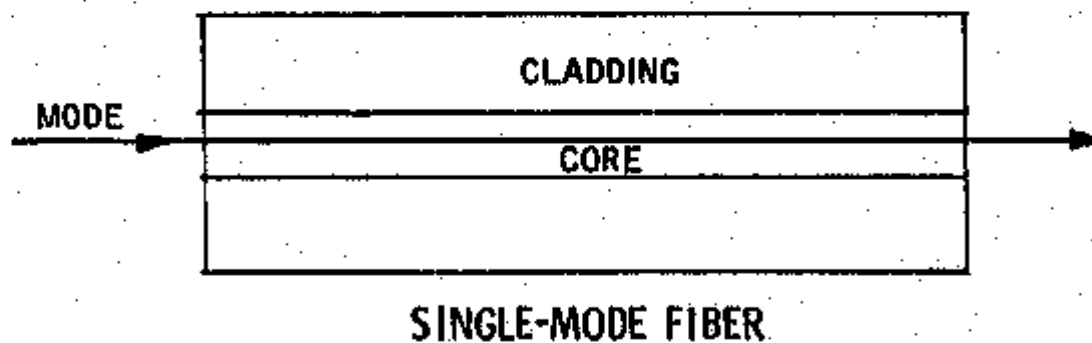
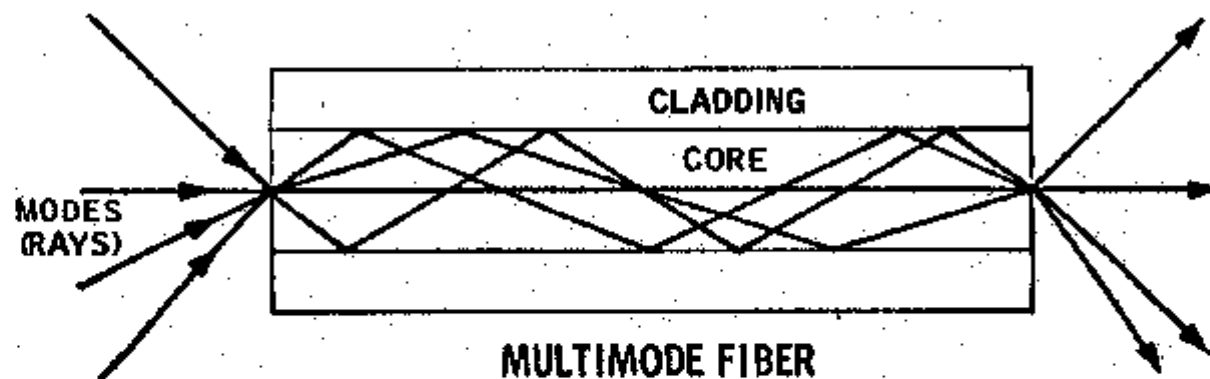
STEP INDEX FIBER



GRADED INDEX FIBER



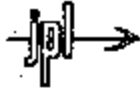
FIBER TYPES



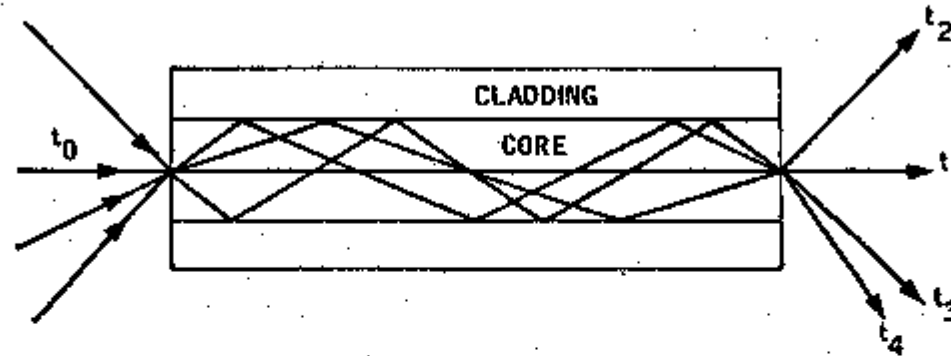


DISPERSION

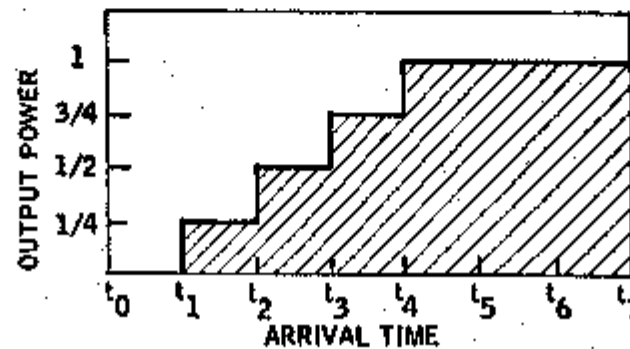
- DISPERSION LIMITS THE BANDWIDTH OF A FIBER
 - 20 MHz-km FOR STEP INDEX FIBER
- THERE ARE THREE TYPES OF DISPERSION
 - INTERMODAL DISPERSION
 - MATERIAL DISPERSION
 - WAVEGUIDE DISPERSION



INTERMODAL DISPERSION



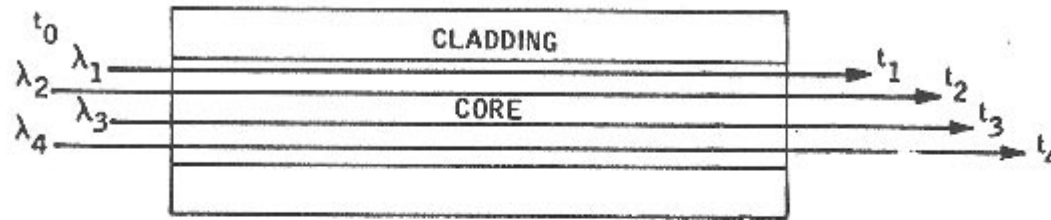
- ALL MODES LAUNCHED AT THE SAME TIME (t_0)
- MODES ARRIVE AT FAR END AT DIFFERENT TIMES
- EACH TRAVELS A DIFFERENT DISTANCE



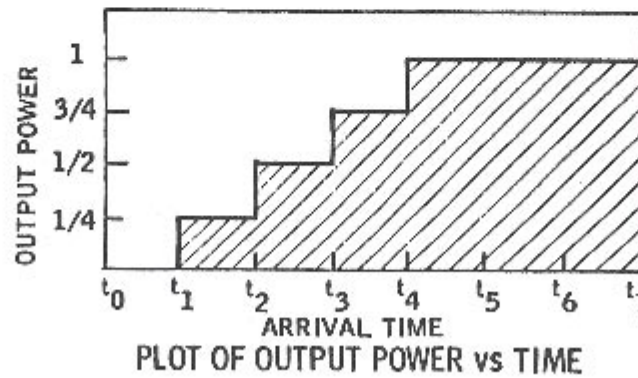
PLOT OF OUTPUT POWER vs TIME



MATERIAL DISPERSION

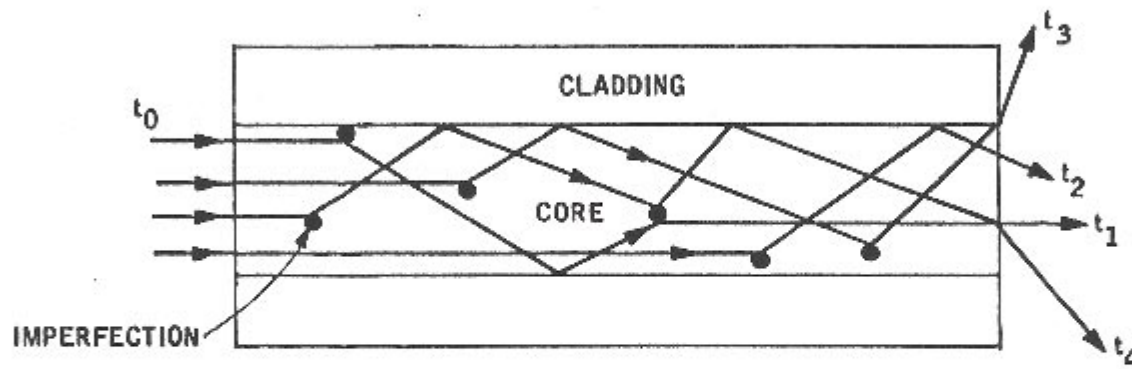


- VELOCITY OF LIGHT IN A FIBER IS DIFFERENT AT EACH WAVELENGTH
- DIFFERENT WAVELENGTHS ARRIVE AT FAR END AT DIFFERENT TIMES





WAVEGUIDE DISPERSION



- IMPERFECTIONS IN THE FIBER DEFLECT THE MODES
 - THIS CHANGES THE DISTANCE TRAVELED
- MODES ARRIVE AT THE FAR END AT DIFFERENT TIMES



REDUCING DISPERSION

- INTERMODAL DISPERSION

- GRADE THE INDEX OF REFRACTION SUCH THAT IT IS LARGEST AT THE CENTER AND DIMINISHES TOWARD THE CLADDING
 - LIGHT TRAVELING DOWN THE CENTER (SHORTEST DISTANCE) GOES SLOWER
 - LIGHT BOUNCING BACK AND FORTH AT THE GREATEST ANGLE TRAVELS FARTHER BUT SPENDS MORE TIME NEAR THE CLADDING WHERE n IS SMALLER. THEREFORE, IT GOES FASTER ON THE AVERAGE.
 - THE NET RESULT IS THAT THE RAYS REACH THE FAR END AT MORE NEARLY THE SAME TIME



REDUCING DISPERSION (cont.)

- INTERMODAL DISPERSION (CONT.)

- REDUCE THE CORE SIZE UNTIL ONLY ONE RAY, WHICH TRAVELS STRAIGHT DOWN THE CENTER OF THE FIBER, IS PASSED (SINGLE-MODE)

- MATERIAL DISPERSION

- OPERATE AT A WAVELENGTH WHERE DISPERSION IS NEAR ZERO (1300 nm FOR PRESENT FIBERS)
- USE A VERY STABLE LIGHT SOURCE THAT EMITS AT ONLY ONE FREQUENCY

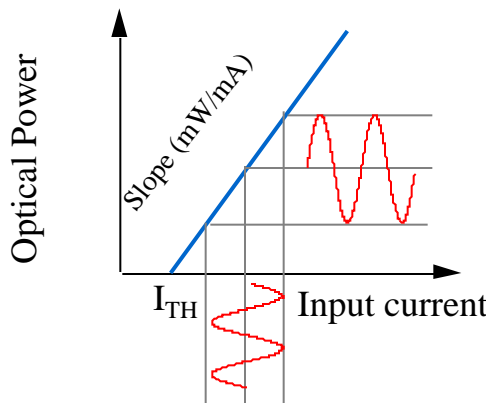
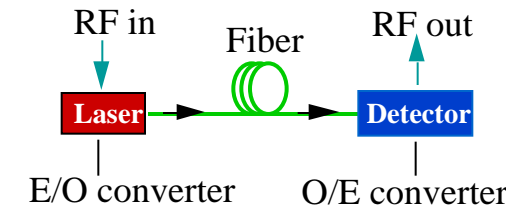
- WAVEGUIDE DISPERSION

- REDUCE IMPERFECTIONS

Basic Photonic links for RF applications

Directly modulated Link

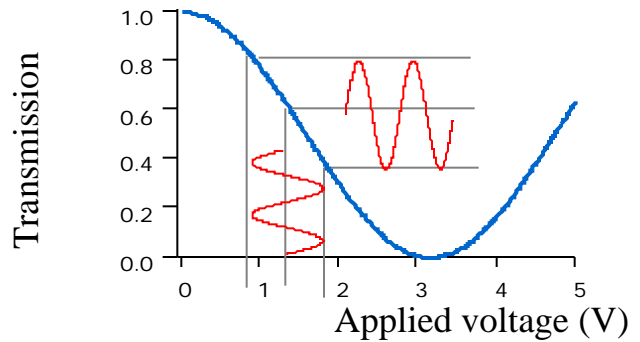
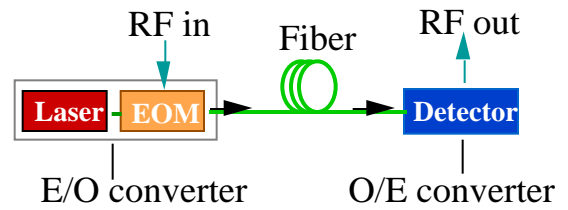
RF signal directly drives the laser



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

Characteristics of Fiber Optic Components

Optical Fiber

- **Multimode fiber**
 - High dispersion, low bandwidth, high modal beating noise.
 - Not recommended for frequency & timing.
- **Standard single mode fiber**
 - low cost: ~\$0.15/m
 - zero dispersion @ 1310 nm
 - thermal-induced delay change: ~ 7 ppm/°C
 - core/cladding sizes: 9/125 um, numerical aperture: 0.13
 - low attenuation: 0.5 dB/km @ 1310 nm, 0.2 dB/km @ 1550 nm
 - polarization fluctuates due to mechanical disturbances
- **Thermally compensated fiber**
 - Extremely low thermal-induced delay change:
 - 0.1 ppm/°C broad range, 0 ppm/°C @ a specific temperature
 - high cost

-- continue Characteristics of Fiber Optic Components

- **Polarization Maintaining (PM) Fiber**
 - support two polarization modes
 - No polarization fluctuation
 - Expensive: ~ \$20.00/m
 - difficult to connect: fiber axis alignment required
 - higher loss: < 2 dB/km @ 1310 nm & 1550 nm
 - Slightly smaller core size & larger NA than standard fiber
- **Polarizing (PZ) Fiber**
 - support only one polarization mode ==> fiber polarizer
 - most expensive ~ \$90.00/m
 - higher loss: <2 dB/km @ 1310 nm, <7 dB/km @ 1550 nm
 - higher bending loss

-- continue Characteristics of Fiber Optic Components

- **Dispersion-shifted fiber (DSF)**
 - Zero dispersion shifted to 1550 nm, where loss is the lowest
 - mode-field/cladding sizes: 8.1/125 μm , NA = 0.17
 - effective area: 50 μm^2
- **Non-zero dispersion-shifted fiber (NZ-DSF)**
 - Minimum **but non-zero** dispersion at 1550nm
 - reducing fiber nonlinear effects
 - mode-field/cladding sizes: 8.4/125 μm , NA = 0.16
 - effective area: 55 μm^2
- **Large core non-zero-dispersion-shifted fiber**
 - Minimum but non-zero dispersion at 1550nm
 - mode-field/cladding: 9/125 μm ,
 - larger effective area: 72 μm^2
 - further reducing fiber nonlinear effects

Choices of operating wavelengths

- **1310 nm range**
 - most analog links & past installed digital links
 - low cost standard fiber off-the-shelf
 - optical amplifier available
 - low noise diode-pumped YAG laser off-the-shelf
 - high speed modulators & detectors off-the-shelf
 - high speed semiconductor laser off-the-shelf
 - high power semiconductor lasers off-the-shelf
 - other fiber optic components off-the-shelf
 - low dispersion ==> low PM to AM noise conversion
 - low loss

Choices of operating wavelengths

- **1550 nm range**
 - most present & future digital links, WDM systems
 - lowest attenuation
 - Er⁺ doped fiber amplifiers (EDFA) off-the-shelf
 - low cost standard fiber off-the-shelf
 - dispersion shifted fibers (DSF) off-the-shelf
 - high speed modulators & detectors off-the-shelf
 - high speed semiconductor laser off-the-shelf
 - high power semiconductor lasers off-the-shelf
 - other fiber optic components off-the-shelf
 - low dispersion with DSF ==> low PM to AM noise conversion
 - most industrial support in the future

Choices of operating wavelengths

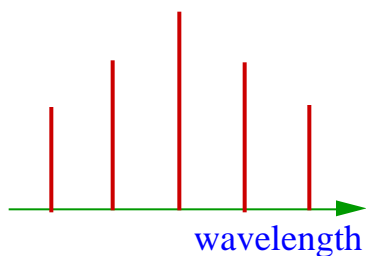
- **Other wavelengths --1060, 820, 780, & 630 nm**
 - high fiber attenuation
 - high cost optical fiber
 - high cost modulator
 - high cost lasers & detectors
 - high speed semiconductor laser not off-the-shelf
 - high power semiconductor lasers (single-mode fiber pigtailed) not off-the shelf
 - expensive custom-made fiber optic components
 - high dispersion ==> high PM to AM noise conversion
 - least industrial support in the future

Commonly used lasers for RF systems

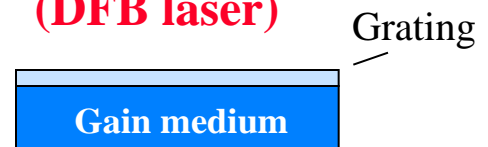
Fabry-Perot laser (F-P laser)



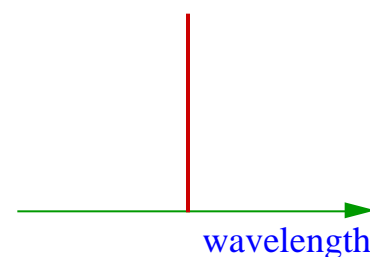
- * Optical feedback provided by the end mirrors
- * multi-longitudinal modes
- * higher noise due to mode competition



Distributed feedback laser (DFB laser)

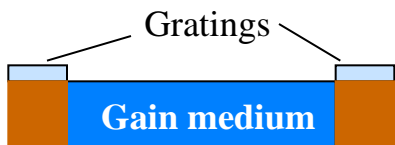


- * Optical feedback provided by the grating on top of the gain medium
- * single longitudinal mode
- * lower noise



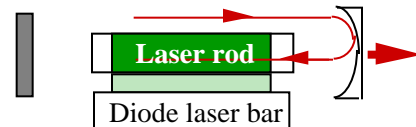
Commonly used lasers for RF systems

Distributed Bragg Reflector (DBR) Laser



- * Bragg gratings are narrow band reflectors
- * Optical feedback provided by grating reflection
- * single/multimodes operation

Diode-pumped solid-state laser



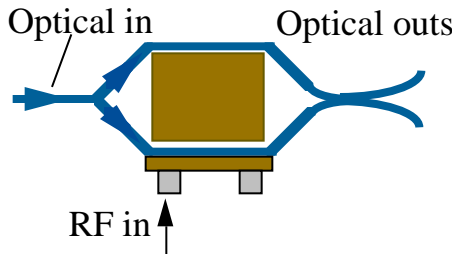
- * Solid state gain medium pumped by diode lasers
- * Narrowest spectral width
- * Lowest noise
- * Most expensive
- * Less reliable

Commonly used Photodetectors

- **InGaAs PIN photodiodes (0.8 - 1.7 μm)**
 - 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 μm)**
 - Lower responsivity: ~ 0.4 A/W
 - Highest speed: 60 GHz commercially available
 - Low saturation power: ~ 2 mW
- **Ge PIN photodiodes (0.8 - 1.8 μm)**
 - High responsivity: ~ 0.9 A/W
 - Higher dark current: ~ 1 nA
 - Not well developed for high speed: $\sim <6$ GHz

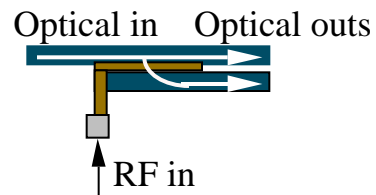
Modulators

Mach-Zehnder modulator



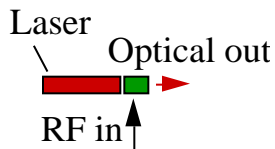
- * Wide Bandwidth: up to 100 GHz
- * Good linearity
- * No chirp (good)
- * Well developed, widely used
- * High drive voltage ==> High RF insertion loss

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: up to 60 GHz
- * Easy integration with diode lasers
- * Extremely compact
- * Low drive voltage * Modulation chirp (not good)

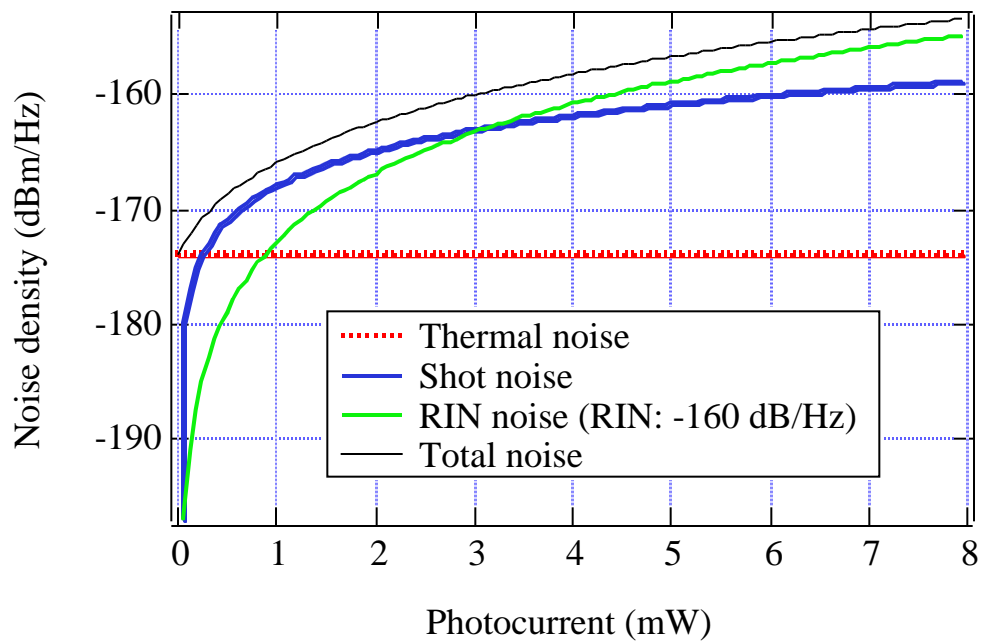
Other fiber optic devices available

- **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

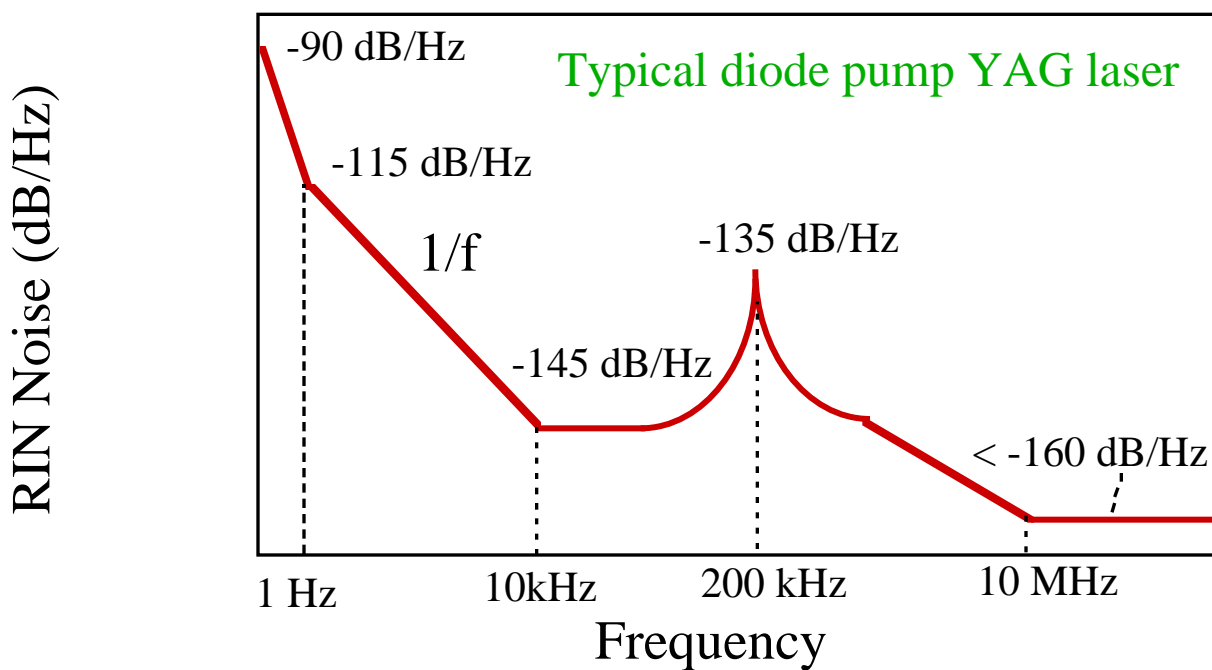
Noise sources in photonic systems

- Thermal noise: kT
- Shot noise: $2eIR$
- Laser RIN (relative intensity noise): $\langle P^2 \rangle / P^2$
- $1/f$ 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

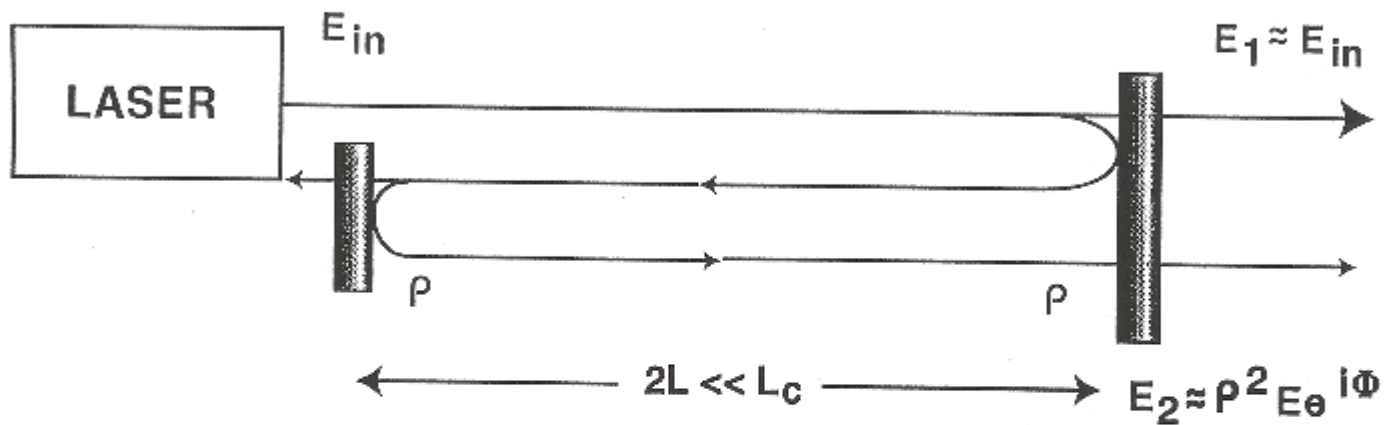
White Noise



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

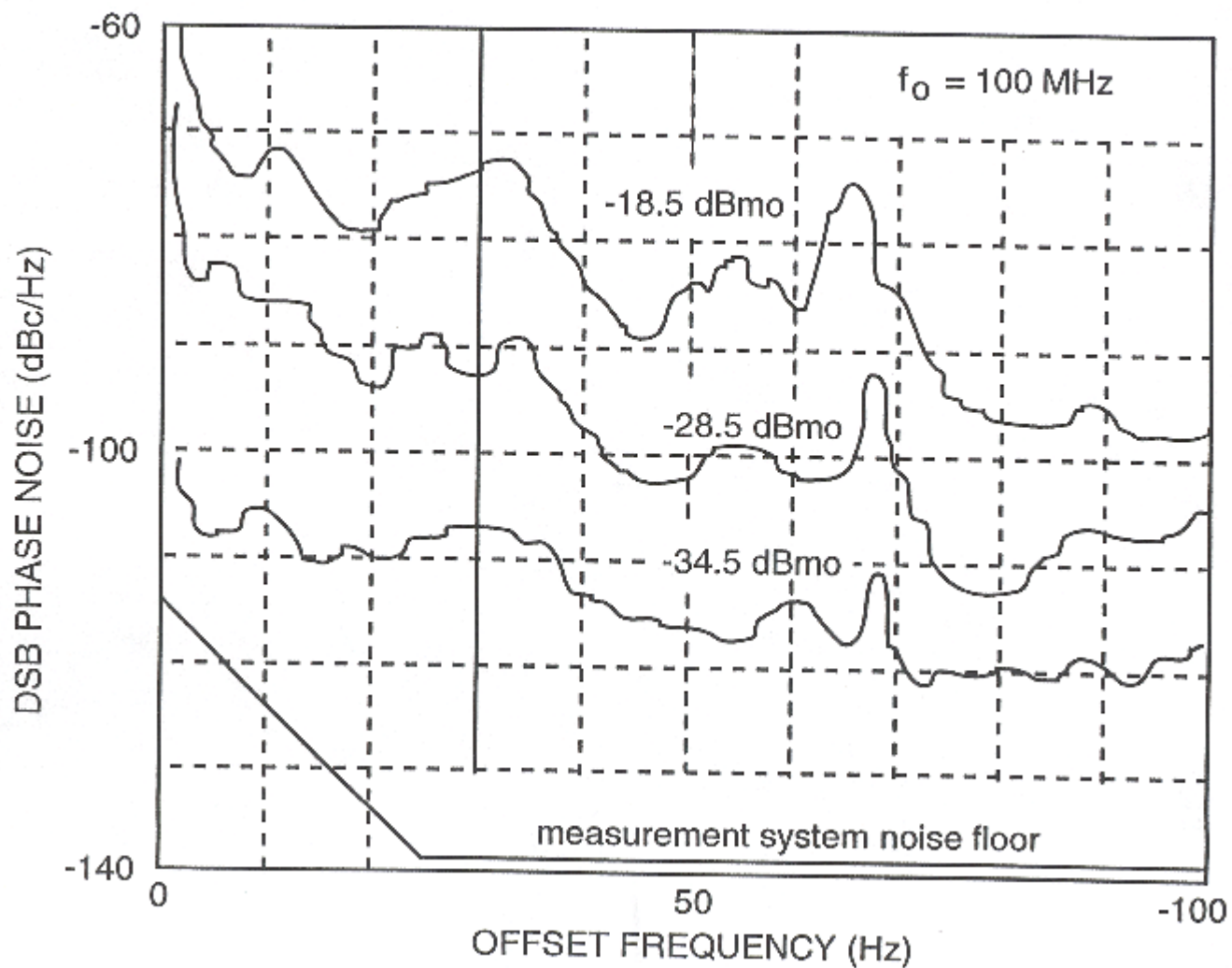


$$I \propto E_T^* E_T = I_{avg} + \Delta I_{pp} \quad \frac{\Delta I_{pp}}{I_{avg}} = \begin{cases} 4\rho^2, & \text{singly polarized} \\ \rho^2, & \text{scrambled} \end{cases}$$

for Fresnel reflection at glass - air: $\rho^2 = 0.04$

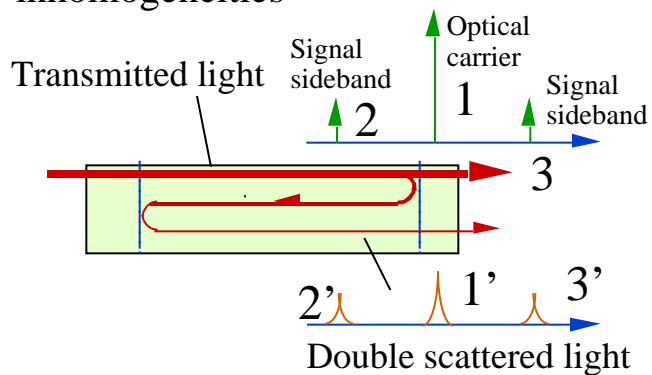


PHASE NOISE VS REFLECTED OPTICAL POWER



Double Rayleigh Scattering

Rayleigh scattering: photon being scattered from random material inhomogeneities



$$1+1', 2+2', 3+3' \implies$$

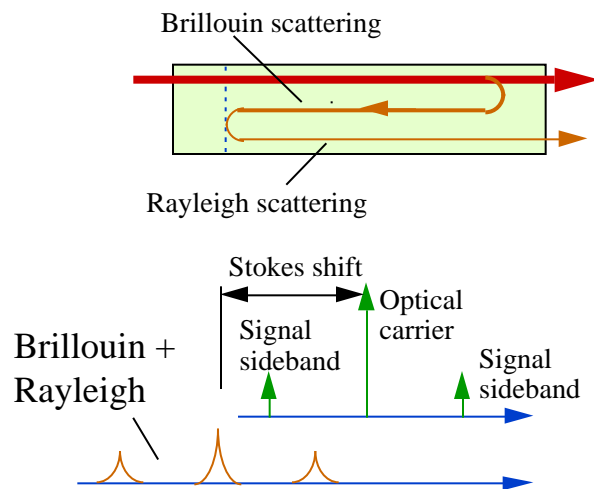
Low freq. noise (< 1 GHz), no wavy

$$1+2', 1+3', 1'+2', 1'+3' \implies$$

noise around signal!!

Brillouin + Rayleigh scattering

Brillouin scattering: photon being scattered by acoustic phonons in the fiber.



Scattered light is frequency down shifted (Stokes shift) from the entering light.

When modulation frequency = Stokes shift \implies noise around signal

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 μm fiber @ 1.3 μm

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

$$L = 100 \text{ m} \implies \langle \delta f \rangle / f \sim 10^{-13}$$

$$L = 10 \text{ km} \implies \langle \delta f \rangle / f \sim 10^{-14}$$

Fiber dispersion mediated noise

Dispersion: different light frequency "see" different fiber lengths

Optical frequency fluctuation
 \implies RF phase fluctuation

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

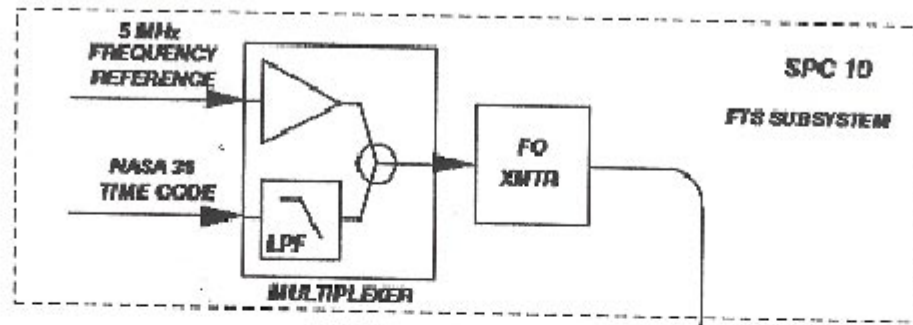
$$\langle \delta f \rangle / f = \langle \delta L \rangle / L \sim 0.6 \times 10^{-5} \quad /$$

/ : laser frequency stability

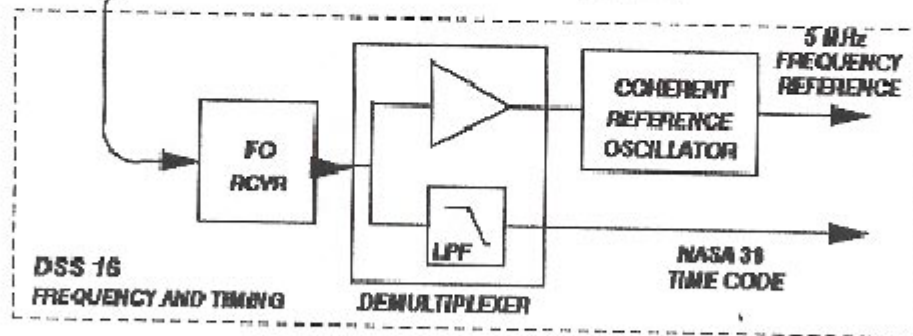
$$/ = 10^{-10} \implies \langle \delta f \rangle / f = 6 \times 10^{-15}$$

Fiber Optic Frequency Standard Distribution

- Frequency standards are extremely expensive
- Multiple users at different location share one standard ==> big money saving
- Distribution system should not degrade the performance of the standard
- In 1981, JPL pioneered the fiber optic frequency standard distribution
- The only workable solution so far



10 KM FIBER OPTIC CABLE

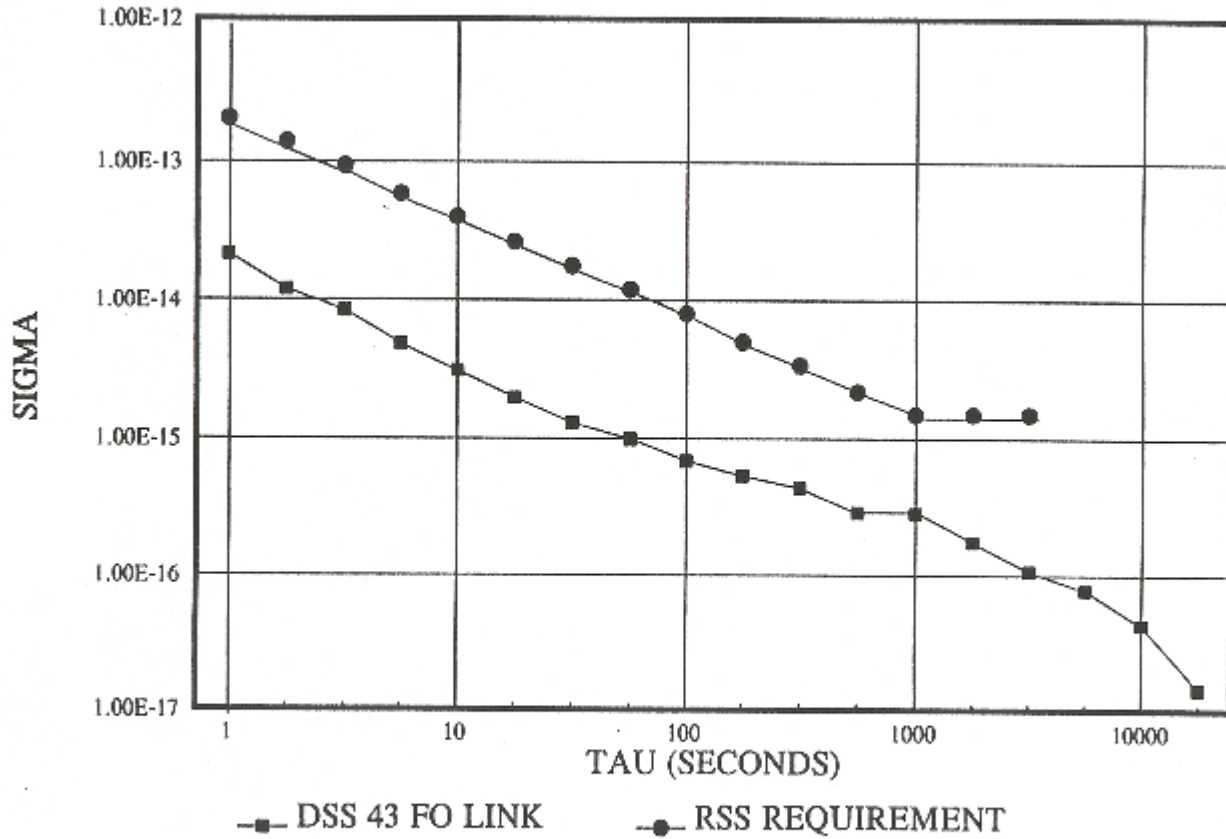


**FIBER OPTIC REFERENCE FREQUENCY
AND TIMING DISTRIBUTION ASSEMBLY
SPC 10 TO DSS 16**

JPL

JET PROPULSION LABORATORY

ALLAN DEVIATION AT CONE OF 70 M DSN ANTENNA



M. CALHOUN
SEC 331 8/5/93



PERFORMANCE vs SPECIFICATIONS

$L(f)$ dBc AT 100 MHz

OFFSET FREQUENCY, Hz	FTS SPEC.	LINK PERFORMANCE
1	-92	-119
10	-103	-128
100	-115	-134
1000	-115	-140
10,000	-115	-140

SPURIOUS OUTPUTS

NONE MEASUREABLE ABOVE NOISE LEVEL IN 1 Hz BANDWIDTH

ALLAN DEVIATION

TAU, SECONDS	FTS SPEC.	LINK PERFORMANCE
1	2E-13	2E-14
10	4E-14	4E-15
100	----	1E-15
1000	1.5E-15	5E-16
3000	1.5E-15	3E-16
10,000	----	2E-16

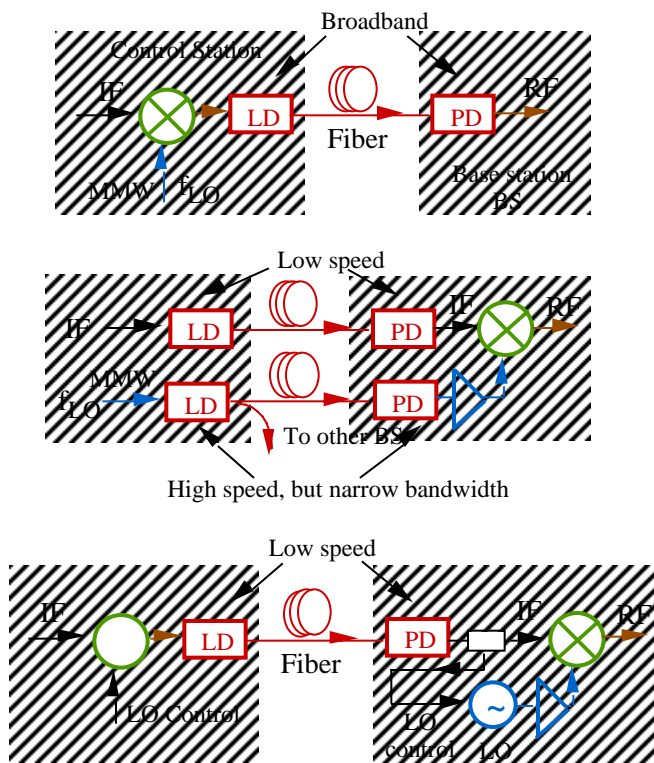


Photonic technology for signal mixing & multiplication

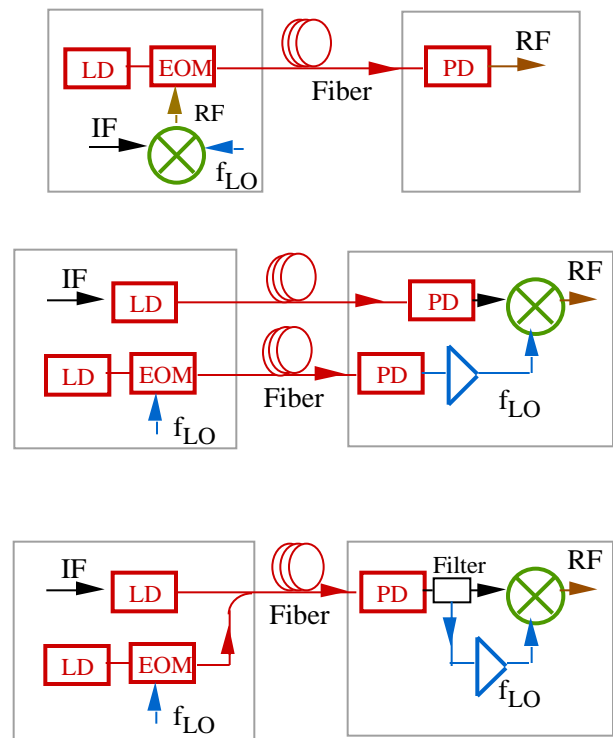
- Photonic links w/ traditional & photonic mixers
- Pros & cons of present photonic signal mixing
- SOA based photonic mixing links
- Brillouin Selective Sideband Amplification (BSSA) of RF signals
- BSSA based photonic mixing links
- OEO based photonic mixing links
- Summary

Fiber Optic Links w/ traditional mixers

Directly Modulated

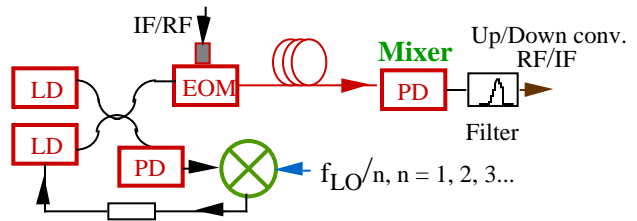
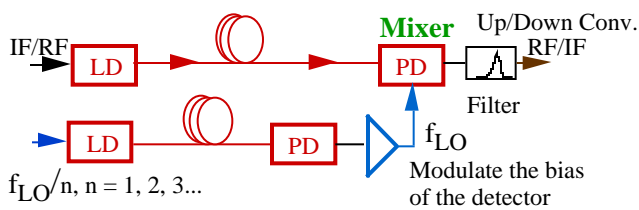
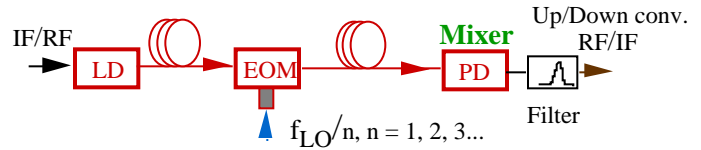
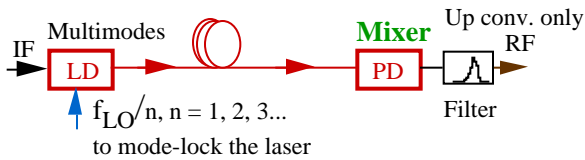
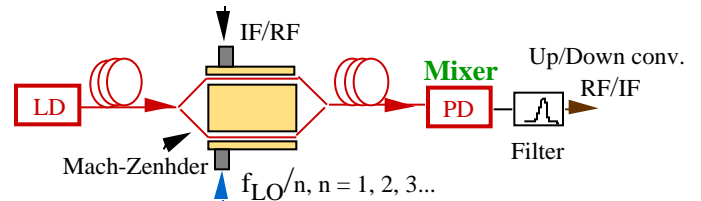


Externally Modulated



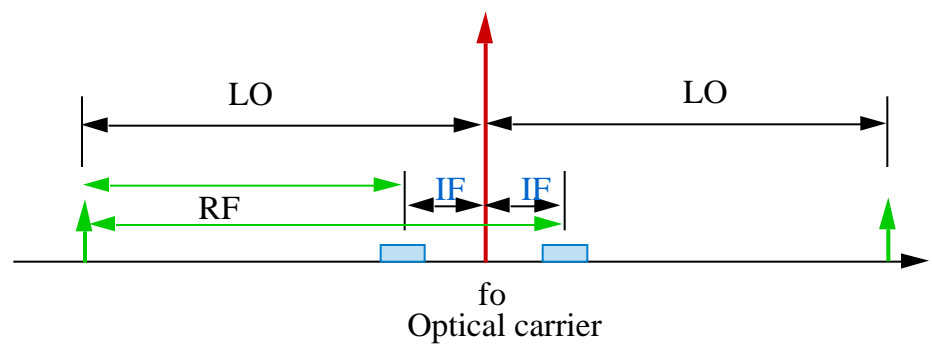
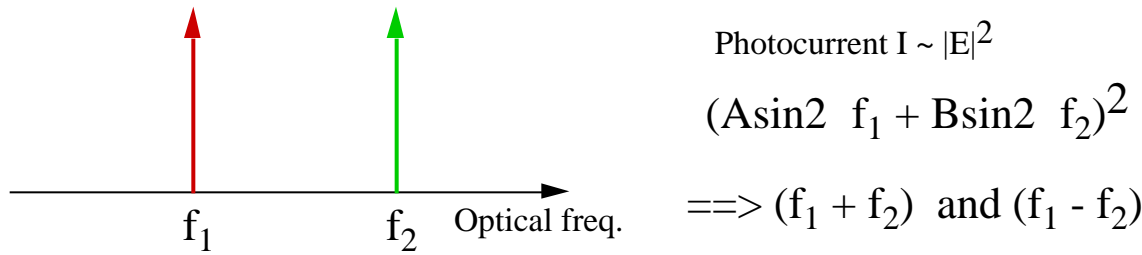
Photonic Mixing Links

- * Photodetector acts as mixer
- * Subharmonics of MMW used as LO to generate optical sidebands



Photodetector as a mixer

Power Law Photodetector ==> acts as a mixer



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

Pros & Cons of Present Photonic Mixing Links

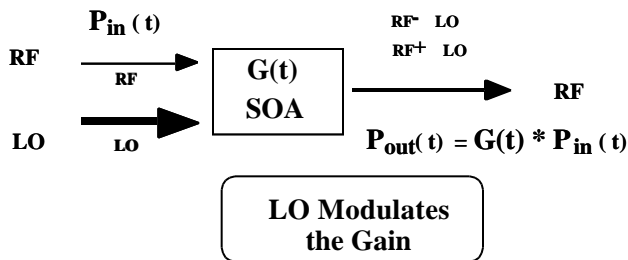
Pros

- * Separate LO trans. not needed
- * Harmonic up/down conversion
==> Lower freq. LO & circuit
- * Slow detector for down conv.
==> lower cost, higher power
- * Slow laser/EOM for up conv.
==> lower cost
- * Infinite isolation: LO & RF

Cons

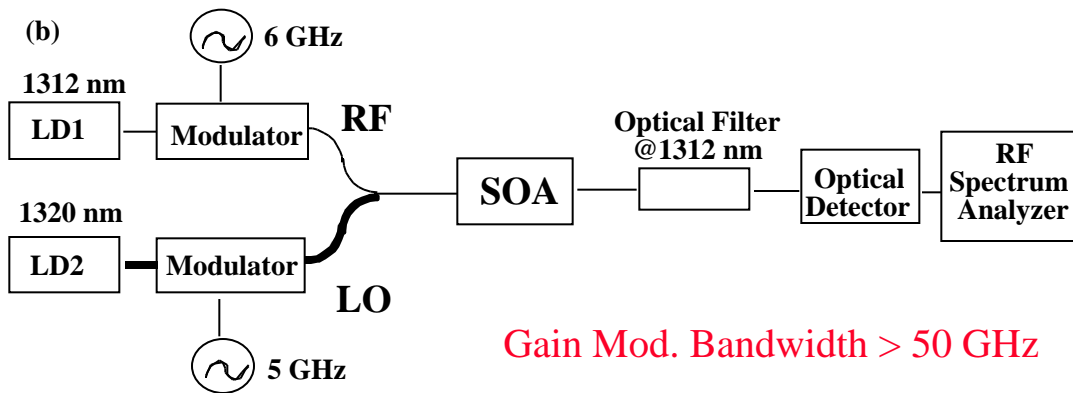
- * Low efficiency (most cases)
- * High LO power (some cases)
- * Freq. locking circuits needed
(some cases)

All-Optical RF Mixing Using a Semiconductor Optical Amplifier (SOA)



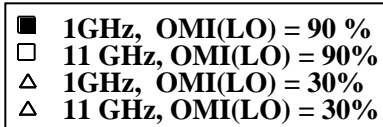
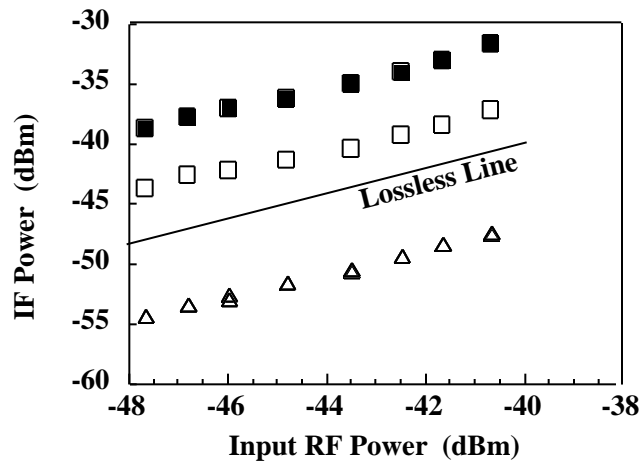
Advantages:

- * Mixing with Gain
- * Flexible LO location
- * LO can be distributed in the network

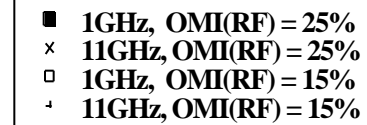
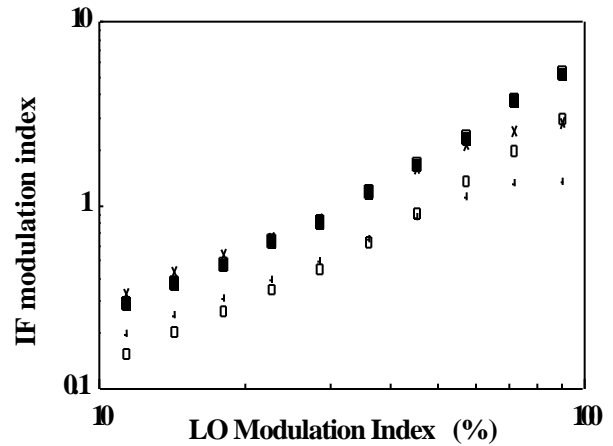


Performance of SOA Based Photonic Mixing Link

IF Gain Measurement



IF Optical Mod. Index

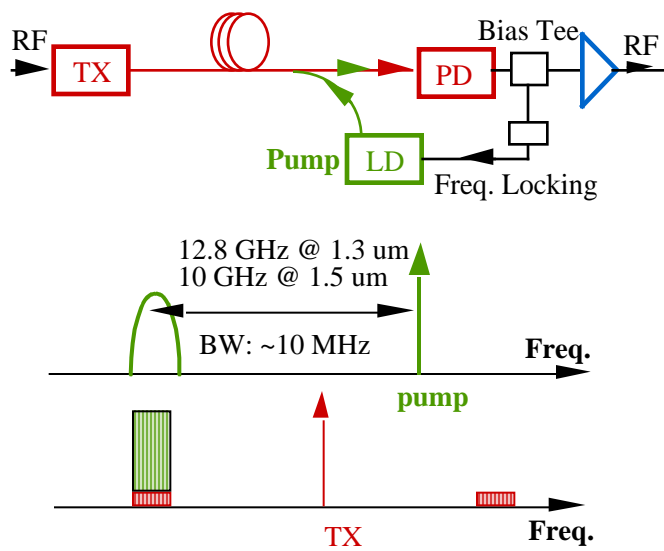


* IF Gain: 8 dB

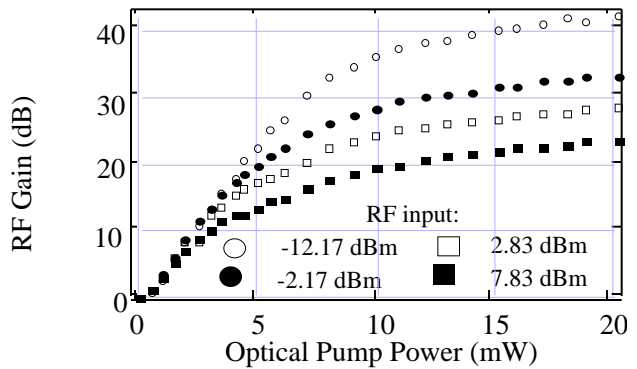
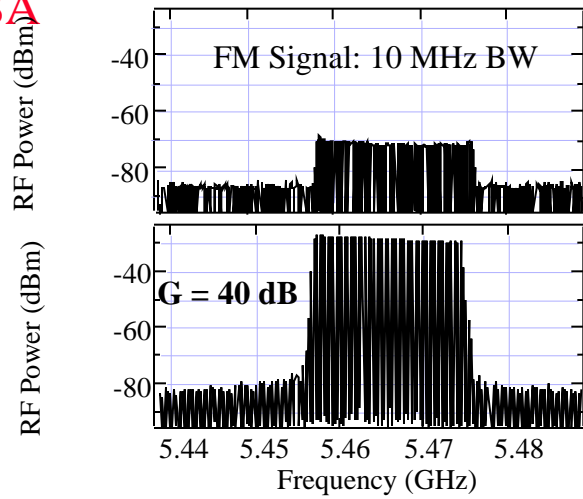
* 3rd Order IMD < 45 dBC

Brillouin Selective Sideband Amplification

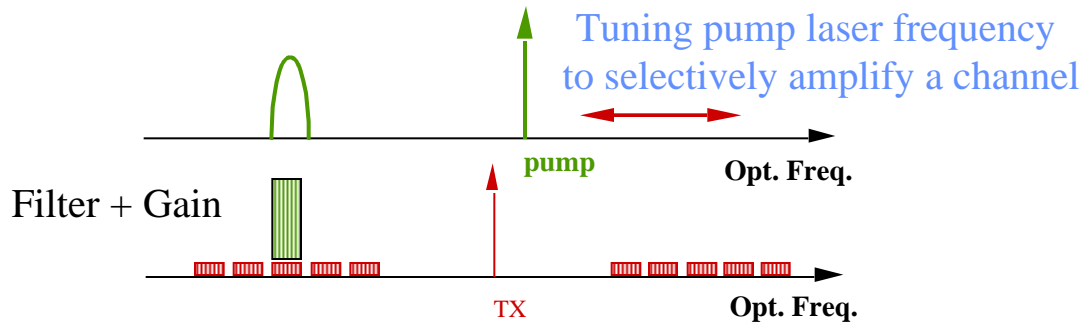
BSSA



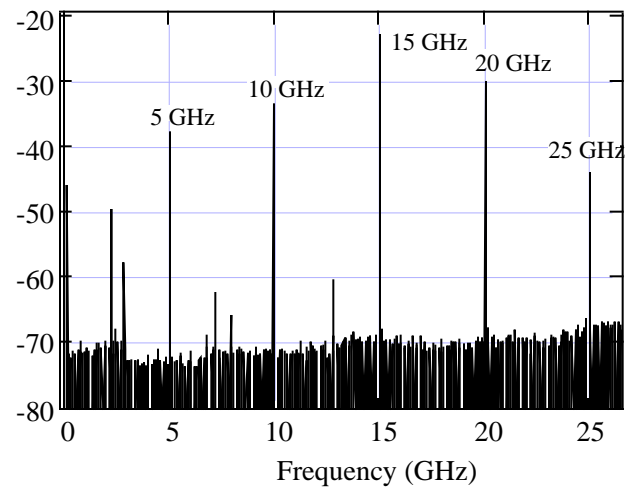
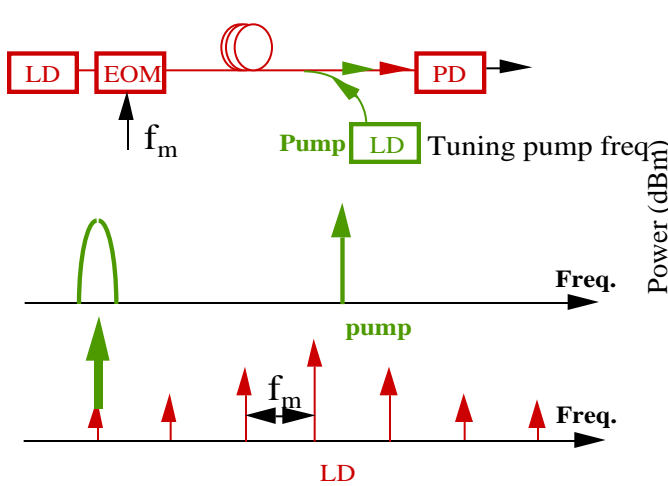
- * Fiber as gain medium
- * Low pump power ~ 10 mW
- * Dispersion robust
- * Highly efficient



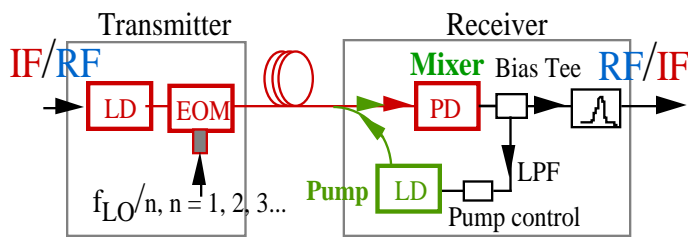
BSSA as a tuner for SCM systems



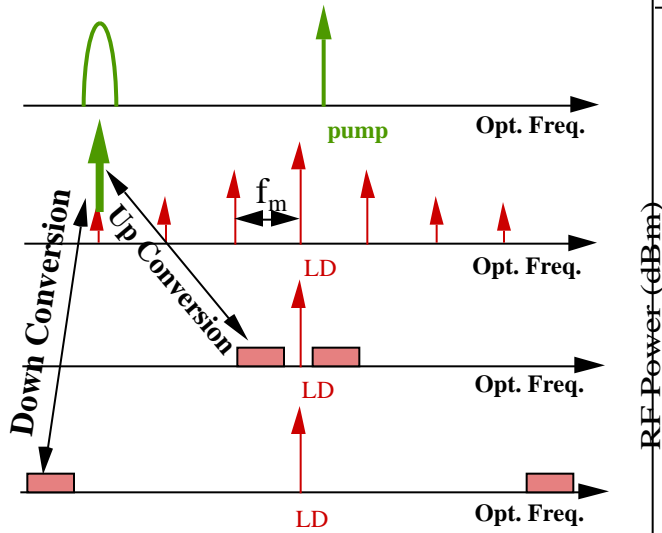
Frequency multiplication



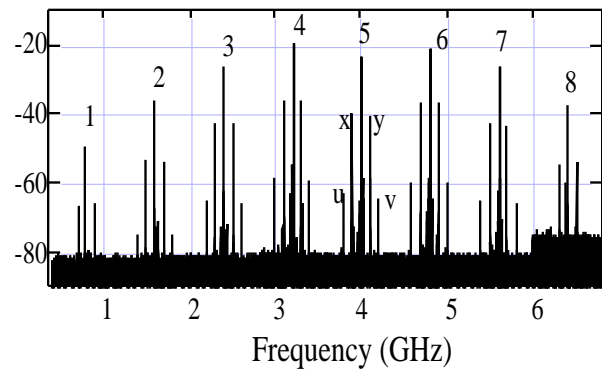
BSSA Assisted Harmonic Up/Down Conversions



- * Slow modulators do fast things
- * Conversions with IF (RF) gain
- * PM modulator OK
=> lower loss, less expensive
- * Low LO driving power

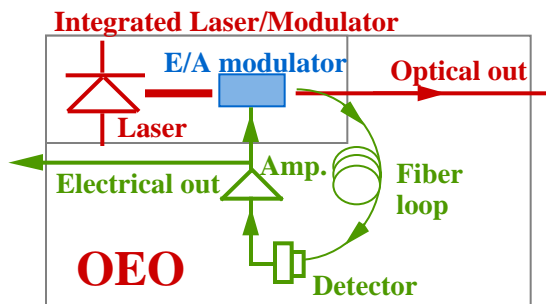


0.5 GHz modulator ==> 8 GHz
 2 GHz modulator ==> 32 GHz
 10 GHz modulator ==> 160 GHz



Opto-electronic Oscillator based Photonic Mixing Links

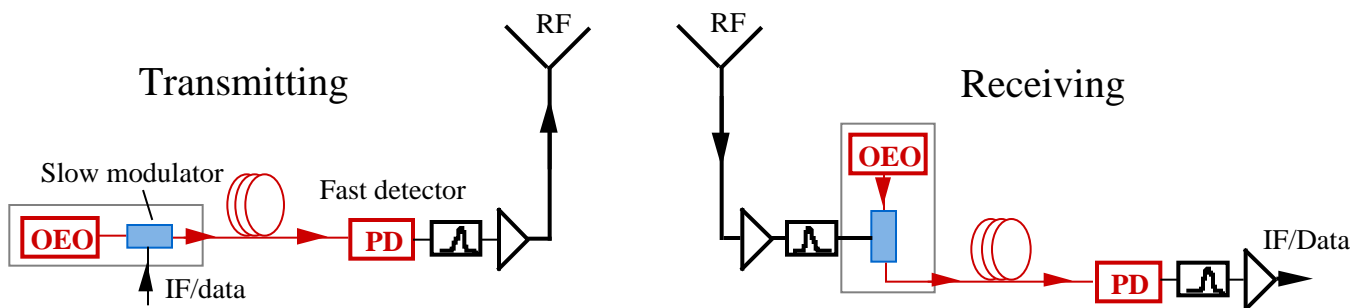
OEO Module



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





Section Summary

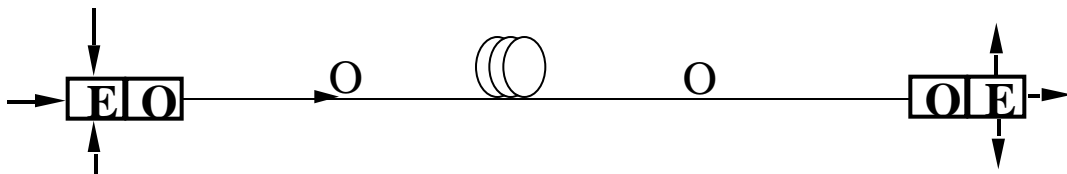
- Photonic mixing makes RF links cost effective
- SOA based mixing provides conversion gain
- BSSA holds promise for RF systems
- BSSA assisted mixing provides conversion gain & harmonic conversion capabilities
- OEO based photonic mixing eliminate electrical LO & greatly simplifies system design.



Photonic Techniques for generating RF signals

- Requirements of Photonic Signal Sources
- Evolution of Oscillators
- Opto-electronic oscillators (OEO)
- Properties of OEO
- Experimental results
- Comparison with other type oscillators
- Coupled Opto-electronic oscillators (COEO)
- Summary

Special Requirement of Signal Sources For Photonic Applications



* Photonic Systems are Electro-Optic Hybrid Systems

====> **Ideal Signal Source:** both Electrical & Optical Signals
Avoid high loss E/O and O/E conversions

====> Can be Interfaced with the System both Electrically & Optically.

* Photonic systems are Broadband Systems

====> High Frequency

====> Wide Tuning Range



Evolution of Oscillators

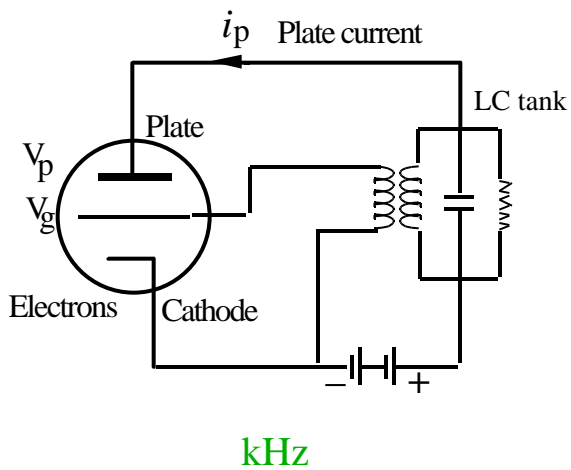
- **Mechanical Oscillators:** Pendulum, tuning fork ==>
- **Electronic Oscillators:** Van der Pol oscillator ==>
- **electromechanical Hybrid Oscillators:** Quartz Oscillator ==>
- **Atomic Oscillators:** Maser, Cesium beam standard ==>
- **Optical Oscillators:** Laser ==>
- **6. Electro-Optic Hybrid Oscillator? ==> OEO & COEO**

OEO is a new class of oscillators

Electrical & Optical Hybrid

OEO vs. van der Pol Oscillator

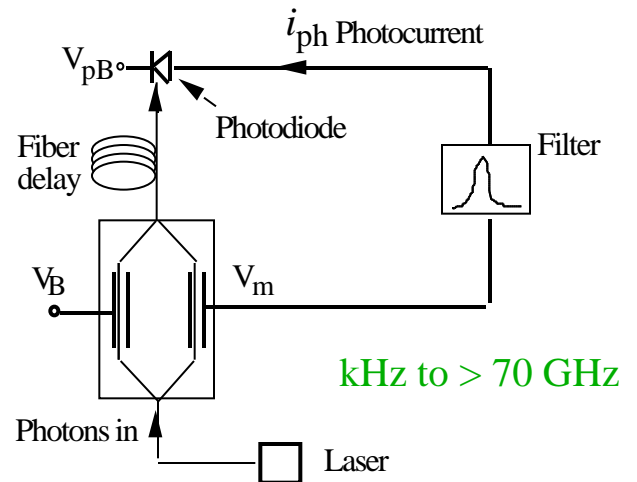
van der Pol Oscillator



kHz

Low Q & Low Frequency

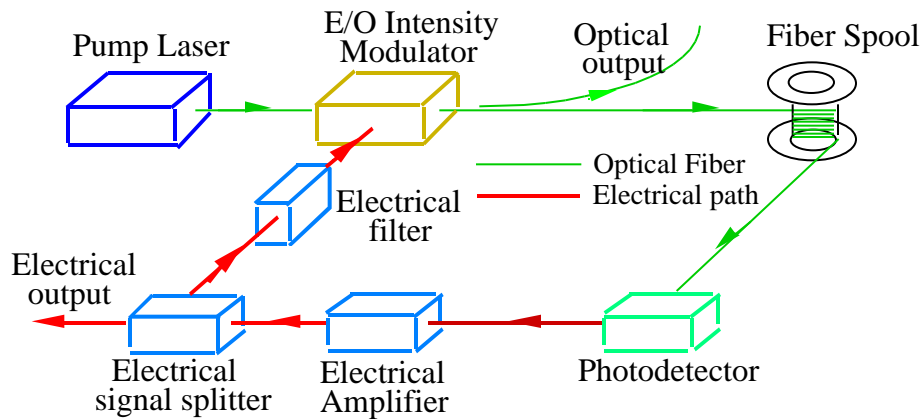
Opto-electronic Oscillator



kHz to > 70 GHz

High Q & High Frequency

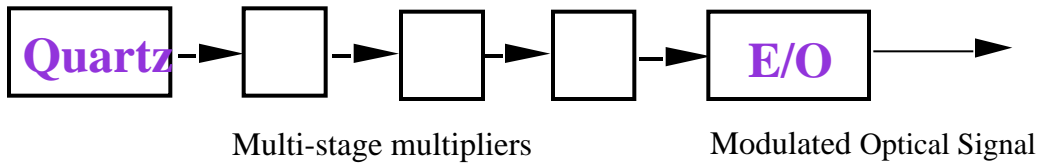
OEO Features



- 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

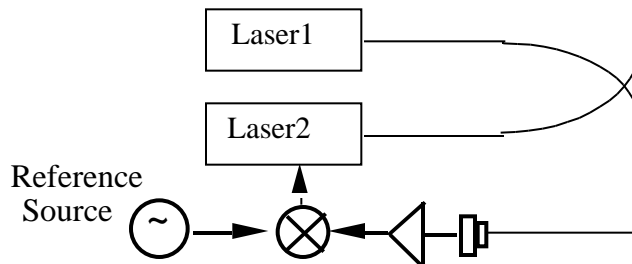
Other Approaches for Generating Photonics Signals

* Multiplier + E/O Conversion



* Beating Two Lasers

Requiring: Phase lock or injection lock to a RF source



Limited by
RF sources

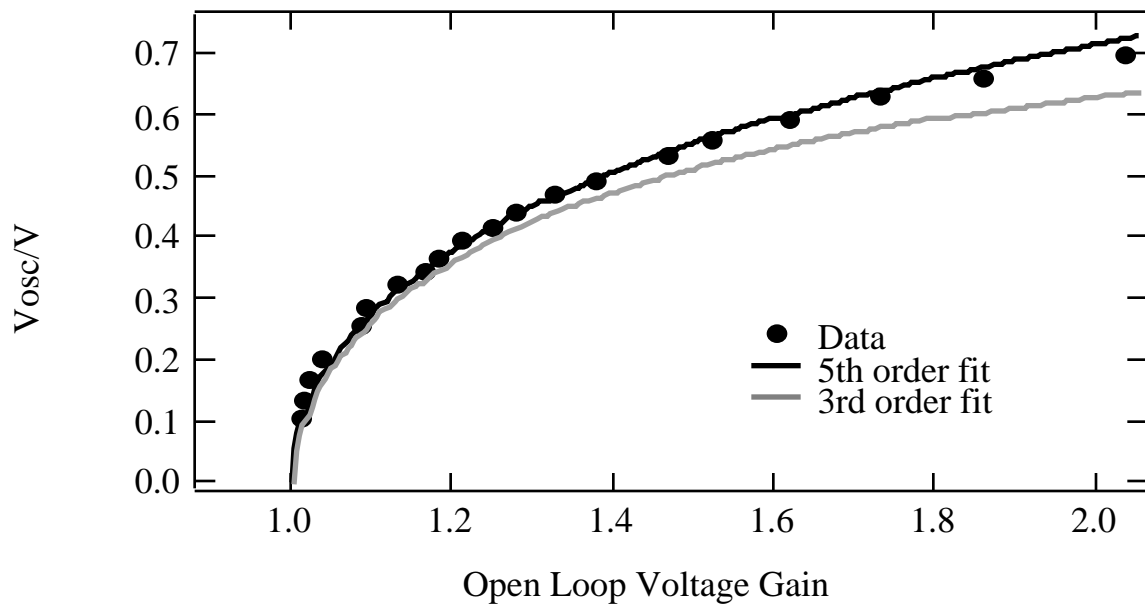
* Beating two modes of a mode locked laser

RF source is also required

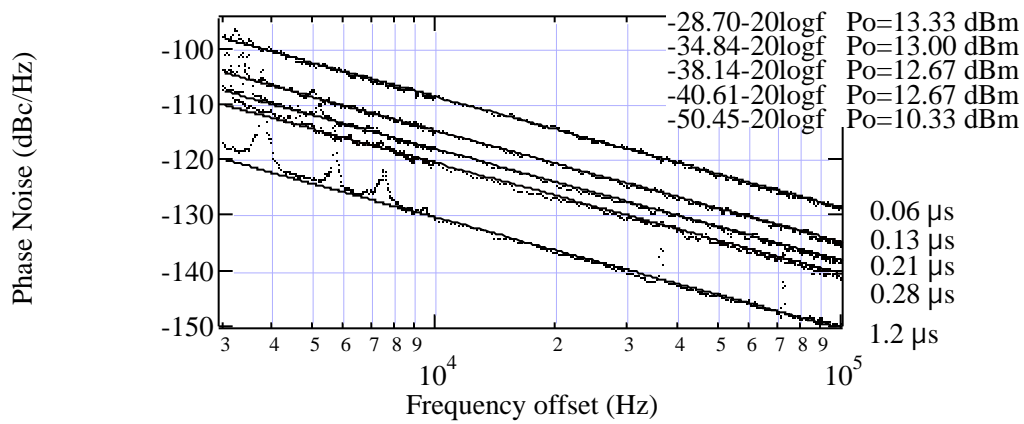
Performance Characteristics of OEO

Oscillation Amplitude vs. Open Loop Gain

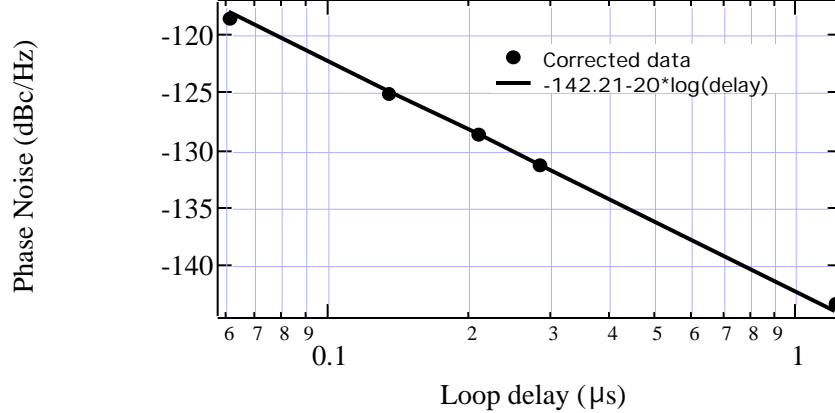
Data & Fit



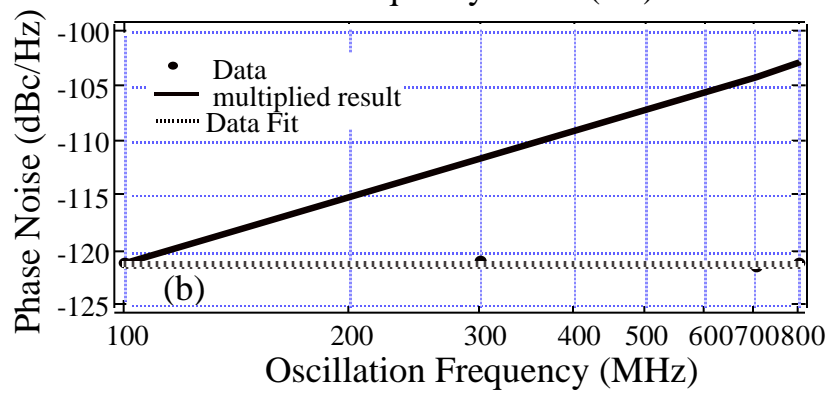
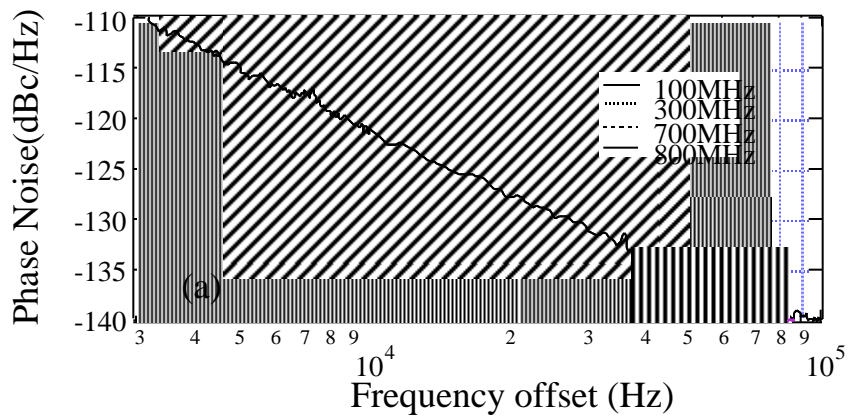
Phase noise vs. frequency offset



Phase noise vs. loop delay time



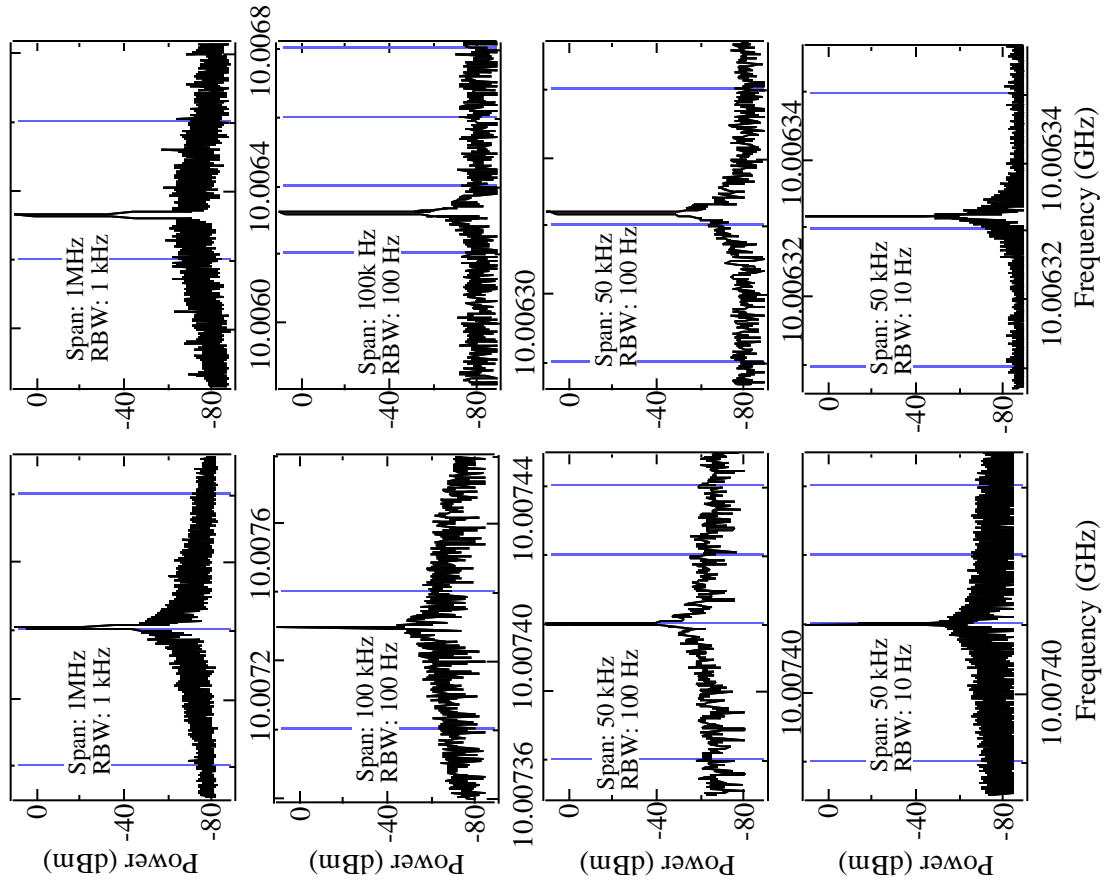
OEO Phase noise as a function of oscillation frequency



Spectral Purity Comparison

HP8671B

OEO

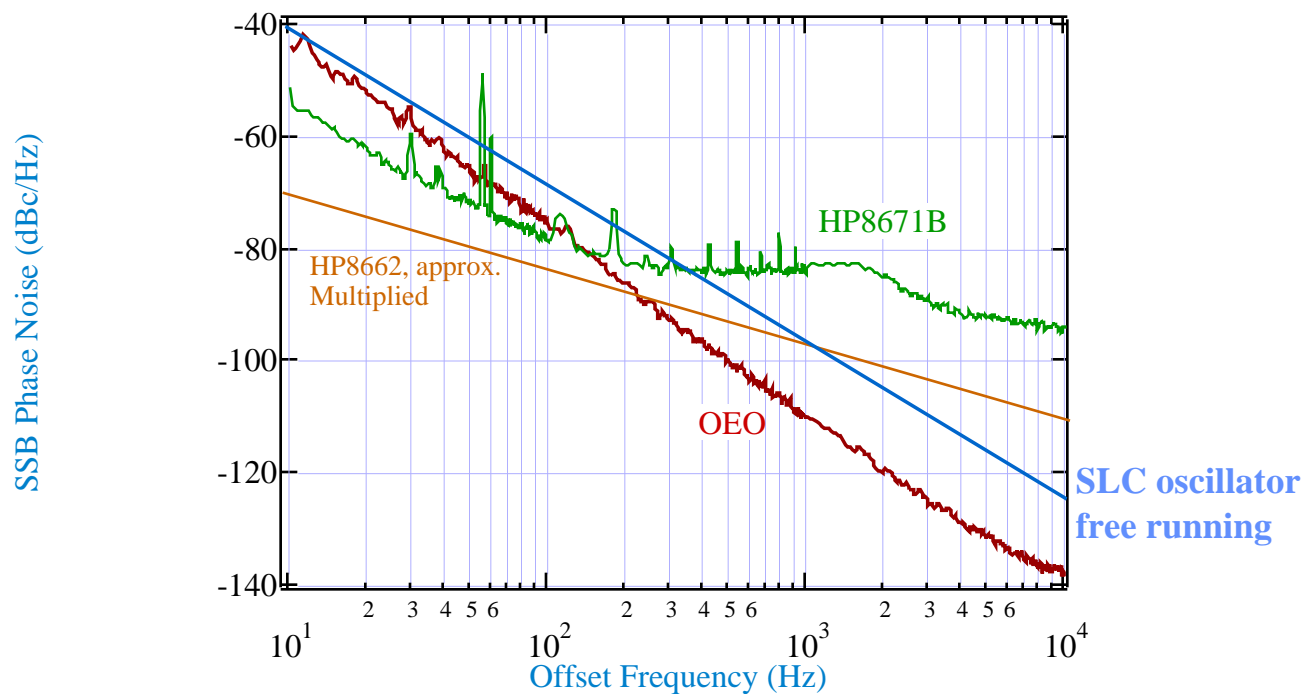


Comparison with Commercial Oscillators

Phase Noise @ 10 GHz, 10 kHz from carrier

- HP high performance synthesizer: -94 dBc/Hz
- Best quartz multiplied to 10 GHz: -114 dBc/Hz
- 1st OEO bench unit at 10 GHz: -140 dBc/Hz

Phase Noise of an OEO at 10 GHz



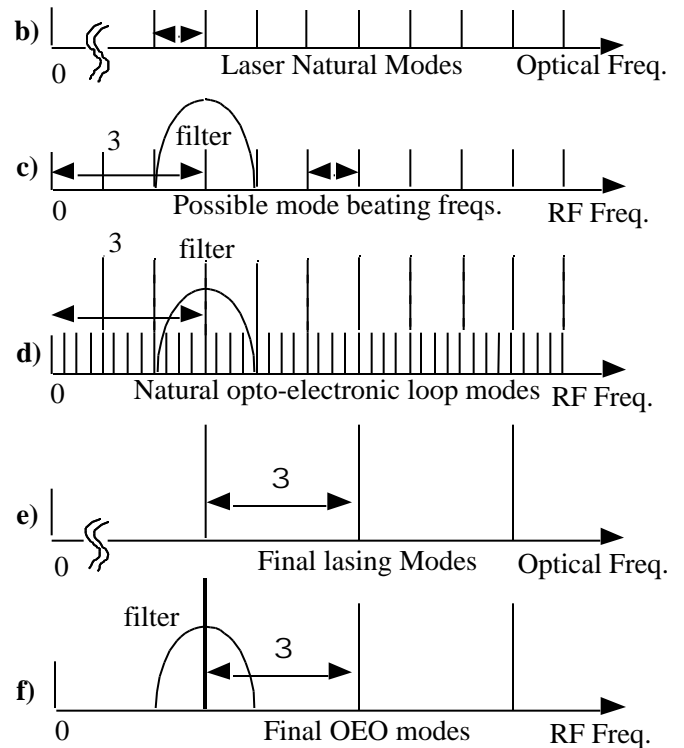
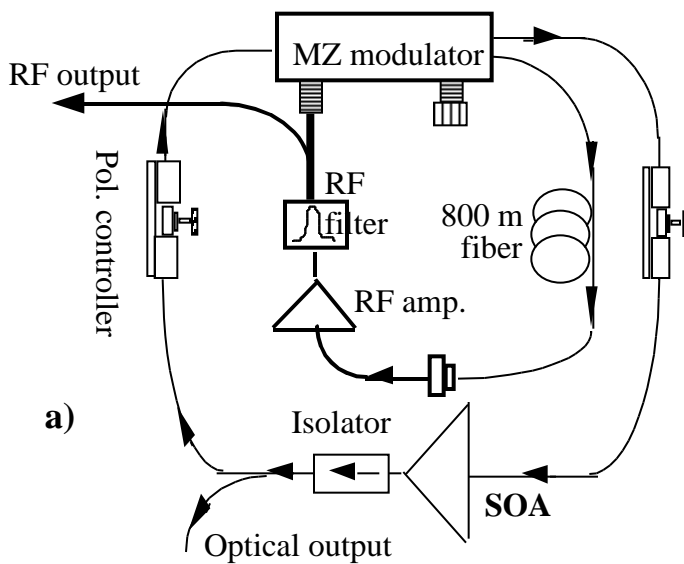
OEO free running @ room temperature

Jitter: 1.6 fs for $f > 1\text{kHz}$, 16 fs for $f > 100\text{ Hz}$

Coupled Opto-electronic Oscillator

A variation of OEO ==>

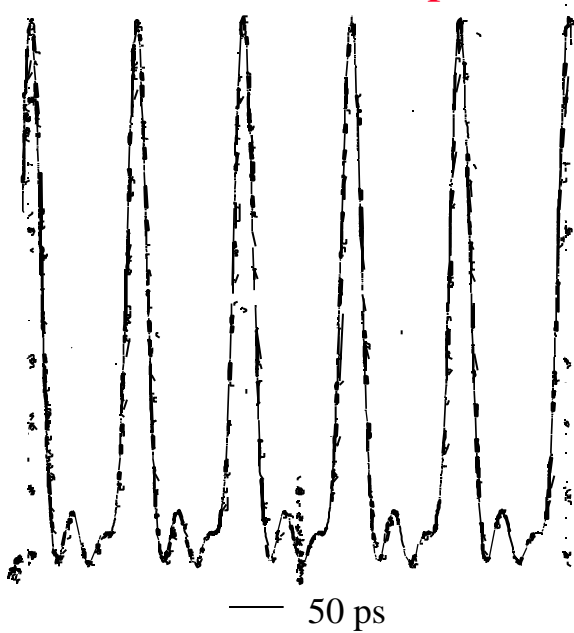
μ -wave & laser oscillations coupled together



Optical Pulse measurement

w/ a 40 GHz detector and Tek CSA 803

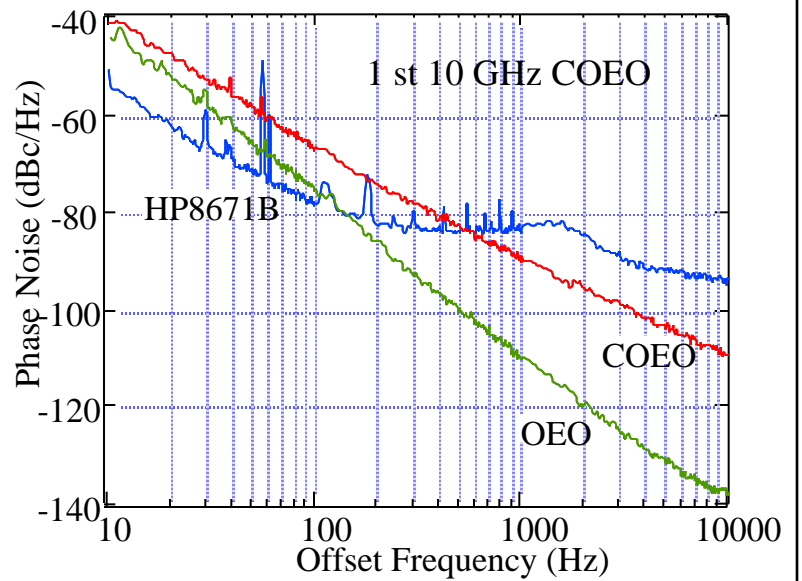
Pulse width: 17 ps



Phase Noise Measurement

Using Frequency Discrimination Method

10 GHz





Section summary

- OEO & COEO hold promise as high freq., low phase noise, & low jitter μ -wave & optical sources
- Lowest phase noise @ 10 GHz of any free running oscillator at room temperature
- Further phase noise reduction using noise reduction techniques
- Low jitter reference signal for μ -wave, mm-wave communication & photonic A/D