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

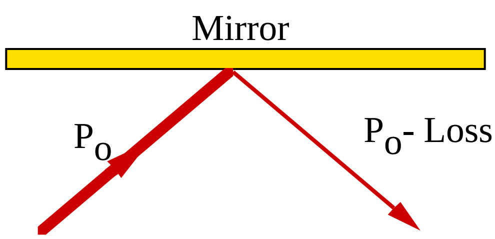
Advantages of Optical Fiber

- 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

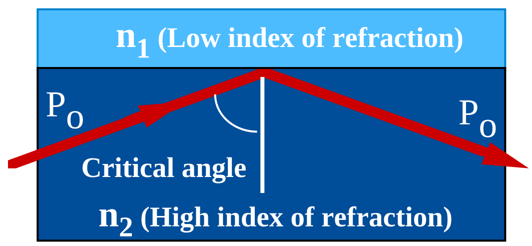
Snell Law

Reflection



All mirrored surfaces have loss!!

Total Internal Reflection

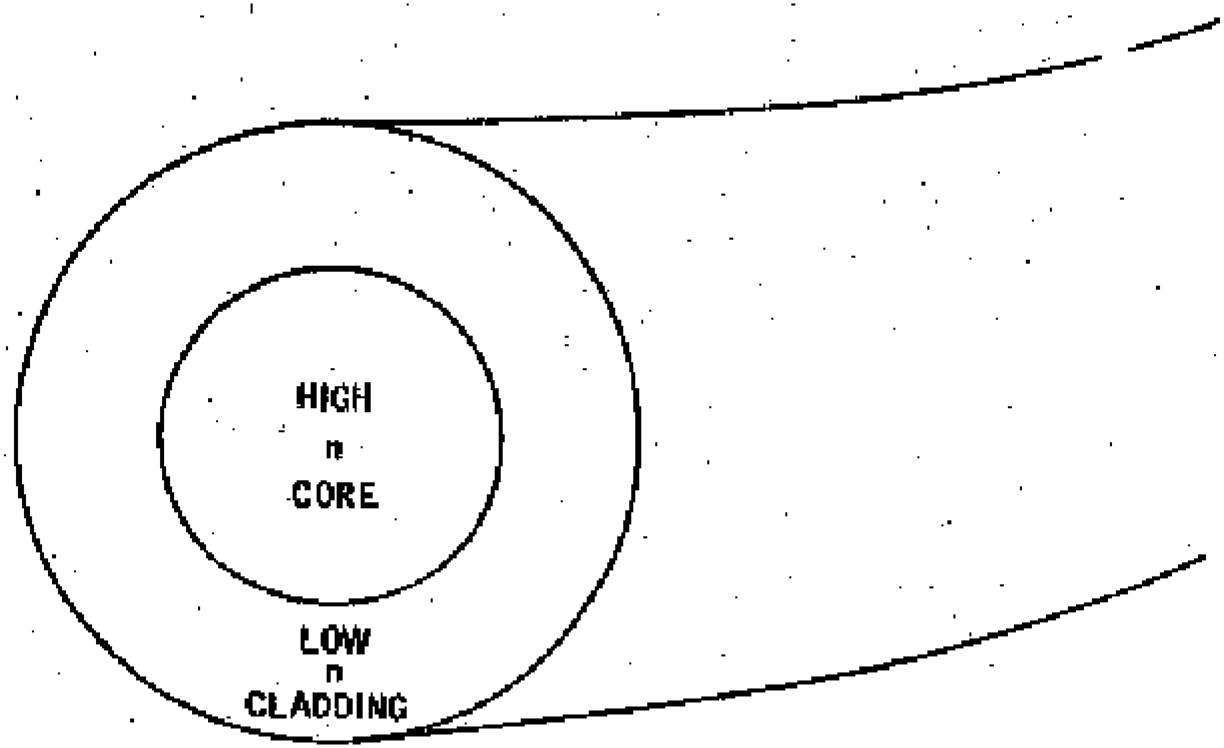


No Loss!!

* $n = c/v$
  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)

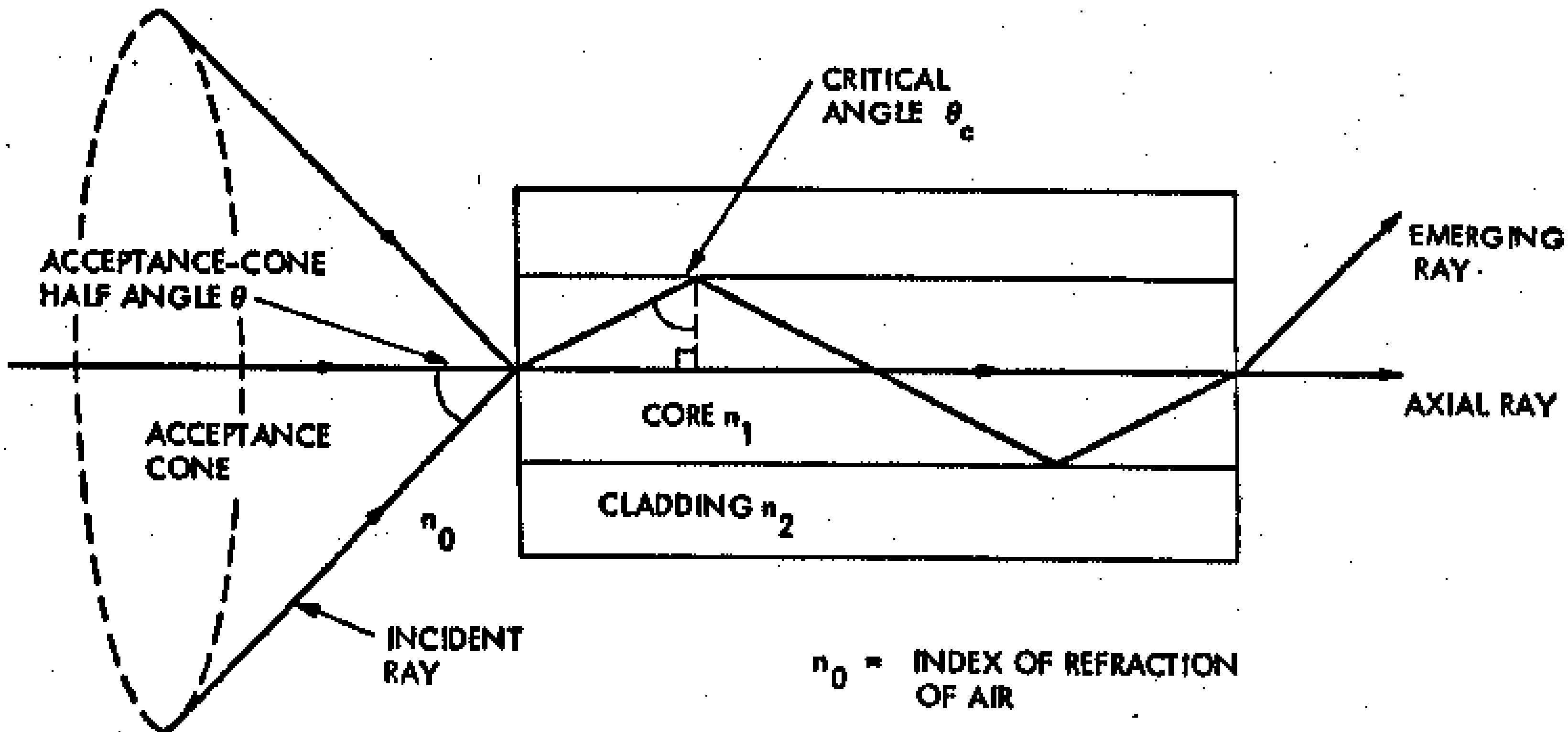
* The index of refraction of glass can be changed by adding impurities (doping)

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

$\theta = \text{ARC SIN} \, (n_2/n_1)$

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

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

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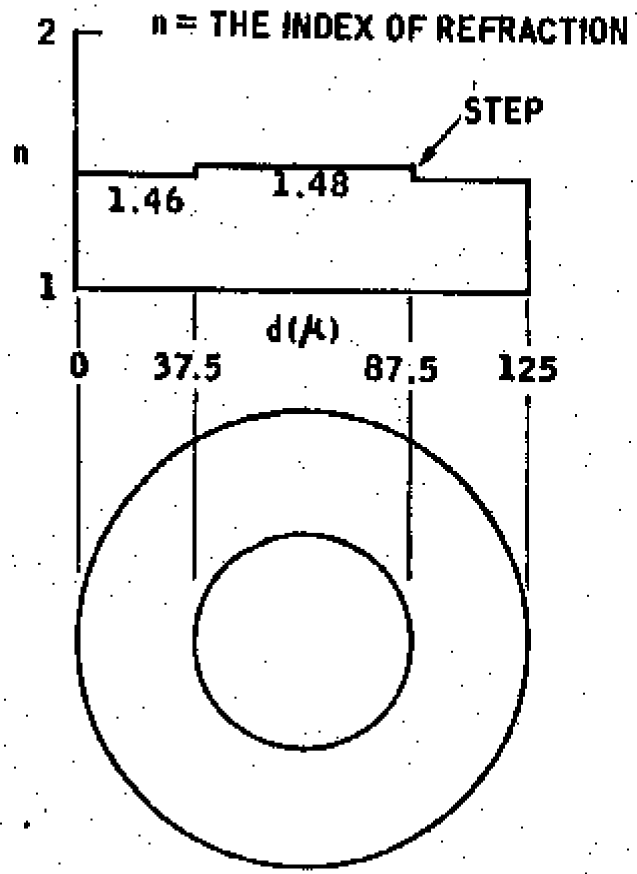
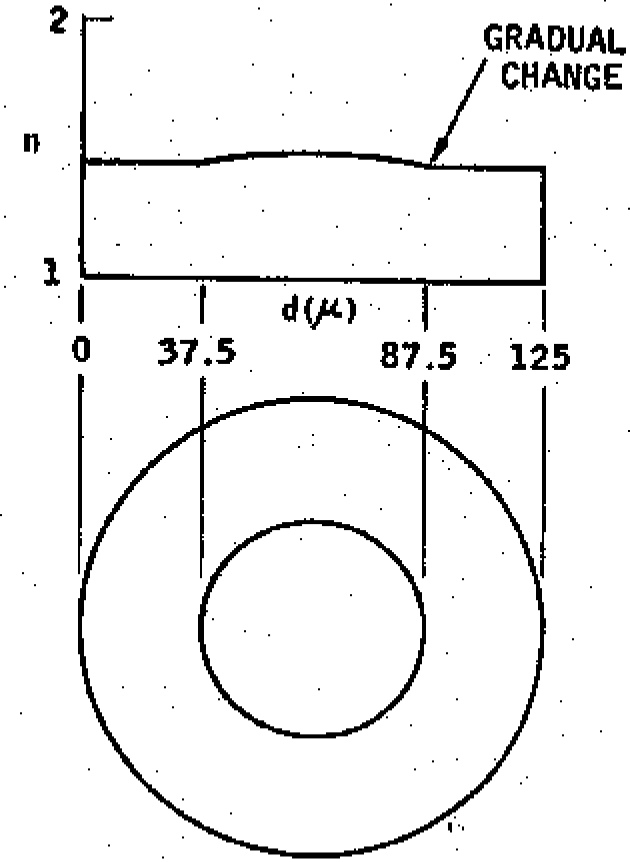
FIBER CONSTRUCTION



STEP INDEX FIBER



GRADED INDEX FIBER

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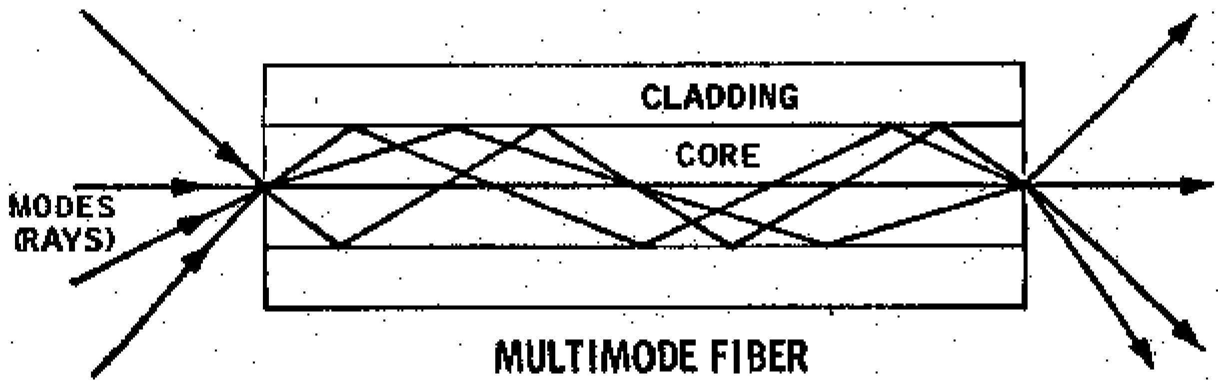
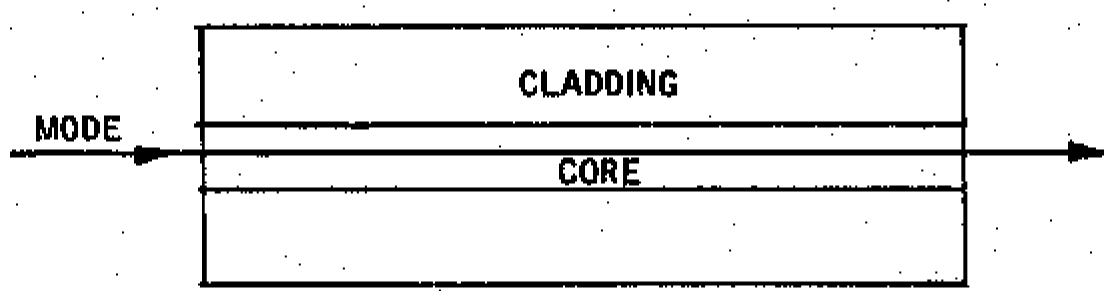
FIBER TYPES



MULTIMODE FIBER



SINGLE-MODE FIBER

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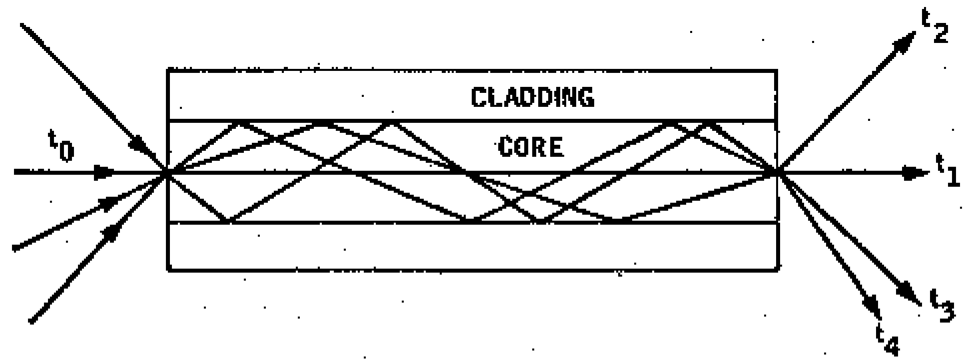
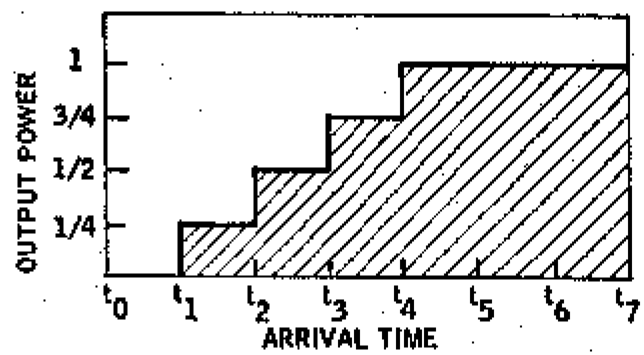
DISPERSION

- 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

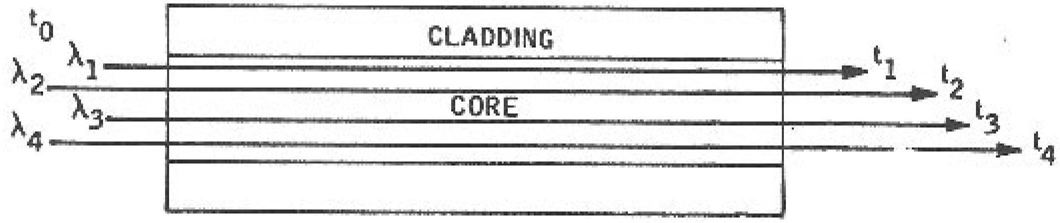


- ALL MODES LAUNCHED AT THE SAME TIME (t_0)
- MODES ARRIVE AT FAR END AT DIFFERENT TIMES
  - EACH TRAVELS A DIFFERENT DISTANCE

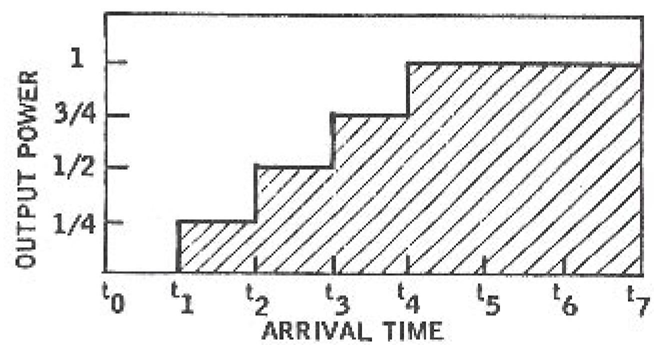


PLOT OF OUTPUT POWER vs TIME

MATERIAL DISPERSION



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



PLOT OF OUTPUT POWER vs TIME

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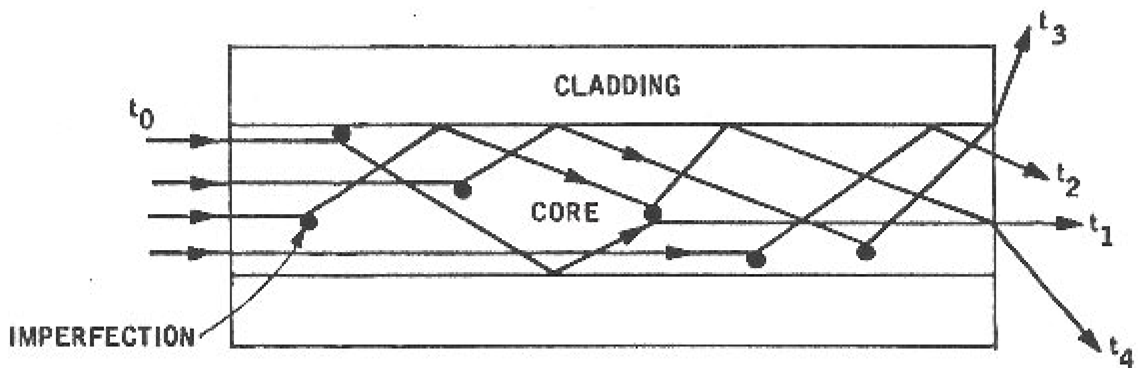
WAVEGUIDE DISPERSION



- 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

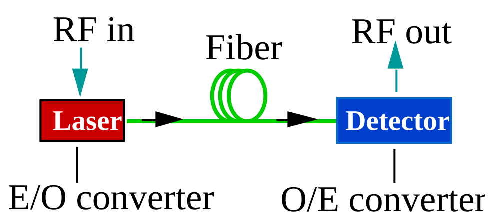
REDUCING DISPERSION (cont.)

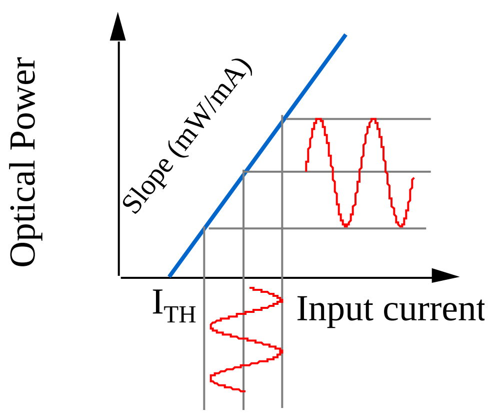
- INTERMODAL DISPERSION (CONT.)
  - REDUCE THE CORE SIZE UNTIL ONLY ONE RAY, WHICH TRAVELS STRAIGHT DOWN THE CENTER OF THE FIBER, IS PASSED (SINGLE-MODE)
- MATERIAL DISPERSION
  - OPERATE AT A WAVELENGTH WHERE DISPERSION IS NEAR ZERO (1300 nm FOR PRESENT FIBERS)
  - USE A VERY STABLE LIGHT SOURCE THAT EMITS AT ONLY ONE FREQUENCY
- WAVEGUIDE DISPERSION
  - REDUCE IMPERFECTIONS

Basic Photonic links for RF applications

Directly modulated Link

RF signal directly drives the laser

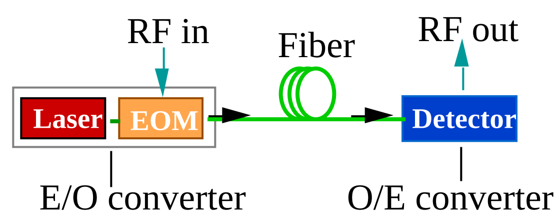


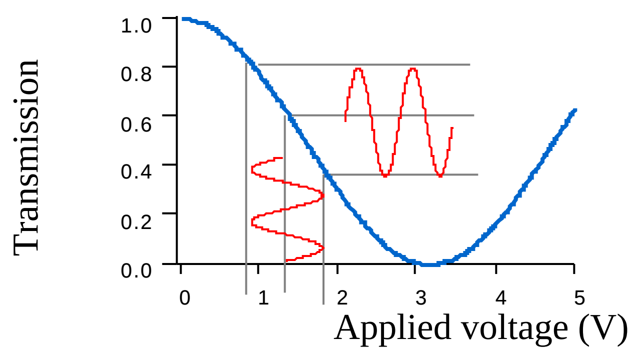


Lower dynamic range
most CATV systems

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

- Mutimode 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

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-- 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 um, NA = 0.17
  - effective area: 50 um^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 um, NA = 0.16
  - effective area: 55 um^2
- Large core non-zero-dispersion-shifted fiber
  - Minimum but non-zero dispersion at 1550nm
  - mode-field/cladding: 9/125 um,
  - larger effective area: 72 um^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

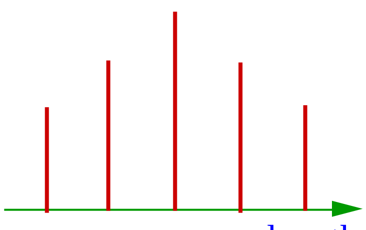
Choices of operating wavelengths

- 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

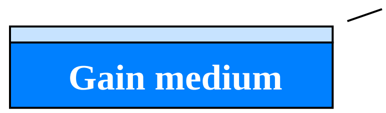
Commonly used lasers for RF systems

Fabry-Perot laser (F-P laser)

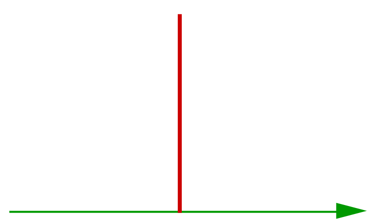
* Optical feedback provided by the end mirrors
* multi-longitudinal modes
* higher noise due to mode competition



Distributed feedback laser (DFB laser)



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



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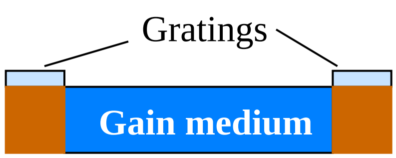
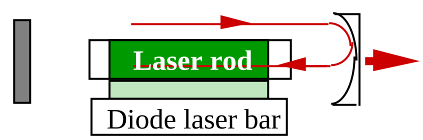
Commonly used lasers for RF systems

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



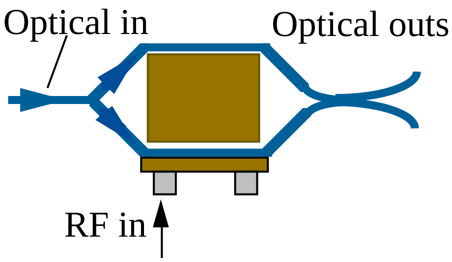
* Solid state gain medium pumped by diode lasers
* Narrowest spectral width
* Lowest noise
* Most expensive
* Less reliable

Commonly used Photodetectors

- InGaAs PIN photodiodes (0.8 - 1.7 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
  - Not well developed for high speed: ~ <6 GHz

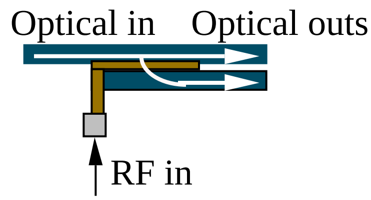
Modulators

Mach-Zehnder modulator



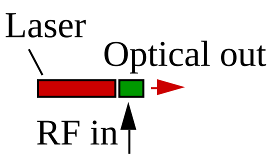
* Wide Bandwidth: up to 100 GHz
* Good linearity
* No chirp (good)
* Well developed, widely used
* High drive voltage ==>
High RF insertion loss

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)

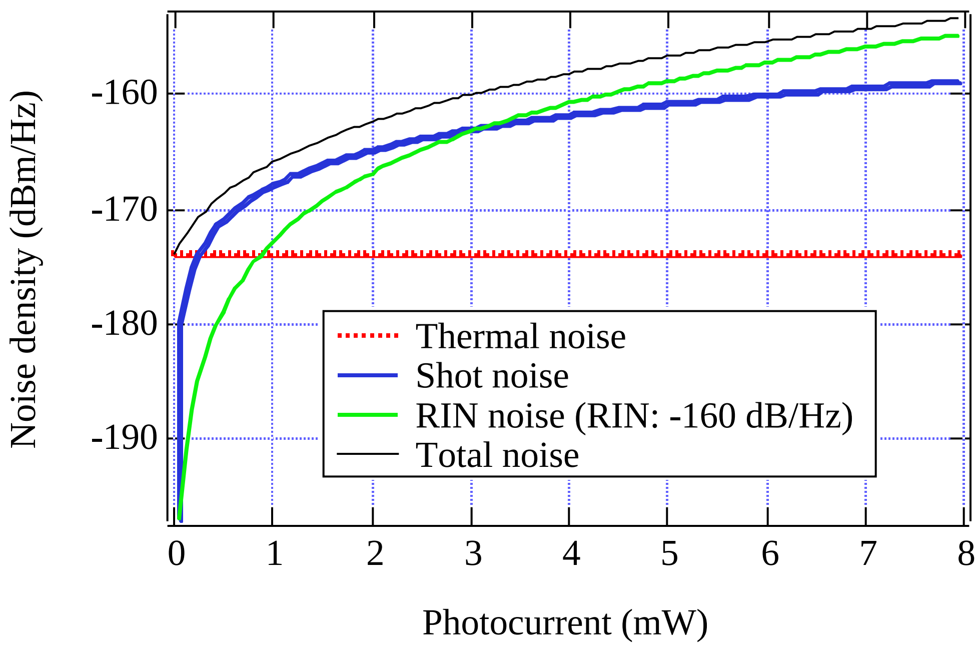
Other fiber optic devices available

- 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

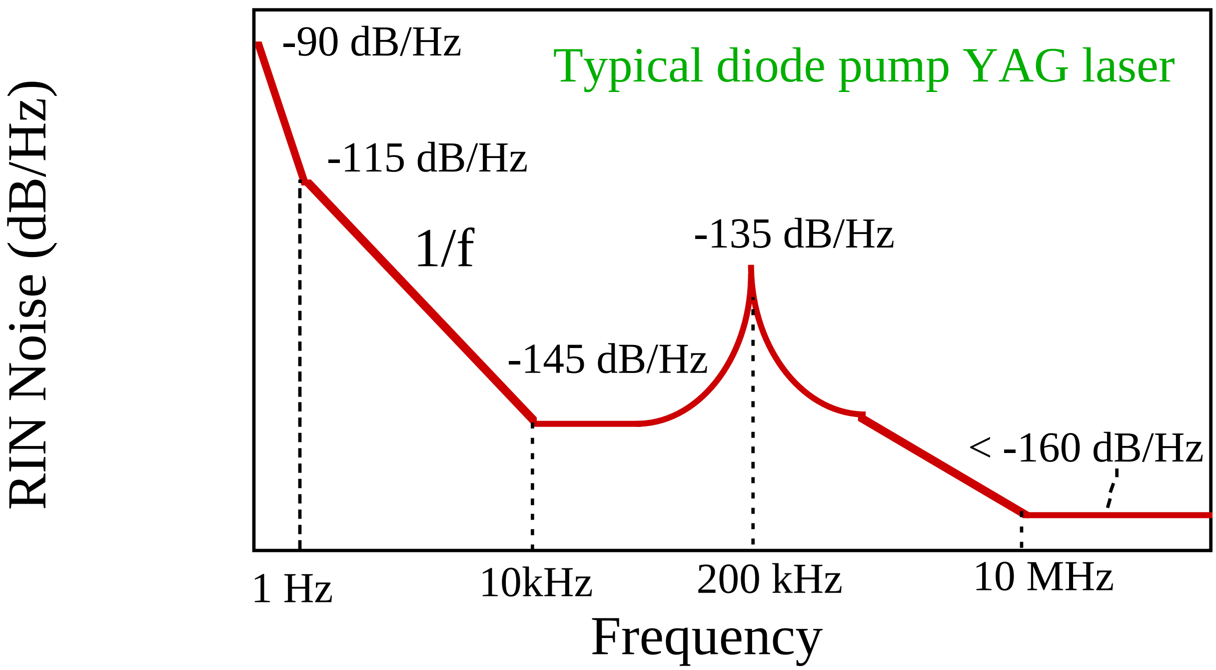
- Thermal noise: kT
- Shot noise: 2eIR
- Laser RIN (relative intensity noise): $<\Delta P^2>/P^2$
- 1/f RIN (at $<$ 10 kHz)
- Relaxation oscillation RIN peak
- Interferometric noise
- Double Rayleigh scattering noise
- Brillouin scattering caused noise
- Fiber dispersion mediated noise
- Fiber thermal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

White Noise



-160
-170
-180
-190
Noise density (dBm/Hz)
0
1
2
3
4
5
6
7
8
Photocurrent (mW)
Thermal noise
Shot noise
RIN noise (RIN: -160 dB/Hz)
Total 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

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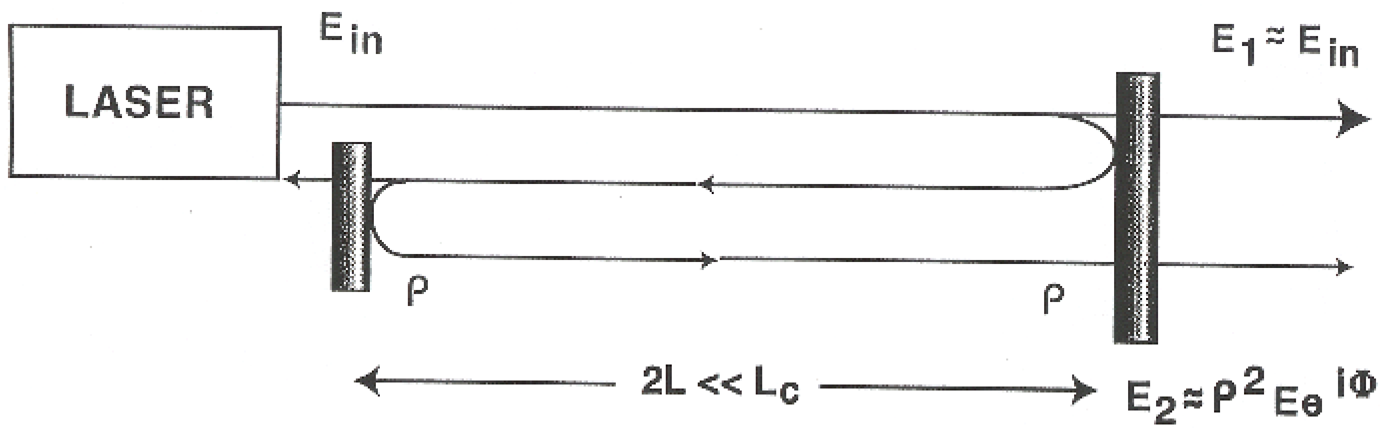
INTERFEROMETRIC INDUCED NOISE



$$I \propto E_T^* E_T = I_{avg} + \Delta I_{pp}$$

$$\frac{\Delta I_{pp}}{I_{avg}} = \begin{cases} 4\rho^2, & \text{singly polarized} \\ \rho^2, & \text{scrambled} \end{cases}$$

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

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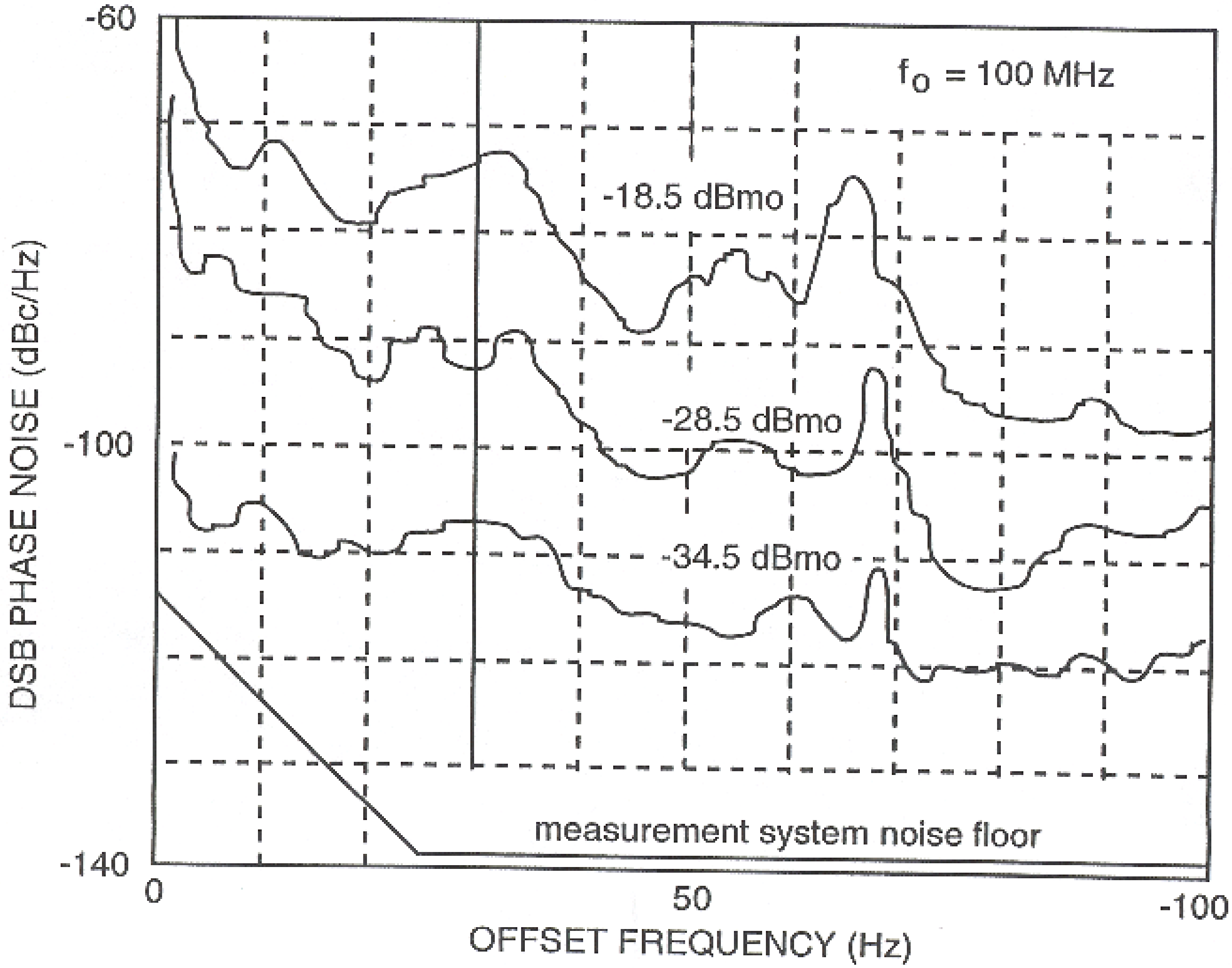
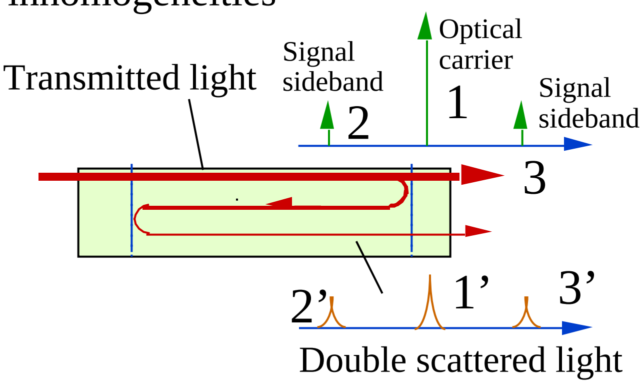
PHASE NOISE VS REFLECTED OPTICAL POWER



Double Rayleigh Scattering

Rayleigh scattering: photon being scattered from random material inhomogeneities



1+1', 2+2', 3+3' ==>

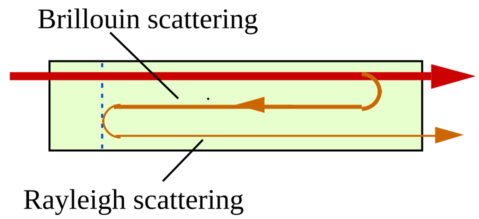
Low freq. noise (< 1 GHz), no wary

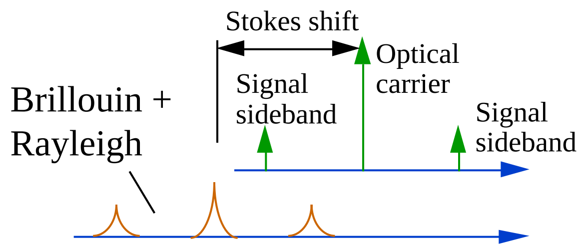
1+2', 1+3', 1'+2', 1'+3' ==>

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 ==> 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 um fiber @ 1.3 um

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

L = 100 m ==> $<\Delta f>/f \sim 10^{-13}$

L = 10 km ==> $<\Delta f>/f \sim 10^{-14}$

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:

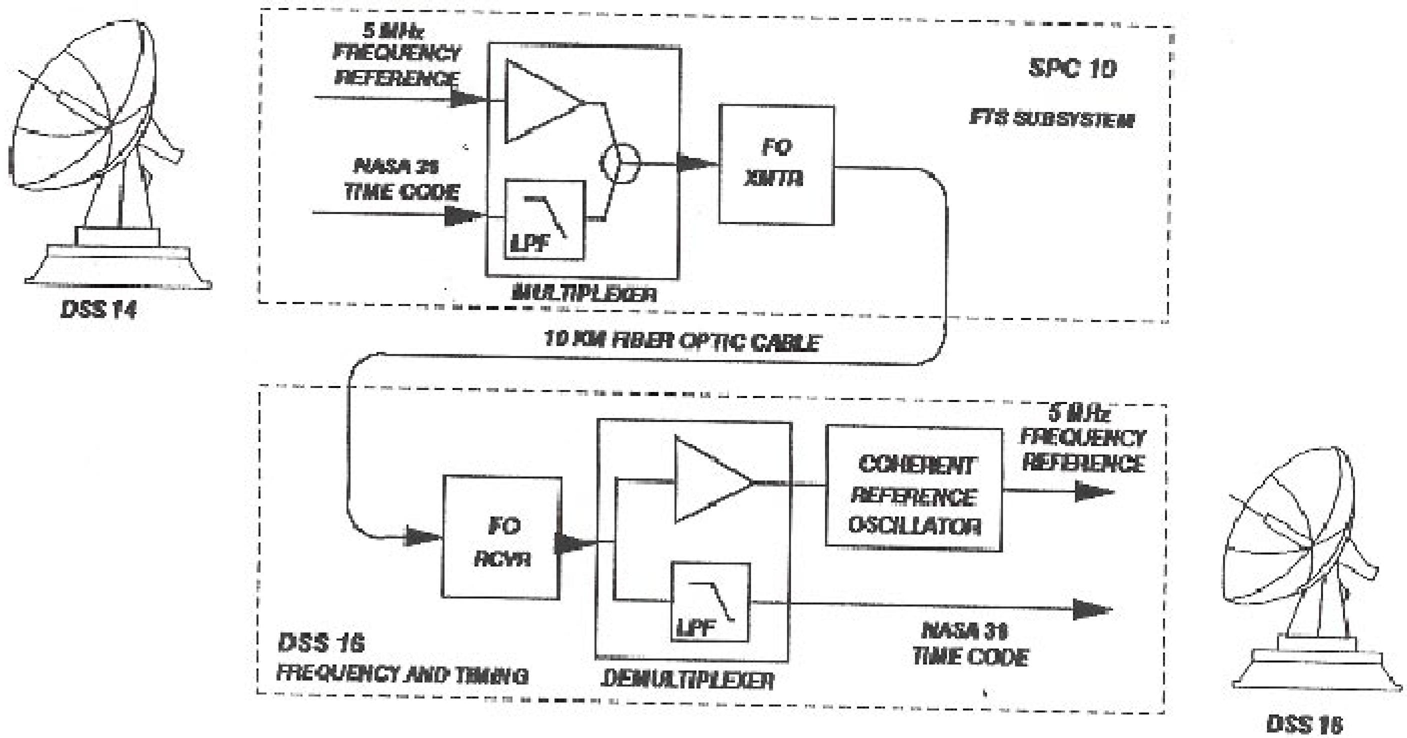
$<\Delta f>/f = <\Delta L>/L \sim 0.6 \times 10^{-5}\ \Delta\upsilon/\upsilon$

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

$\Delta\upsilon/\upsilon = 10^{-10}$ ==> $<\Delta f>/f = 6 \times 10^{-15}$

Fiber Optic Frequency Standard Distribution

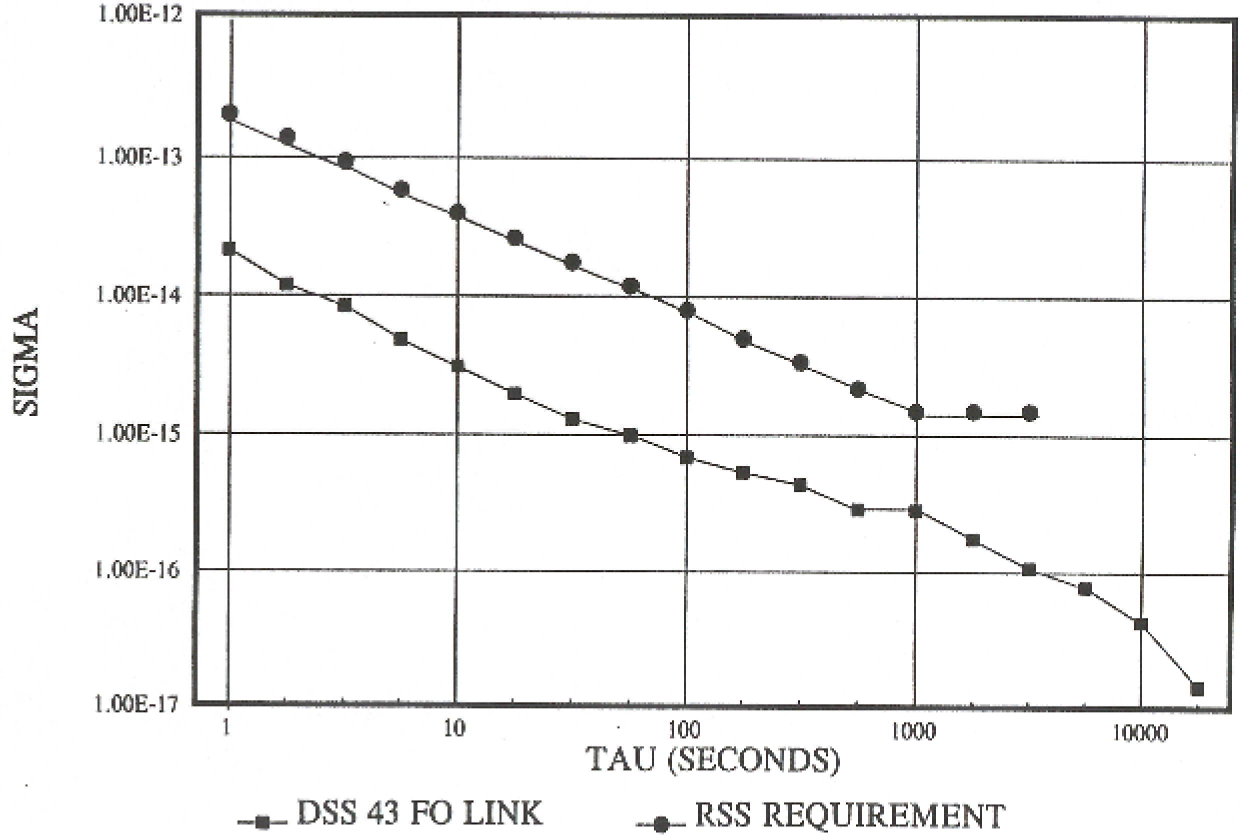
- Frequency standards are extremely expensive
- Multiple users at different location share one standard ==> big money saving
- Distribution system should not degrade the performance of the standard
- In 1981, JPL pioneered the fiber optic frequency standard distribution
- The only workable solution so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



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

ALLAN DEVIATION AT CONE OF 70 M DSN ANTENNA

JET PROPULSION LABORATORY



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SEC 331 8/5/93

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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

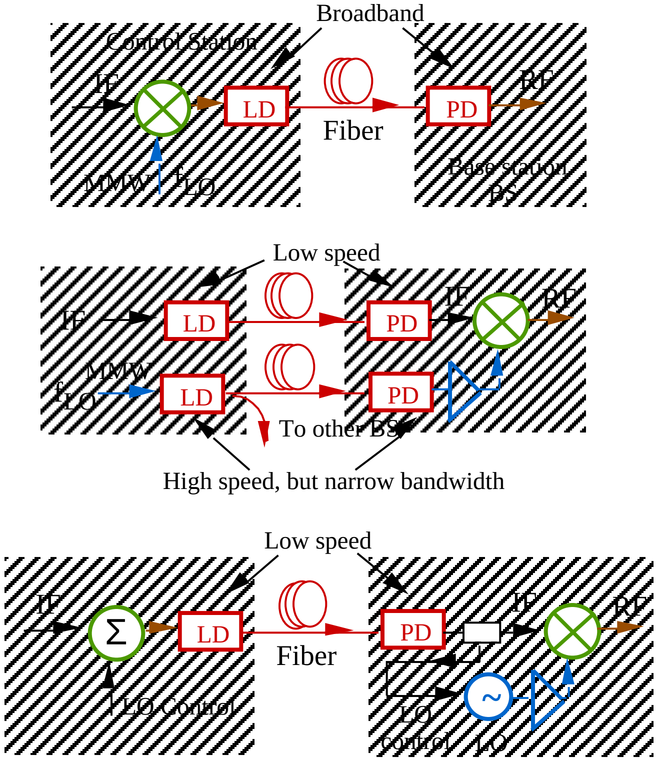
TAU, SECONDS	FTS SPEC.	LINK PERFORMANCE
1	2E-13	2E-14
10	4E-14	4E-15
100	----	1E-15
1000	1.5E-15	5E-16
3000	1.5E-15	3E-16
10,000	----	2E-16

Photonic technology for signal mixing & multiplication

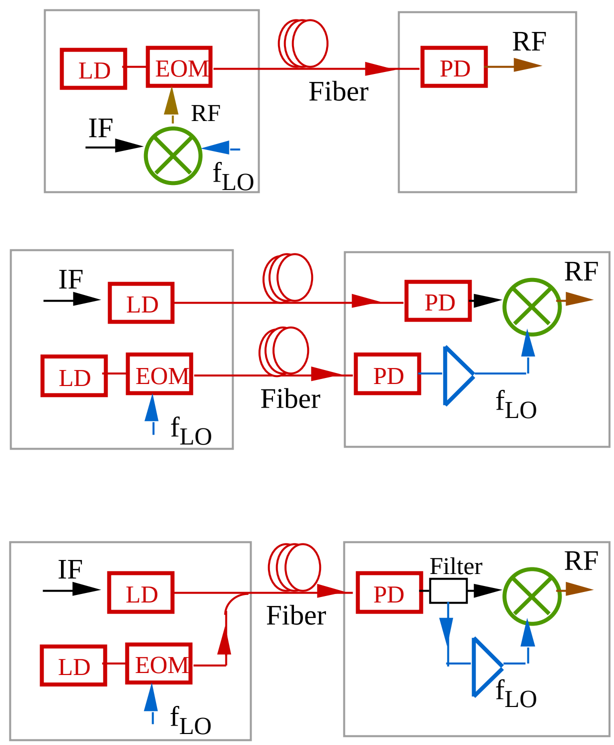
- Photonic links w/ traditional & photonic mixers
- Pros & cons of present photonic signal mixing
- SOA based photonic mixing links
- Brillouin Selective Sideband Amplification (BSSA) of RF signals
- BSSA based photonic mixing links
- OEO based photonic mixing links
- Summary

Fiber Optic Links w/ traditional mixers

Directly Modulated

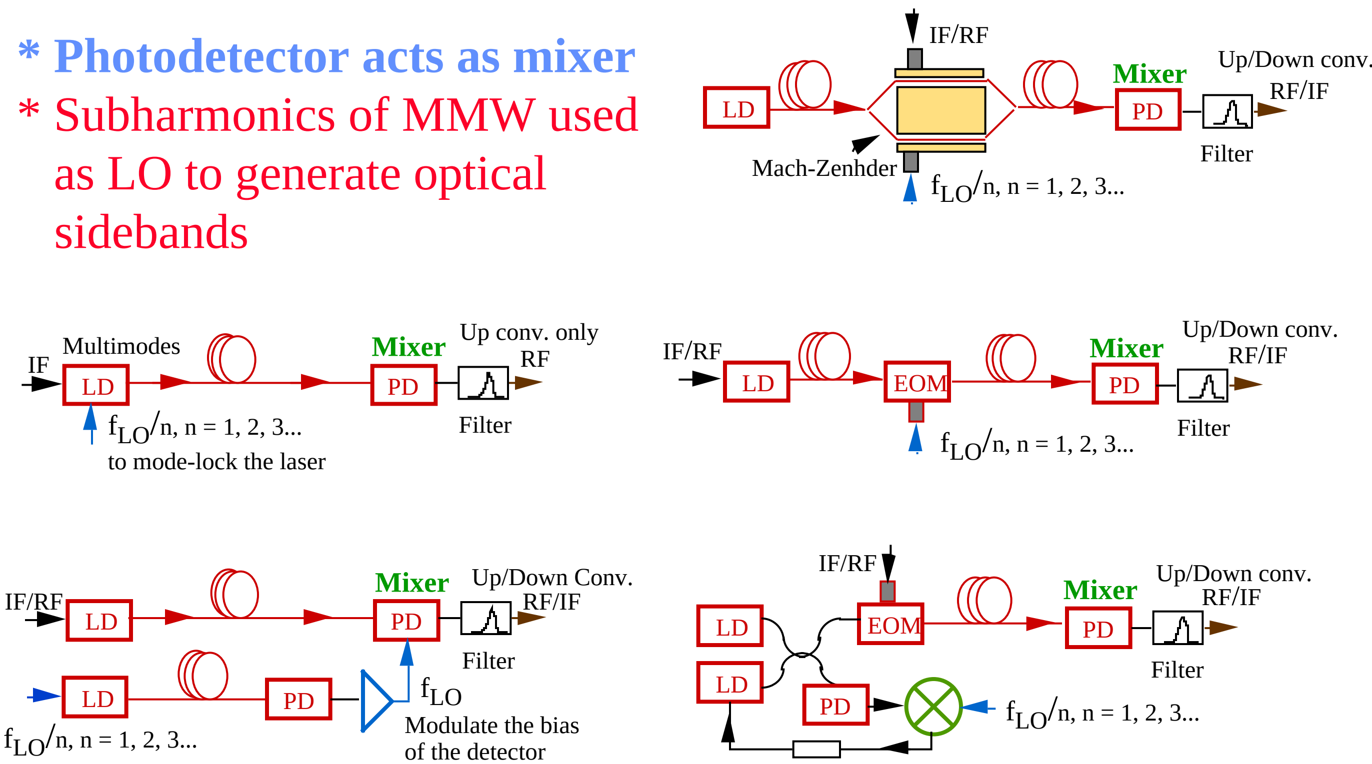


Externally Modulated



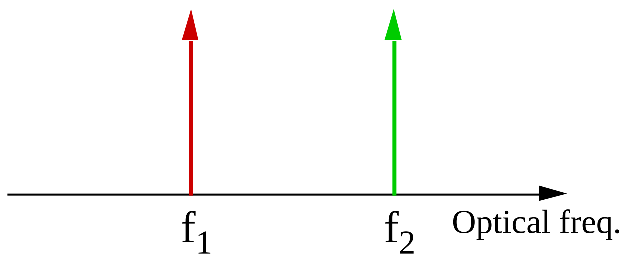
Photonic Mixing Links

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



Photodetector as a mixer

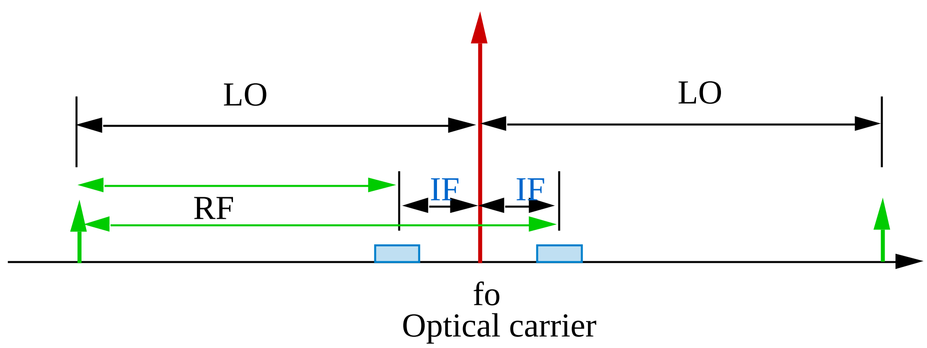
Power Law Photodetector ==> acts as a mixer



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

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

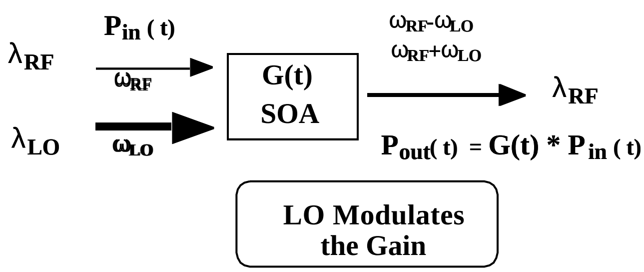
Cons

* Low efficiency (most cases)

* High LO power (some cases)

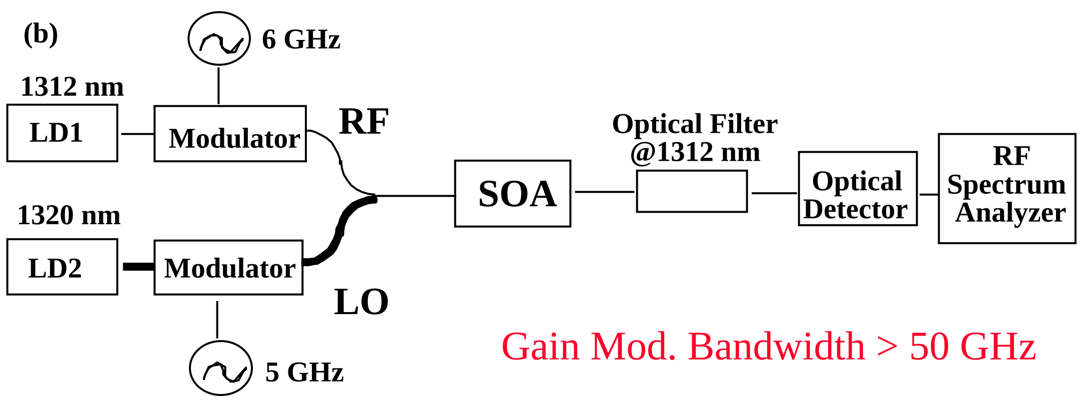
* Freq. locking circuits needed
  (some cases)

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



Advantages:

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



Gain Mod. Bandwidth > 50 GHz

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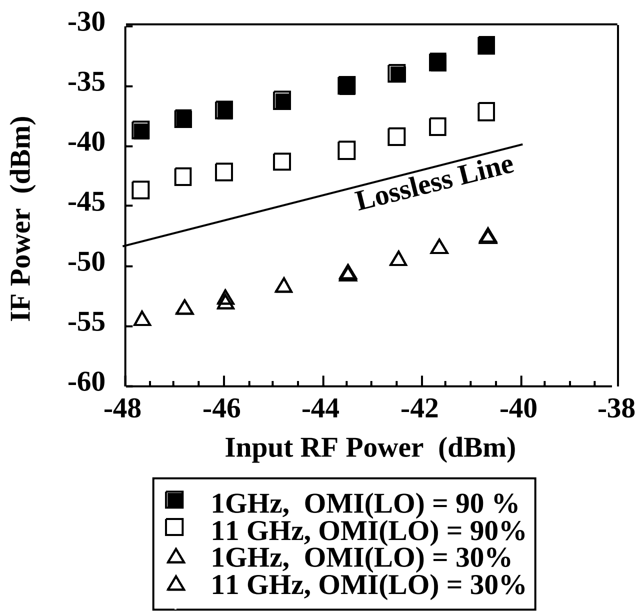
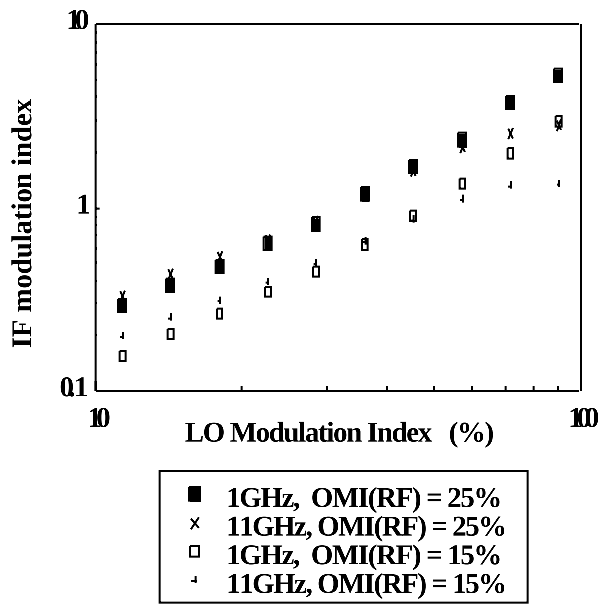
Performance of SOA Based Photonic Mixing Link

IF Gain Measurement



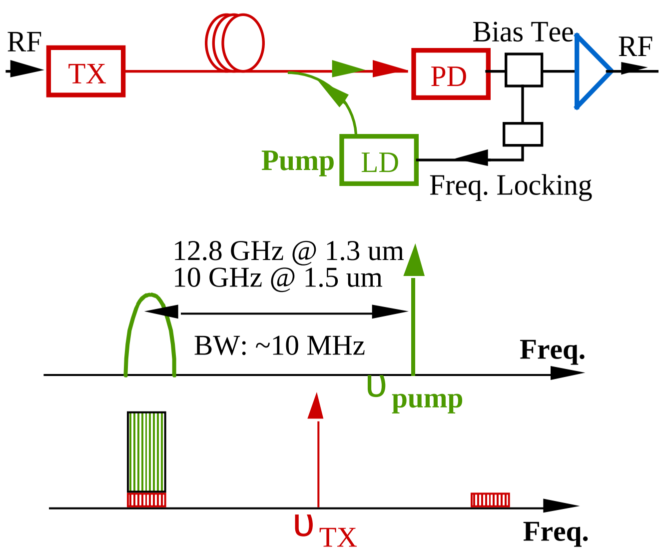
IF Optical Mod. Index

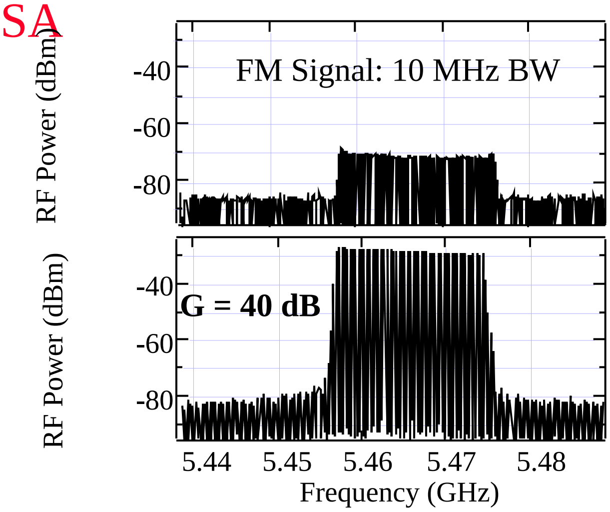


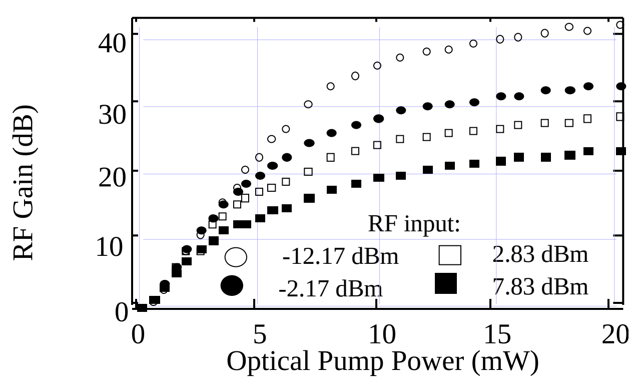
* IF Gain: 8 dB * 3rd Order IMD < 45 dBC

Brillouin Selective Sideband Amplification

BSSA







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

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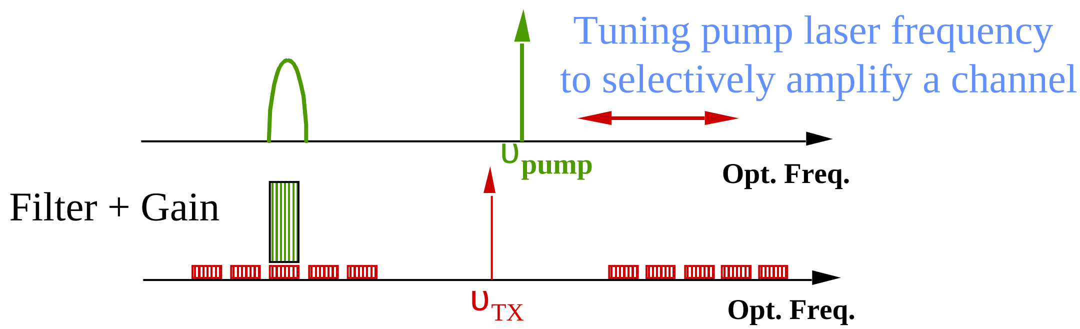
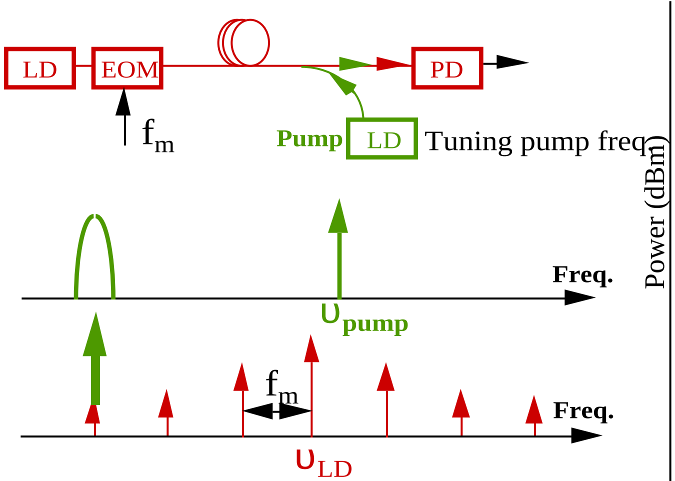
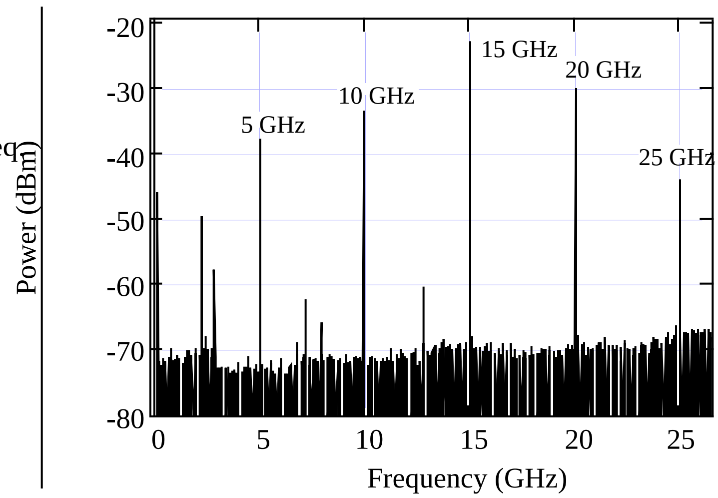
BSSA as a tuner for SCM systems



Frequency multiplication





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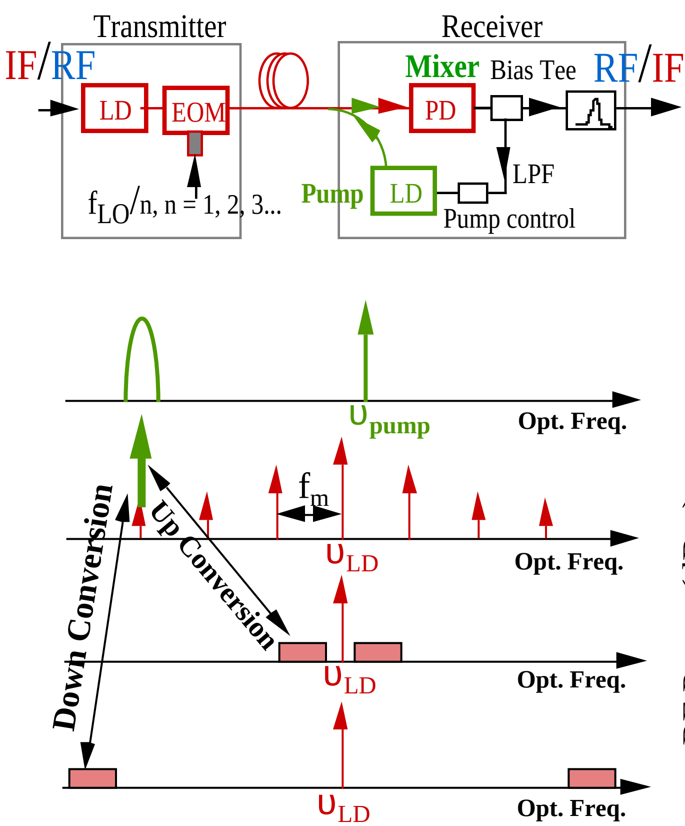
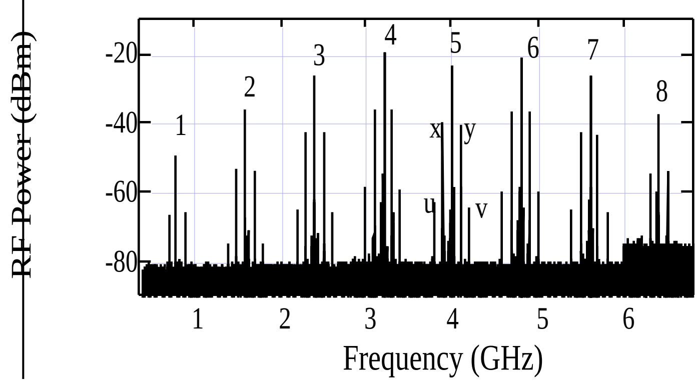
BSSA Assisted Harmonic Up/Down Conversions



* 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



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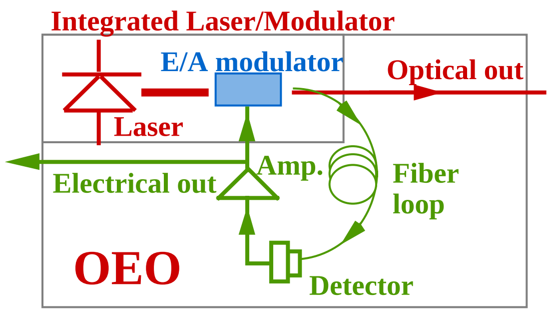
Opto-electronic Oscillator based Photonic Mixing Links

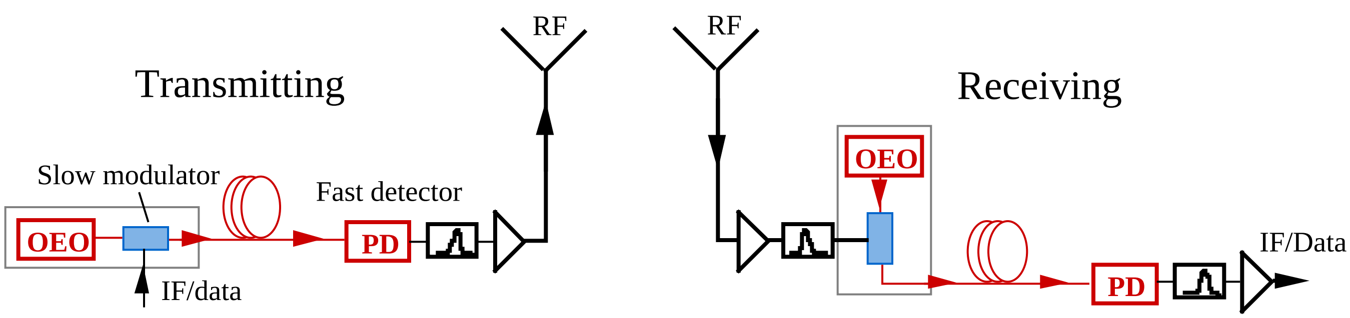
OEO Module



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



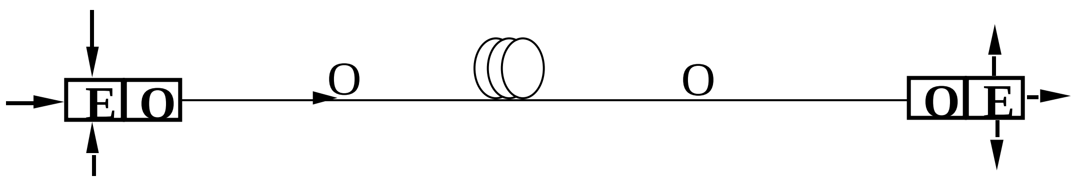
Section Summary

- 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

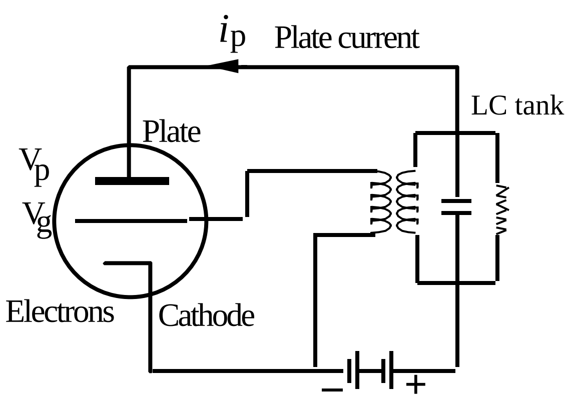
- Mechanical Oscillators: Pendulum, tuning fork ==>
- Electronic Oscillators: Van der Pol oscillator ==>
- electromechanical Hybrid Oscillators: Quartz Oscillator ==>
- Atomic Oscillators: Maser, Cesium beam standard ==>
- Optical Oscillators: Laser ==>
- 6. Electro-Optic Hybrid Oscillator? ==> **OEO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

OEO is a new class of oscillators

Electrical & Optical Hybrid

OEO vs. van der Pol Oscillator

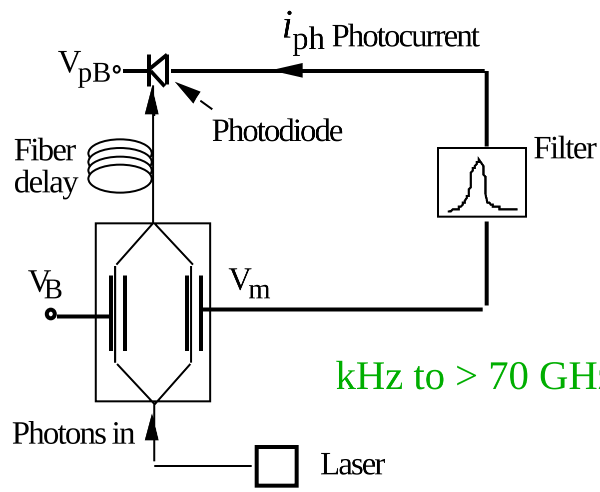
van der Pol Oscillator



kHz

Low Q & Low Frequency

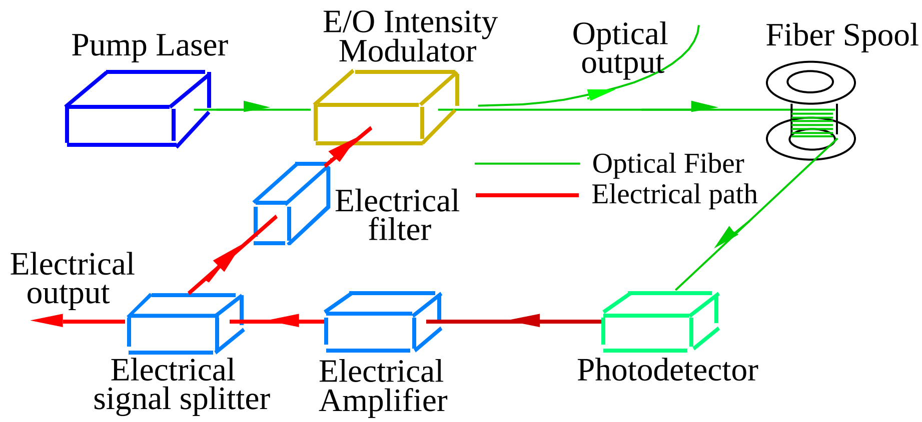
Opto-electronic Oscillator



kHz to > 70 GHz

High Q & High Frequency

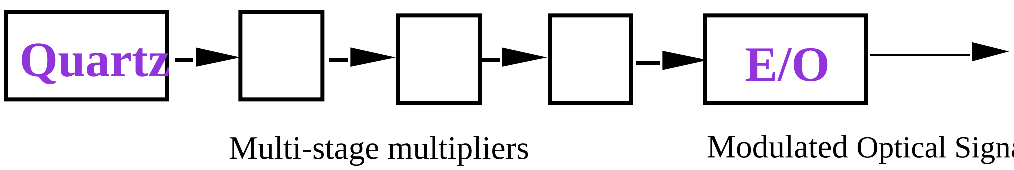
OEO Features



- 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

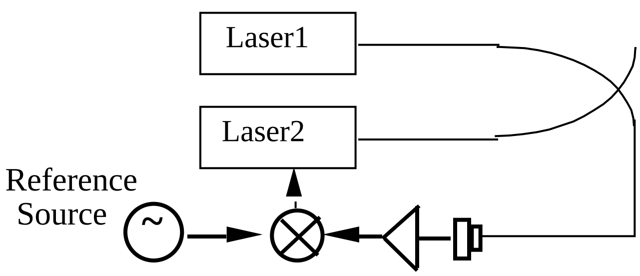
Other Approaches for Generating Photonics Signals

* 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

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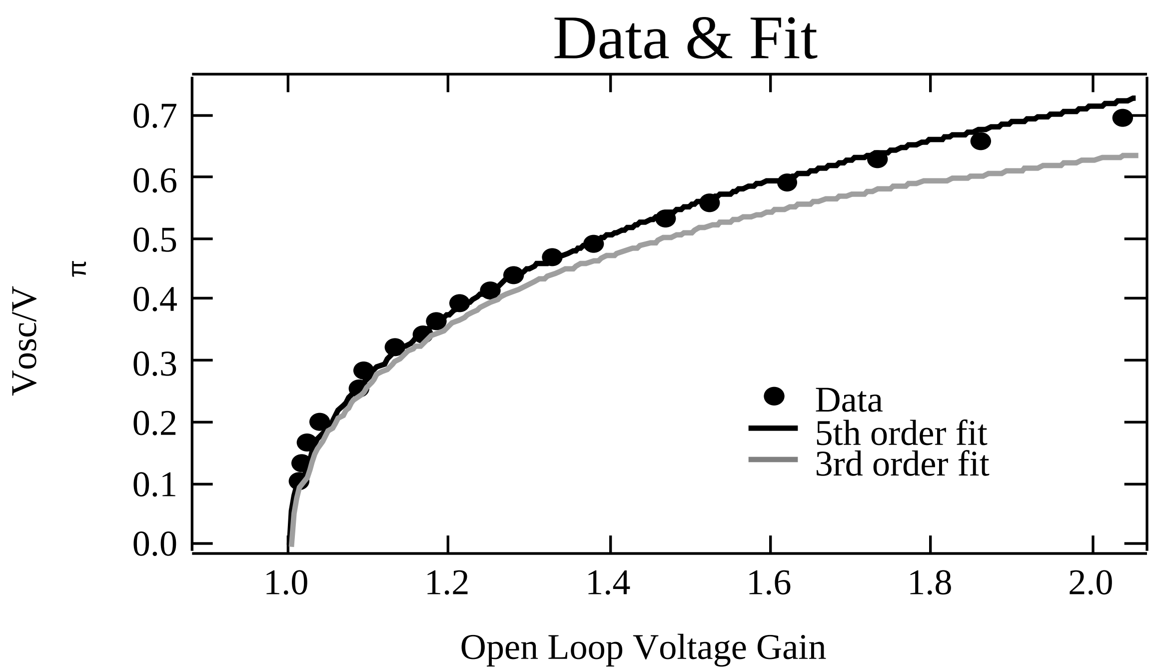
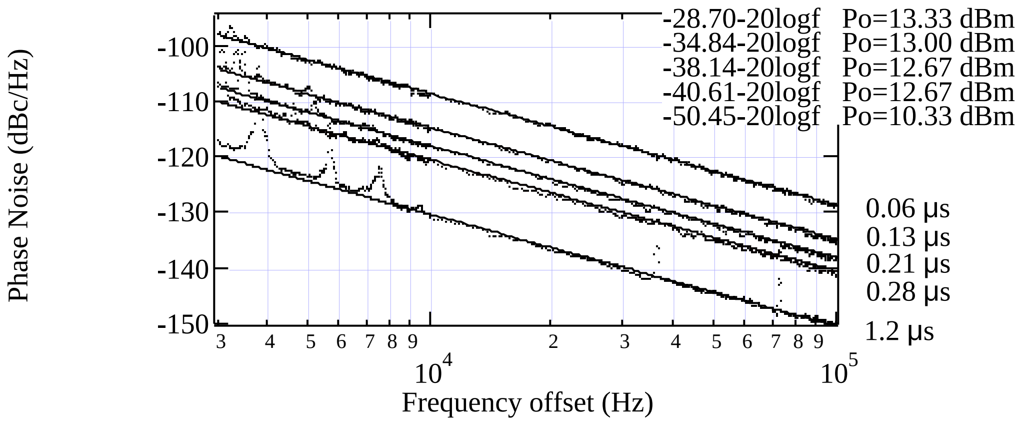
Performance Characteristics of OEO

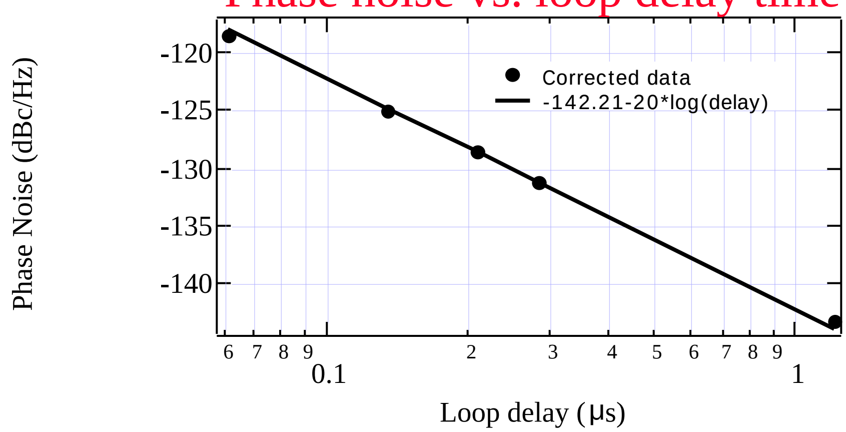
Oscillation Amplitude vs. Open Loop Gain



Phase noise vs. frequency offset



Phase noise vs. loop delay time



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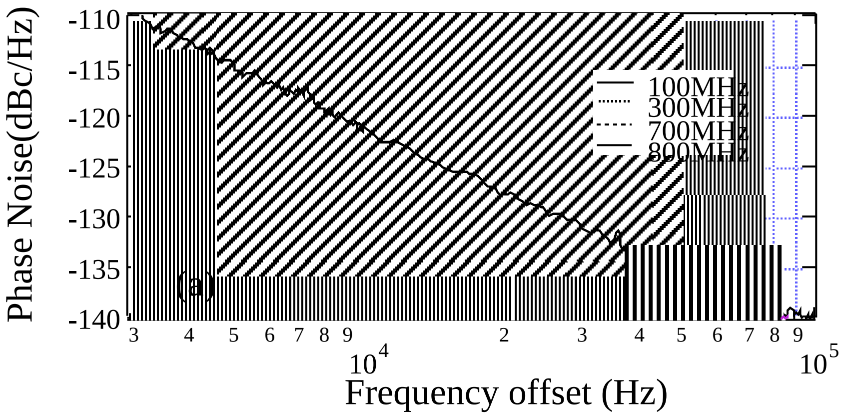
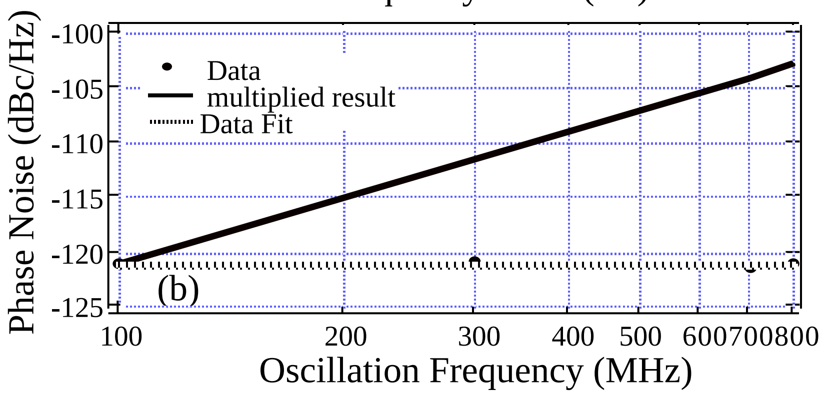
OEO Phase noise as a function of oscillation frequency





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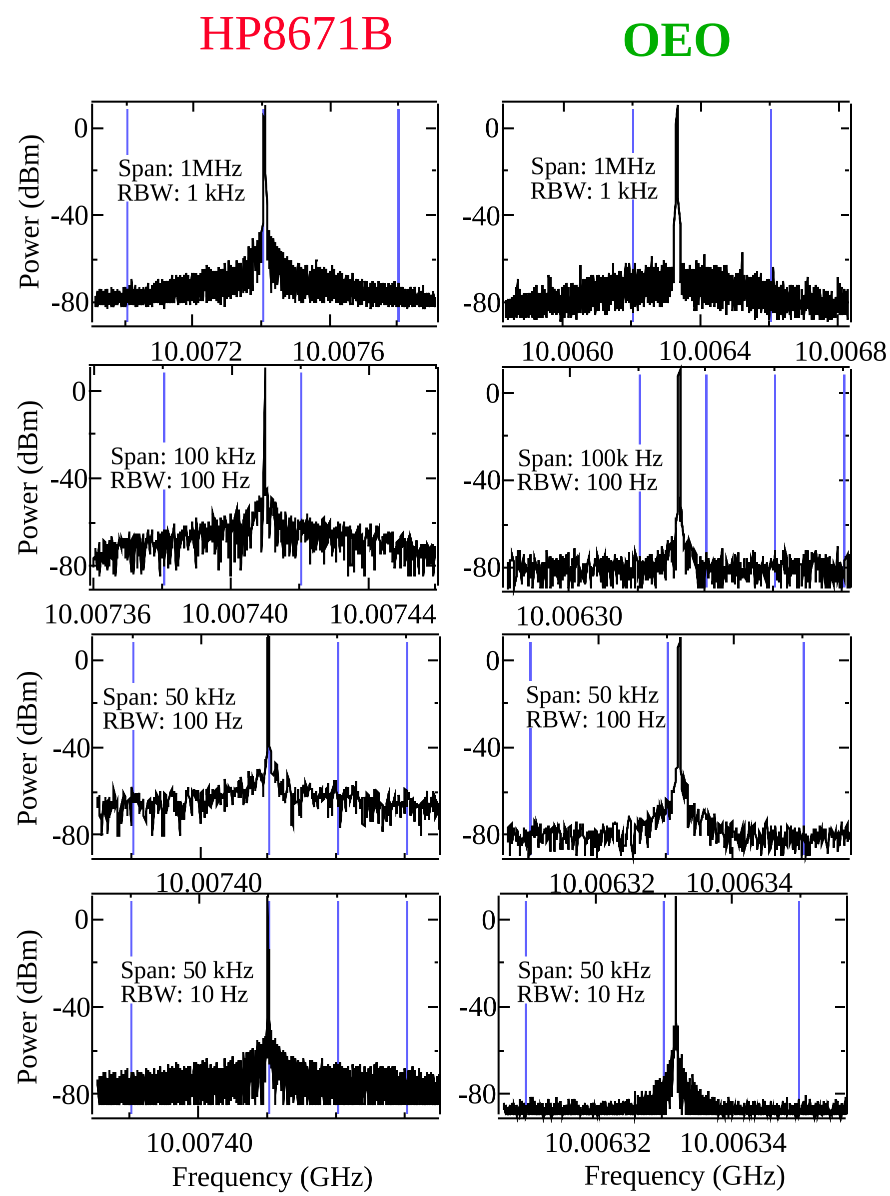
Spectral Purity Comparison



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

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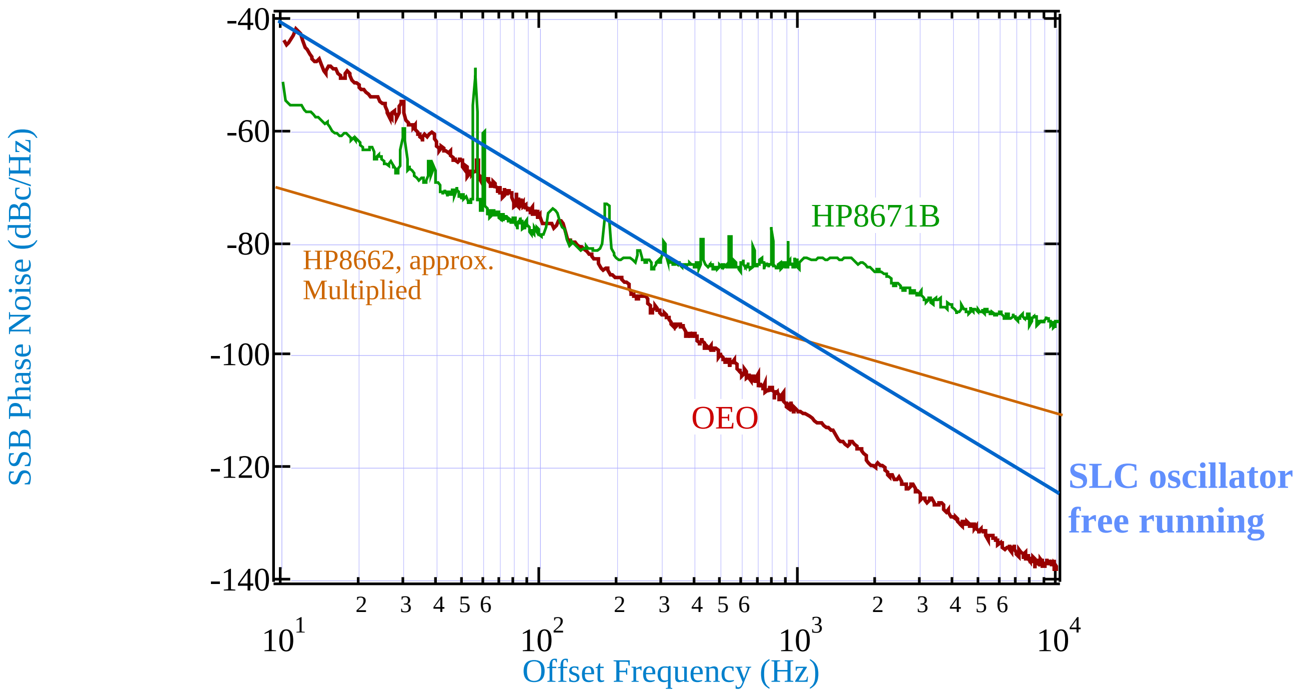
Phase Noise of an OEO at 10 GHz



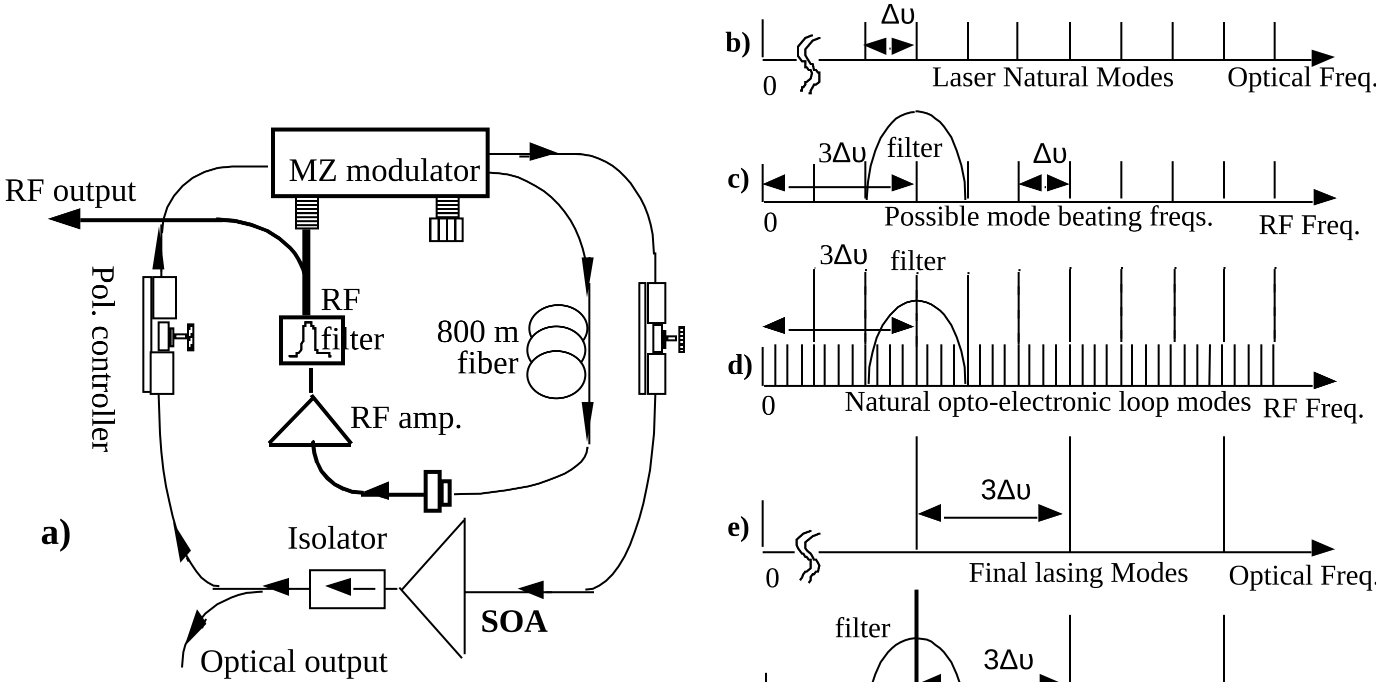
OEO free running @ room temperature

Jitter: 1.6 fs for f >1kHz, 16 fs for f > 100 Hz

Coupled Opto-electronic Oscillator

A variation of OEO ==>

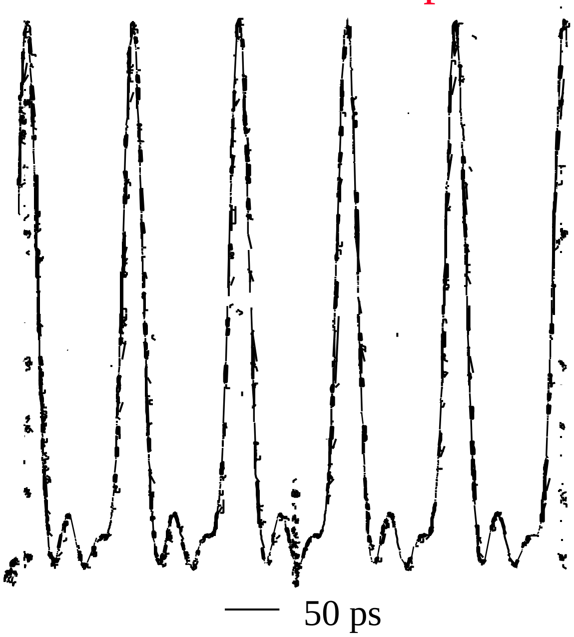
μ-wave & laser oscillations coupled together



Optical Pulse measurement

w/ a 40 GHz detector and Tek CSA 803

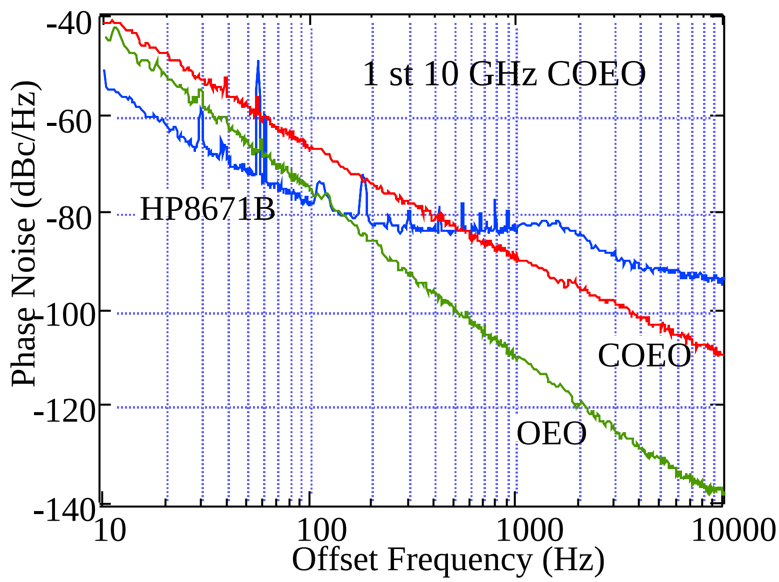
Pulse width: 17 ps



Phase Noise Measurement

Using Frequency Discrimination Method

10 GHz



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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