High Dynamic Range, 100km

RADIO OVER FIBER LINKS

Red Mountain Radio

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Washington, DC

Optical fiber is now ubiquitous

- High Capacity (Pb/s)
- Low Loss (0.2 dB/km [opt])
- Long Haul (Digital)

  Transatlantic, Internet Backbone
- ✅ Last Mile (RF/ Radio Over Fiber [RoF])

  FiOs, CATV, Fiber-to-the-Home

📷 Stealth Communications - CC3.0

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Fiber delivers LOW-LOSS RF transmission over large distances

Parameter	Wireless (isotropic)	Coax (LMR-400)	Radio over Fiber
Loss@ 1km (5.8 GHz)	107 dB	354 dB	0.6 dB
Bandwidth	~10%	100%	100%
Main Issues	Regulatory Issues, Wireless Channel Impairments	Extremely High Loss	Cost/ Complexity, Dynamic Range

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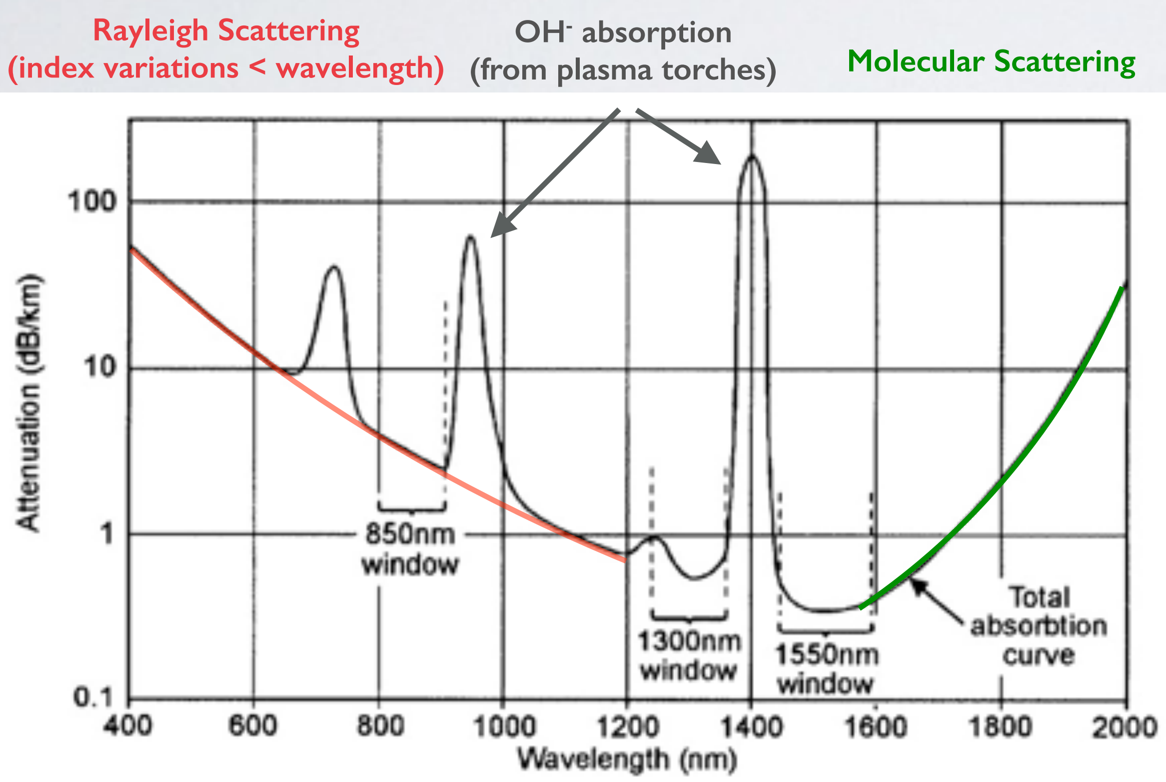
1550 nm is an optimal wavelength

SMF28 Fiber Attenuation



Source: nutsvolts.com

- 1550 nm - Minimum Loss Window
  - ✅ 0.18 dBo/km attenuation
  - ✅ Compatible with erbium doped fiber amplifiers
  - ❎ Optical dispersion present
- 1310 nm - Minimum Dispersion Window
  - ❎ 0.32 dBo/km attenuation
  - ✅ Negligible dispersion

Note: dBo connotes optical gain/loss
dB connotes traditional RF gain/loss

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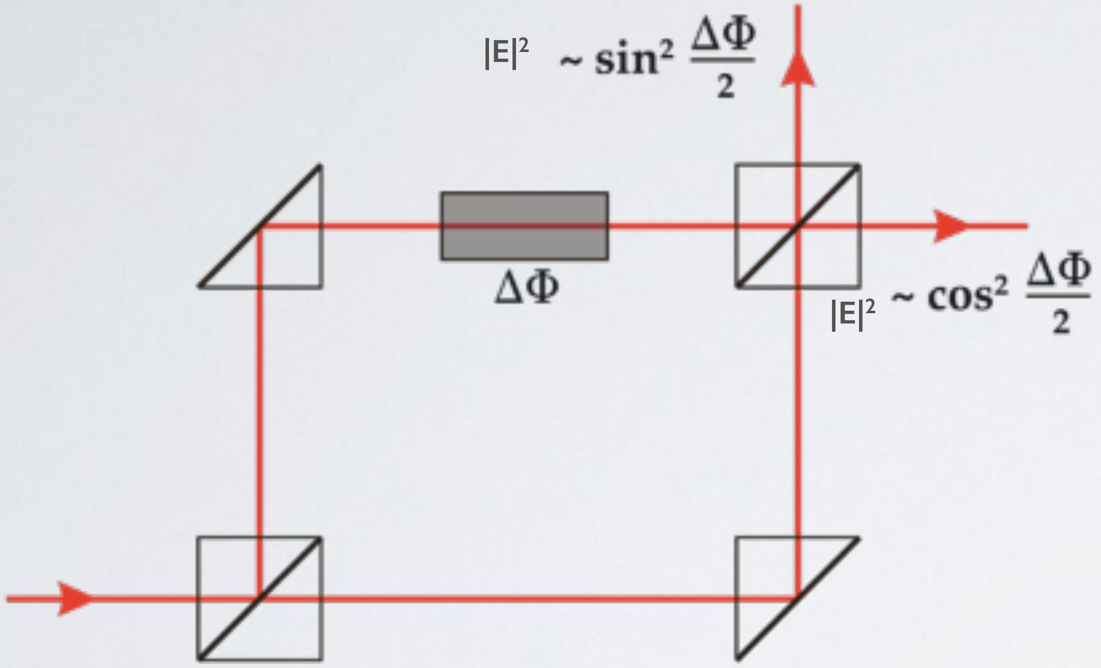
PRINCIPLE: Optical interferometer



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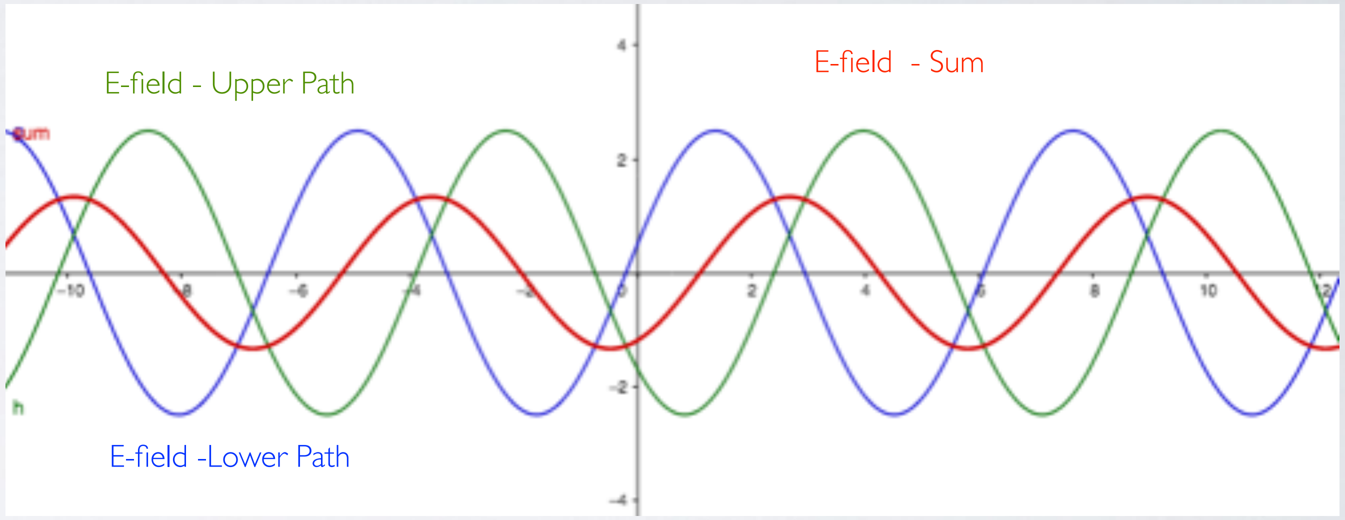

geogebra.org

- Small differences in phase (ΔΦ) between the two paths cause constructive or destructive interference.
- Interferometer converts *phase shifts* into *intensity changes.*

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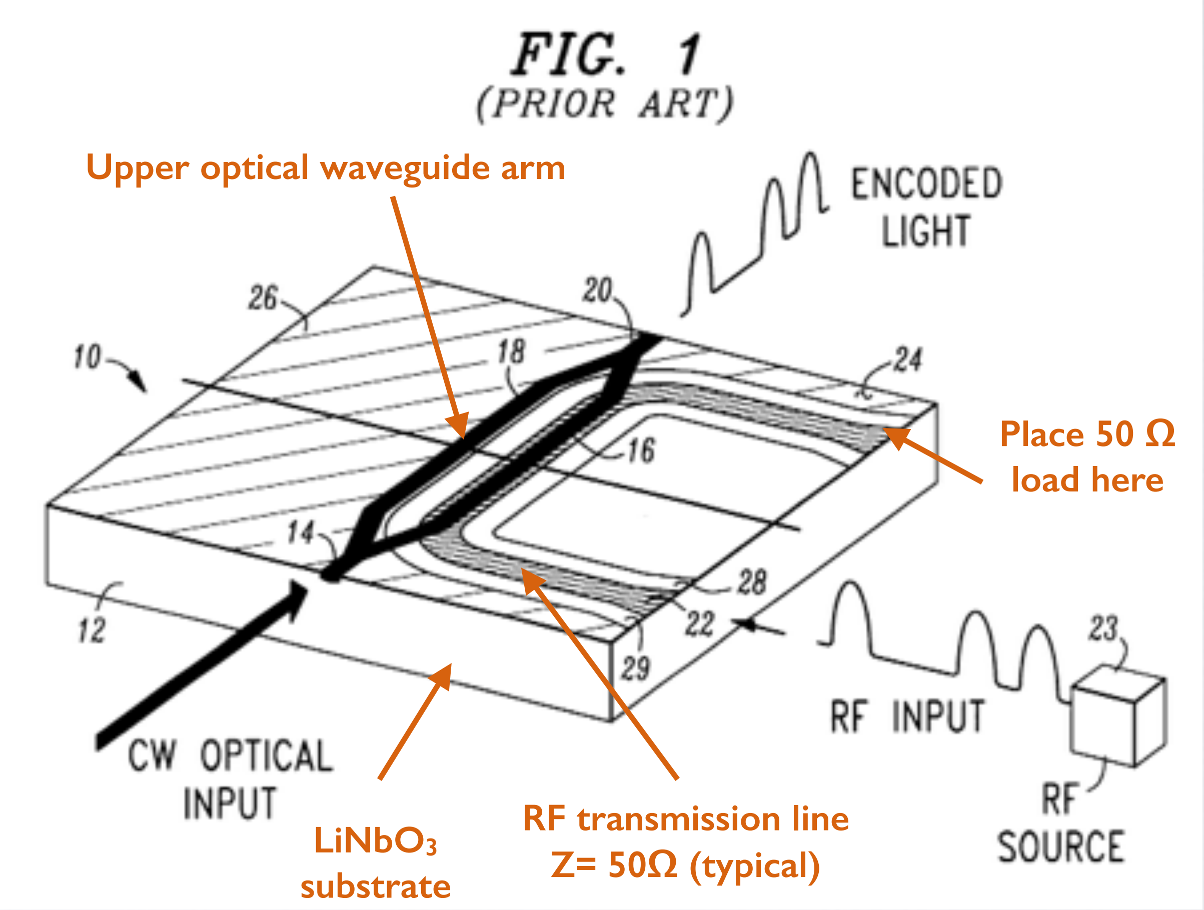
PRINCIPLE: The Mach Zehnder Modualtor (MZM)

- The Mach Zehnder Modulator (MZM) is an **interferometer** made with optical waveguides.
- The MZM encodes changes in **input voltage** onto the **optical intensity**.
  - Step 1: Applied (RF) voltages modulate the index of refraction in the lower arm path via the electro-optic effect.
  - Step 2: Changes in index of refraction modulate the optical phase in the lower arm.
  - Step 3: When we recombine the top and bottom arms, constructive/destructive interference between the paths causes the optical intensity to change with applied voltage.
- When optical and electrical velocities are well matched, modulation bandwidth >40 GHz.



Source: Patent US6501867

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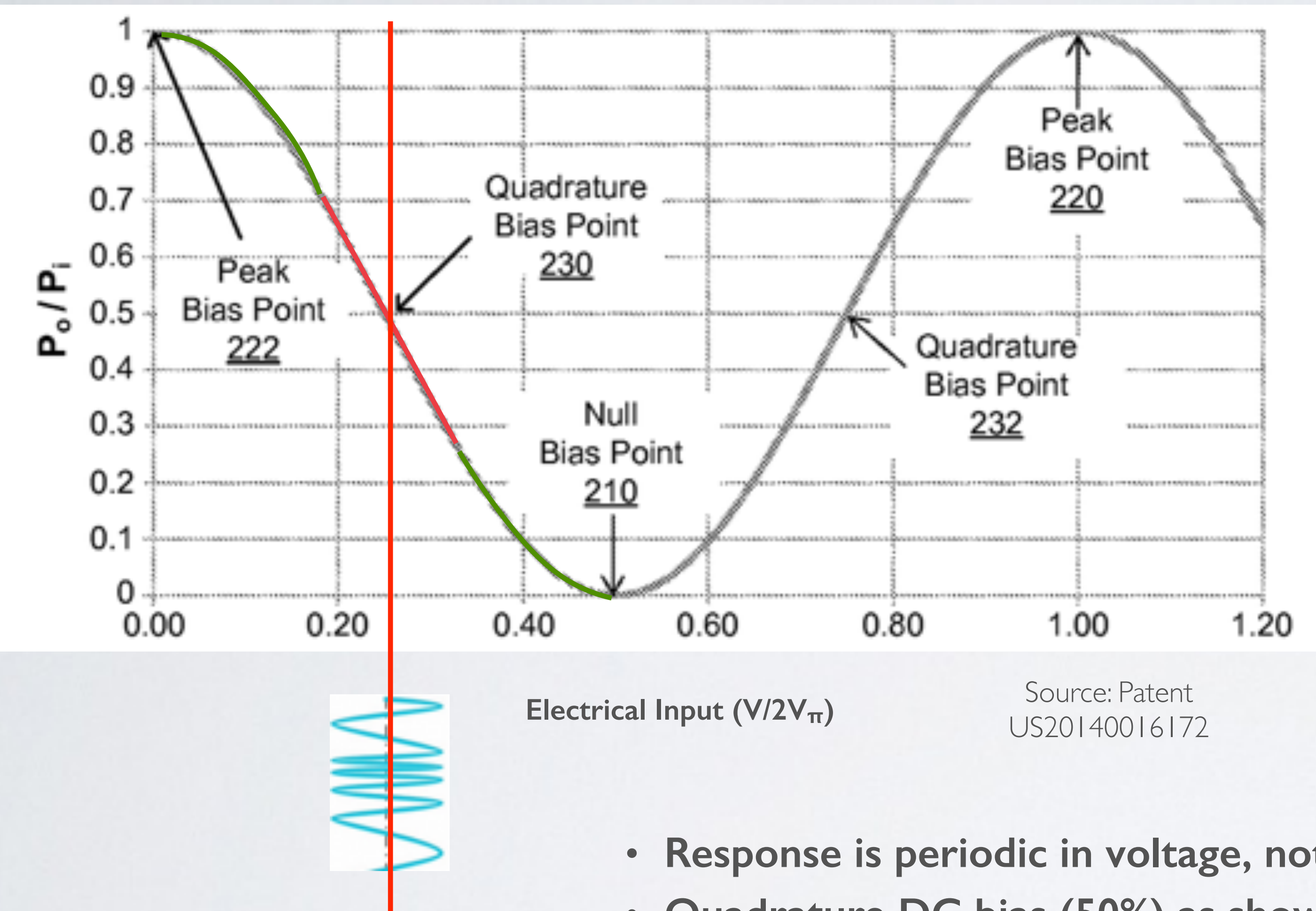
Input Optical power: P_o (1)

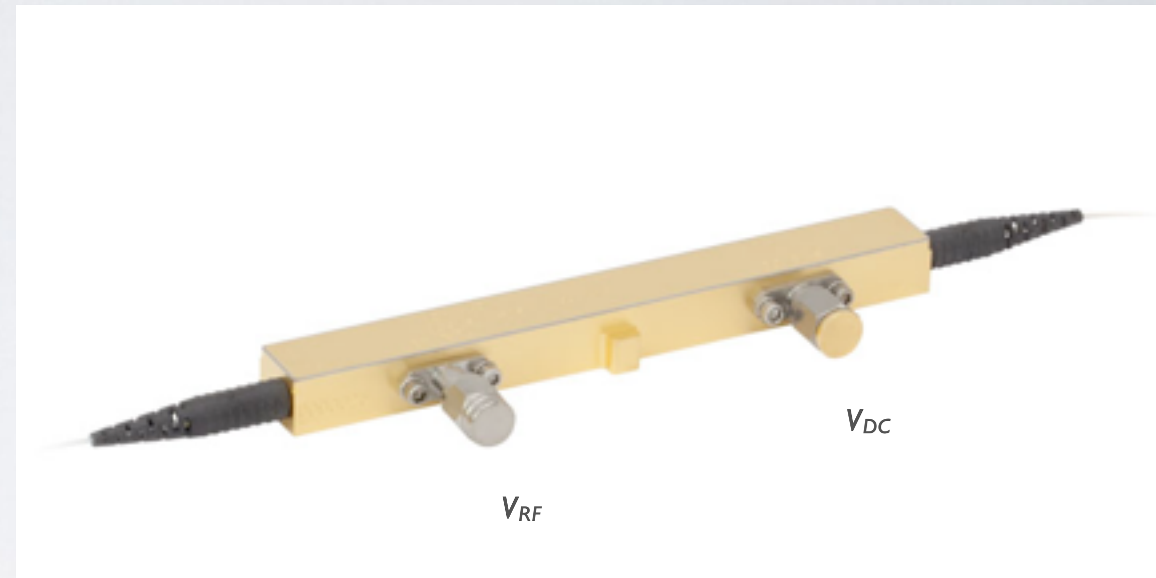
Input RF power (RMS): $P_{rf\text{-}in} = V_{rf\text{-}in}^2/2Z$ (2)

Signal Distortion depends on MZM bias setting



$V_{DC} = V_\pi/2$

Source: Patent US20140016172



ThorLabs - LN05S-FC - 40 GHz Intensity Modulator

- Response is periodic in voltage, not linear
- Quadrature DC bias (50%) as shown above ⇒ linear portion of the response.

- Green areas excursions cause odd order distortion products
- The *n*th order (rms) OPTICAL INTENSITY products follow a Bessel series (just like for PM and FM in radio communications).

$$P_{mzm}\ (DC) = P_o/2 \qquad (3)$$
$$P_{mzm}\ (f1) = P_o J_1(\pi V_{rf}/V_\pi) \qquad (4)$$
etc.

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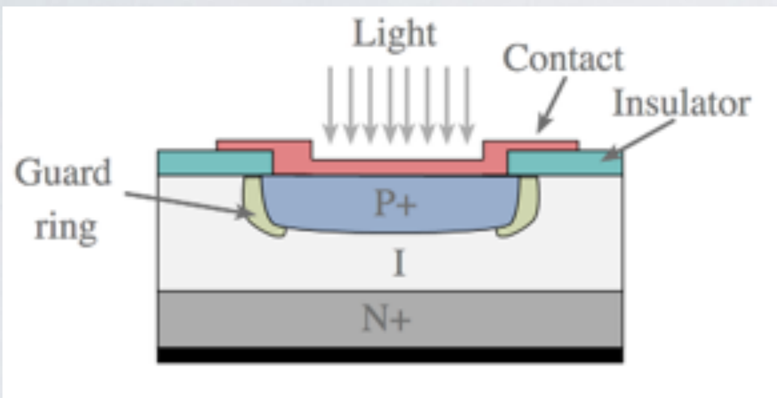
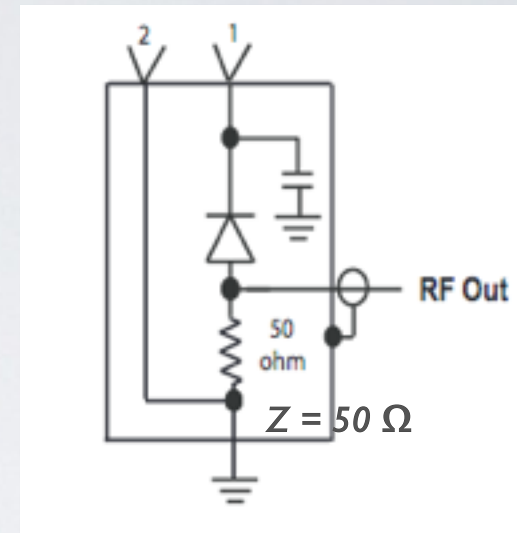
Optical-to-Electrical PIN InGaAs Photodiode



Source: electronics-notes.com

Source: Emcore -
2522 PIN Photodiode
22 GHz - 0.7 A/W@1550 nm



Source: Emcore -
2522 PIN Photodiode
22 GHz - 0.7 A/W@1550 nm

Optical Intensity → RF Current

$$I = \Re P_{opt}$$

Using (1) - (4) the RF output power can be now written in terms of just electrical parameters

$$P_{rf-out} = \frac{1}{2} I_{DC}^2 Z \frac{\pi V_{rf}}{V_\pi} \qquad (5)$$

NOTE: RF power goes as the square of optical power.
RF attenuation is twice the optical attenuation (in dB).

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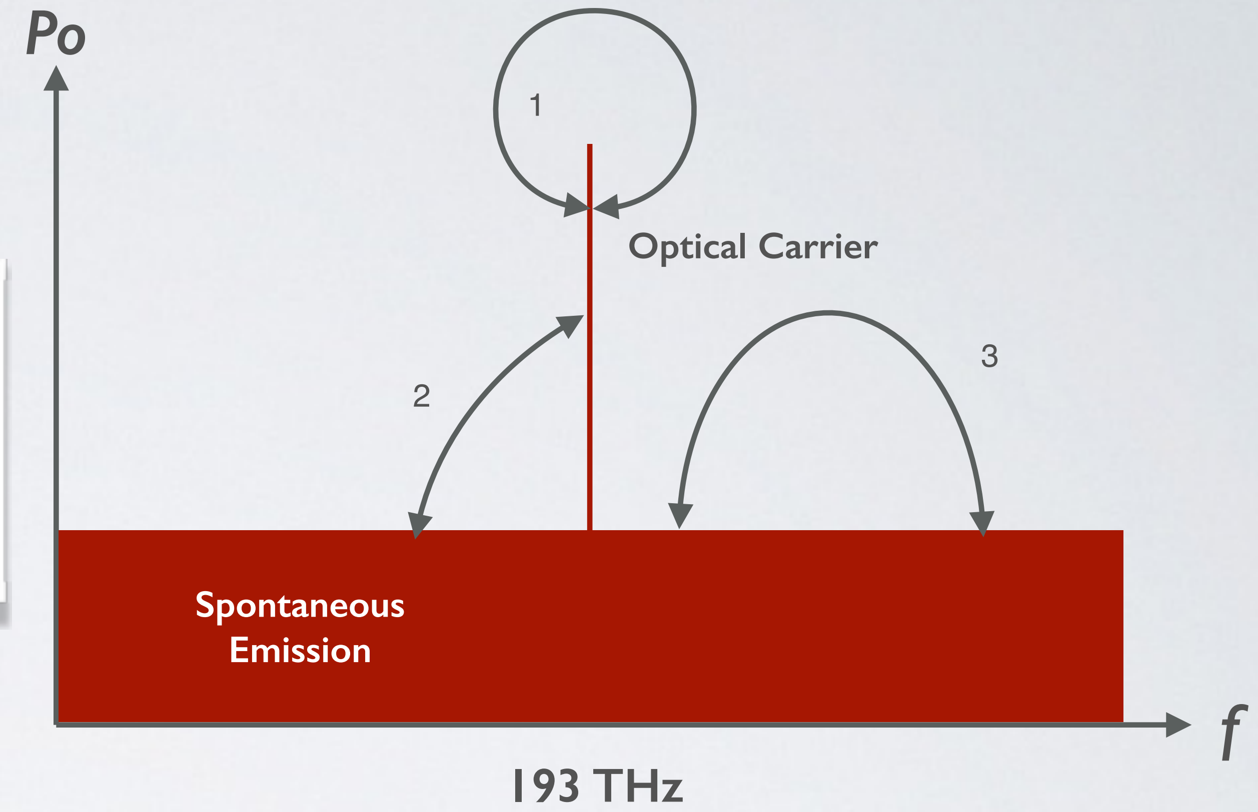
The photodiode is an optical homodyne detector

$$I \propto P_o \propto \vec{E} \cdot \vec{E}$$

[1] SIGNAL: Carrier × Carrier = Optical Intensity
[2] NOISE: Carrier × Spontaneous noise.

- Optical noise figure, NF_{opt}
- NF_{opt} cascades like RF noise figure.
- NF_{opt} & G_{opt} = 0 dB → quantum **shot noise limit**.



$$N_{sig-sp}[dBm/Hz] = -169 + 10\log(\Re\, I_{DC}[mA]) + G_{opt}[dB] + NF_{opt}[dB] \quad (6)$$

$$NF_{RF}[dB] = 174 - G_{RF}[dB] + N_{sig-sp}[dBm/Hz] \quad (7)$$

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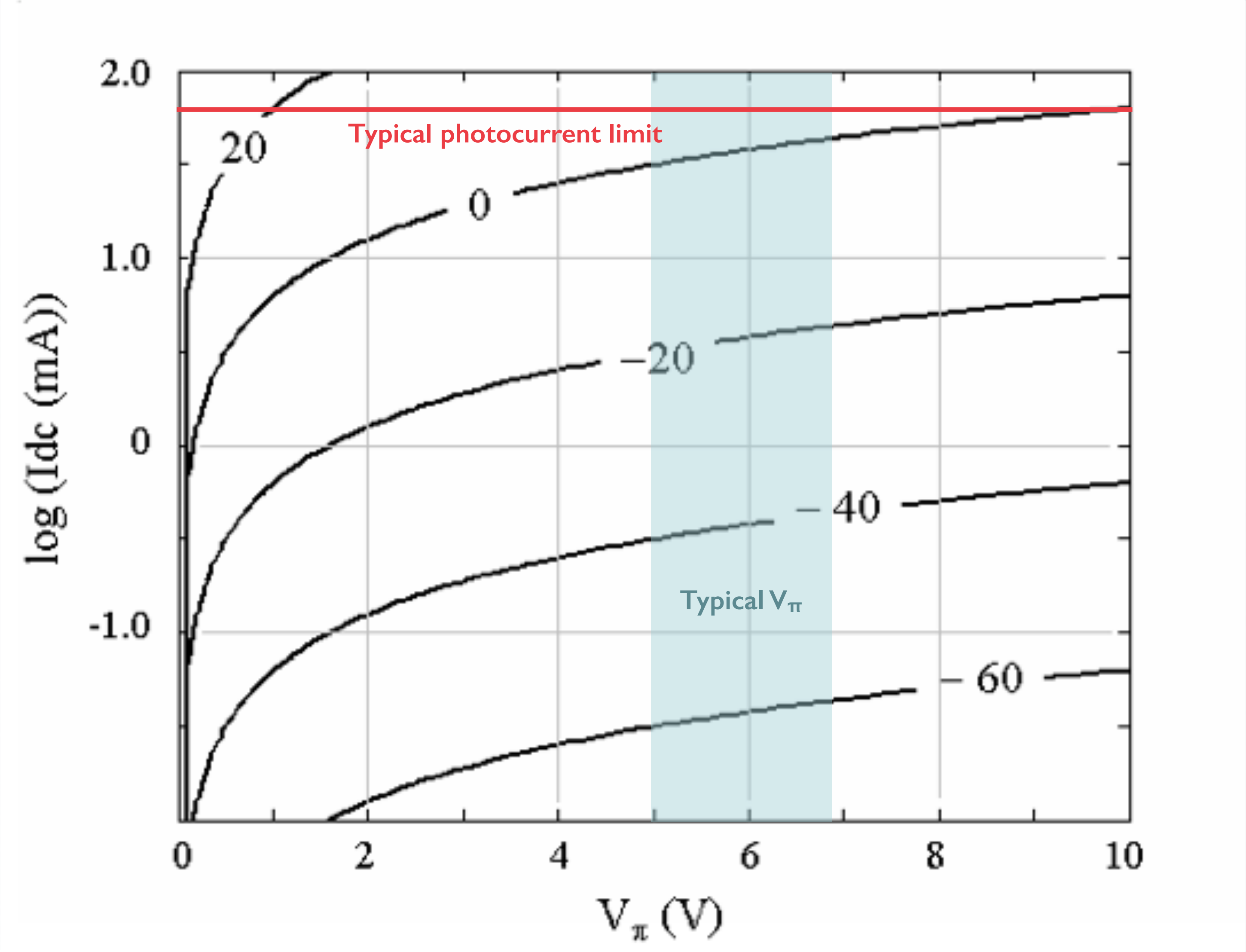
Other sources of noise are typically negligible

[3] - sp-sp - spont. noise heterodynes with itself.
[4] -RIN - relative intensity noise. Carrier heterodynes with its own noise sidebands (BW<1 MHz).
Thermal Noise in the diode is negligible compared to these other products.

Calculating the RF GAIN Modulator to Photodiode

A typical link is just *slightly* lossy without added RF amplification.



$$G_{RF} = \frac{P_{rf-out}}{P_{rf-in}} = \left(I_{DC} Z\pi \;/ V_\pi \right)^2 \quad (8)$$

$$G_{RF}[dB] = -16 - 20\log\left(V_\pi\,[V]\right) + 20\log\left(I_{DC}[mA]\right) \quad (9)$$

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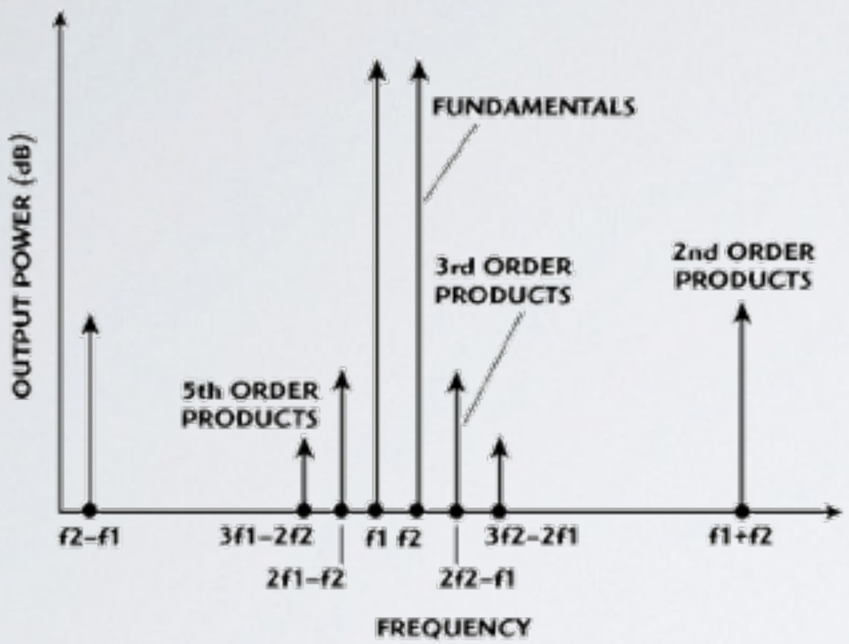
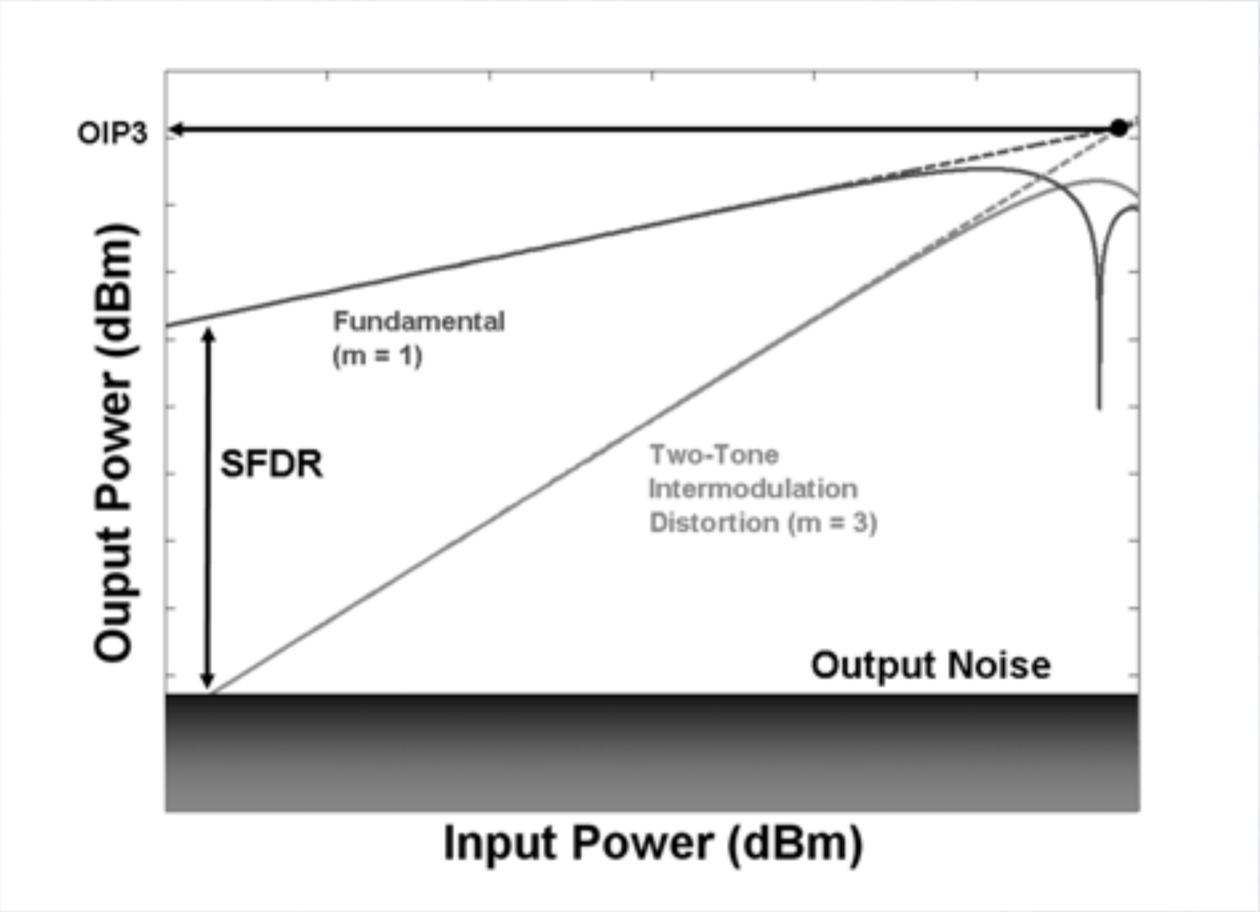
PRINCIPLE: Distortion & Dynamic Range



- 3rd-order distortion of multiple **large signals** produces adjacent spurious signals in <u>all practical RF systems</u>.
- +1dB in fundamentals → **+3dB in 3rd order distortion.**
- Our OIP3 can be determined from the MZM's Bessel Series.

Terminology

- *Spur-free-dynamic range* = range over which distortion is "lost in the noise."
- *Output Third order intercept (OIP3)* is the output power where the fundamental and distortion lines intersect.



$$OIP3[dBm]=-7+20\log(I_{dc}[mA]) \quad (10)$$

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We can now write down the KEY RF SYSTEM PARAMETERS

Gain

$$G_{RF}[dB]=-16-20\log(V_{\pi}\,[V])+20\log(I_{DC}[mA]) \quad (9)$$

Noise Figure

Using (7) and (9)

$$NF[dB]=21+20\log(V_{\pi}\,[V])-10\log(\Re\, I_{dc}[mA])+G_{opt}[dB]+NF_{opt}[dB] \quad (11)$$

Linearity

$$OIP3[dBm]=-7+20\log(I_{dc}[mA]) \quad (10)$$

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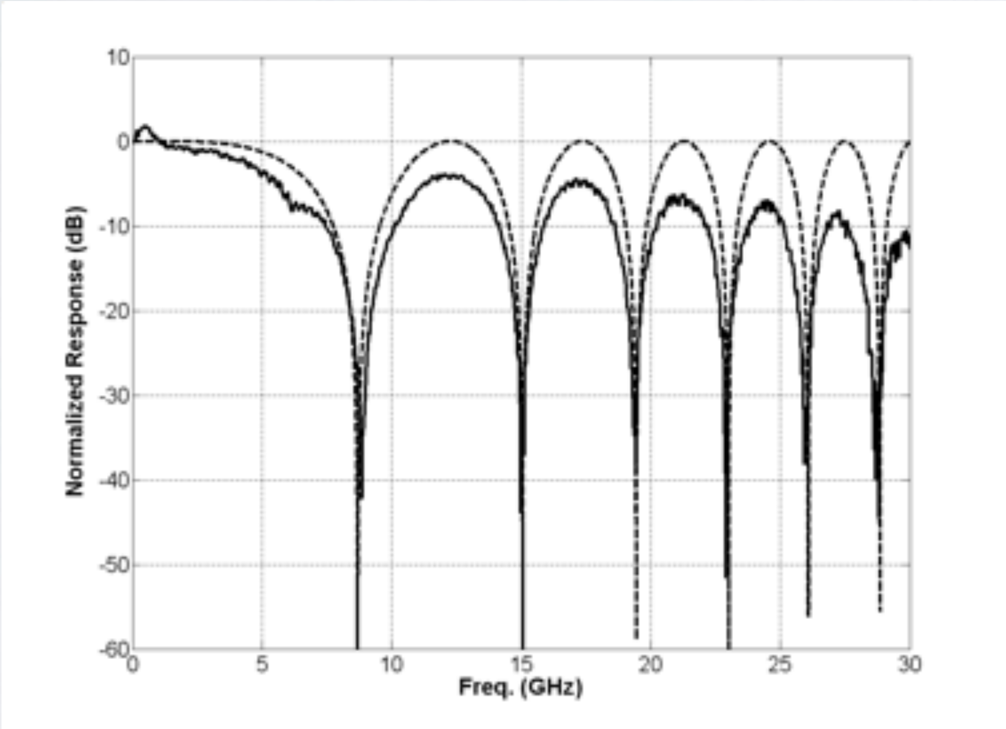
TAKEAWAYS

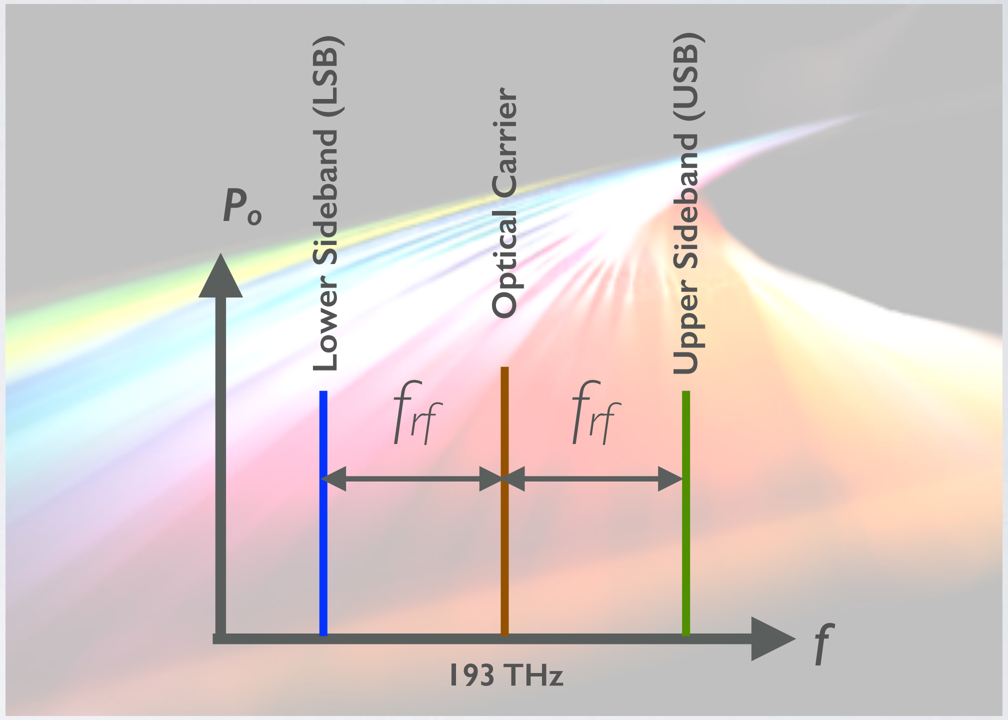
Maximize photocurrent.
Minimize the optical noise figure.
Minimize V_{π}.

Managing Dispersion

- **Upper and lower sidebands travel at slightly different velocities.**
- **The heterodyned output from LSB and USB may get out of phase and cancel at certain frequencies.**

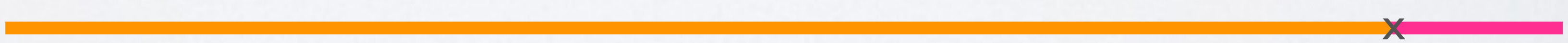


Measured (solid) and calculated (dashed) dispersion response for a ROF channel through 50 km of SMF-28 fiber.



RF_{out} = (carrier x LSB) + (carrier x USB)

SOLUTION: Dispersion Compensating Fiber (DCF)



SMF-28®
+18 ps/nm•km

Fujikura - DCF
-155 ps/nm•km

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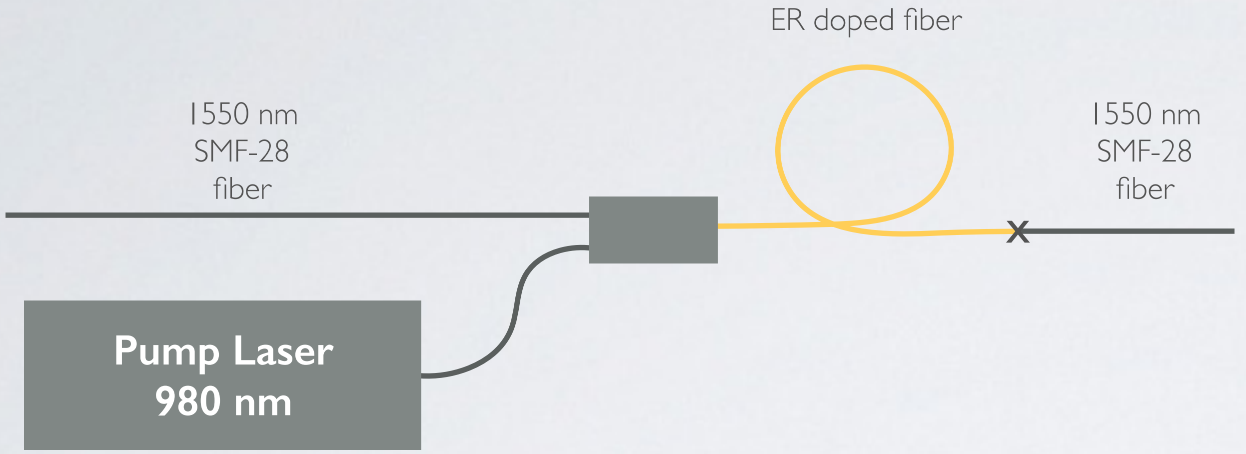
Extending the reach to 10 km and beyond with *Erbium Doped Fiber Amplifiers*



thorlabs.us
>20dB gain, 5 dB Noise Figure

- In-fiber amplification at 1550 nm
- Inject PUMP photons at 980nm to produce an excited state in atoms
- Excited atoms produce stimulated emission at 1550nm
- 1550nm signal is amplified.
- Like a laser without end mirrors (no feedback)
- No oscillation, just amplification

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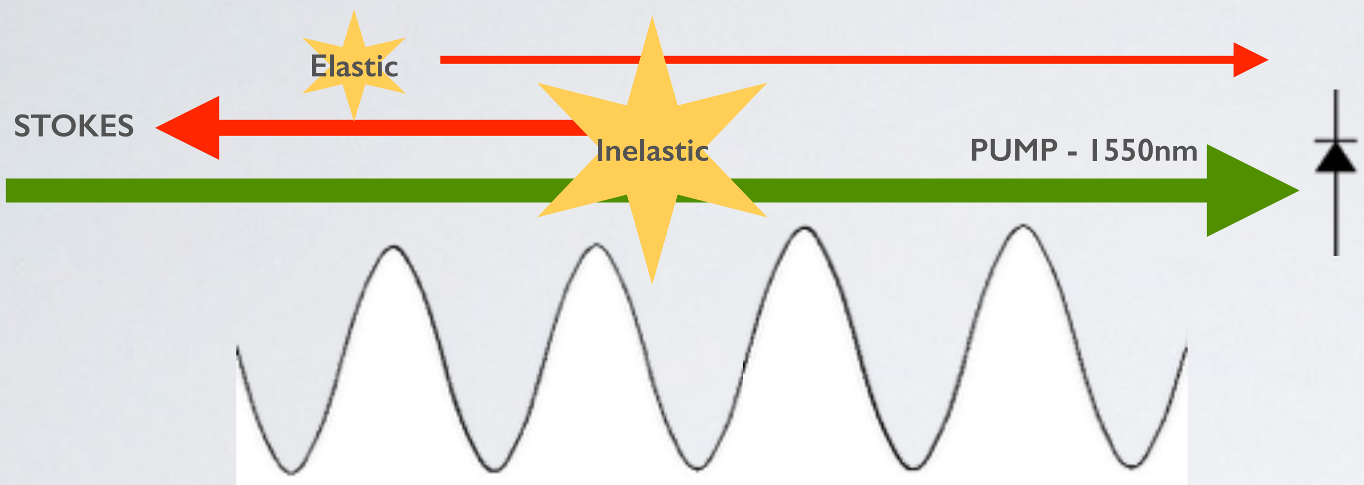
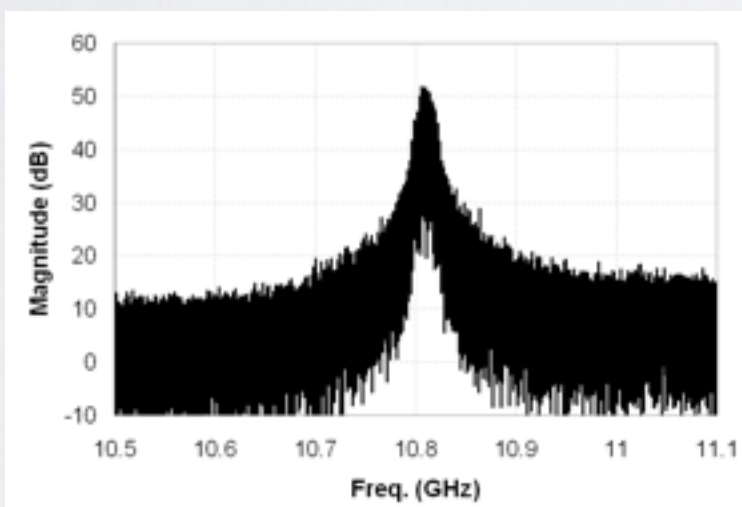
Optical Power Limit
Stimulated Brillouin Scattering (SBS)

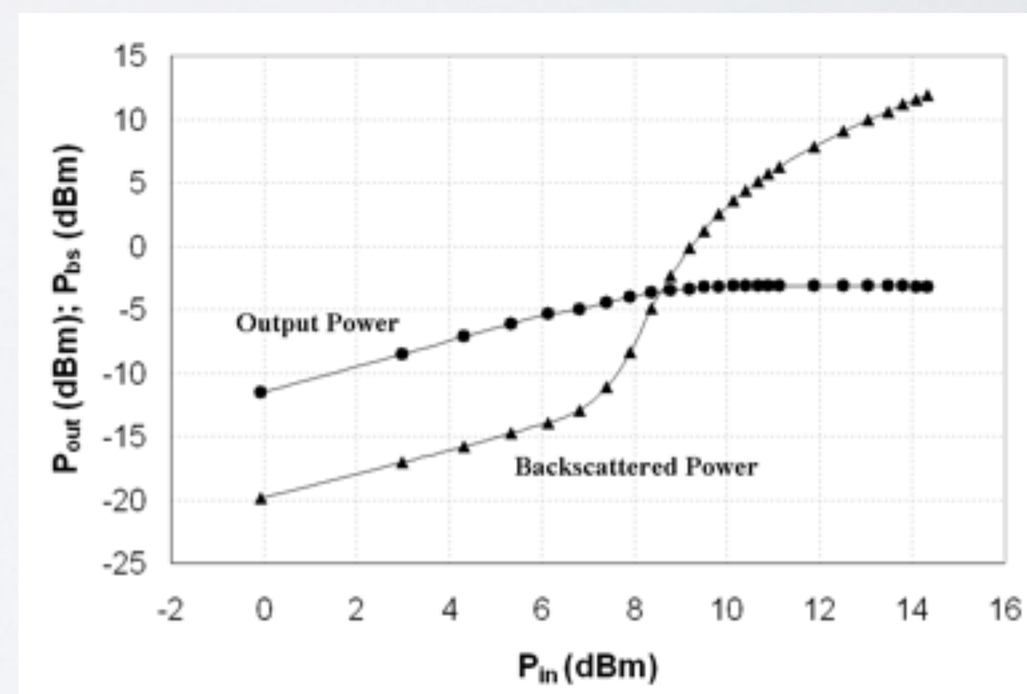


ACOUSTIC WAVE/ INDEX CHANGES



Noise spectrum at the photodiode caused by Stokes wave heterodyning with Pump wave.

- Incident high power photons in PUMP scatter exciting vibrations in the glass.
- Acoustic waves cause ripple in refractive index (photo-elastic effect).
- Refractive index ripple forms a grating and scatters the optical signal backwards in a (red shifted) STOKES wave.
- Red shifted by resonant acoustic (phonon) frequency of ~10.8 GHz.
- Scattered forward again by (elastic) Rayleigh scattering.



SBS: 1551 nm DFB semiconductor laser through 20 km of SMF-28, having an SBS threshold of approximately 7 dBm.

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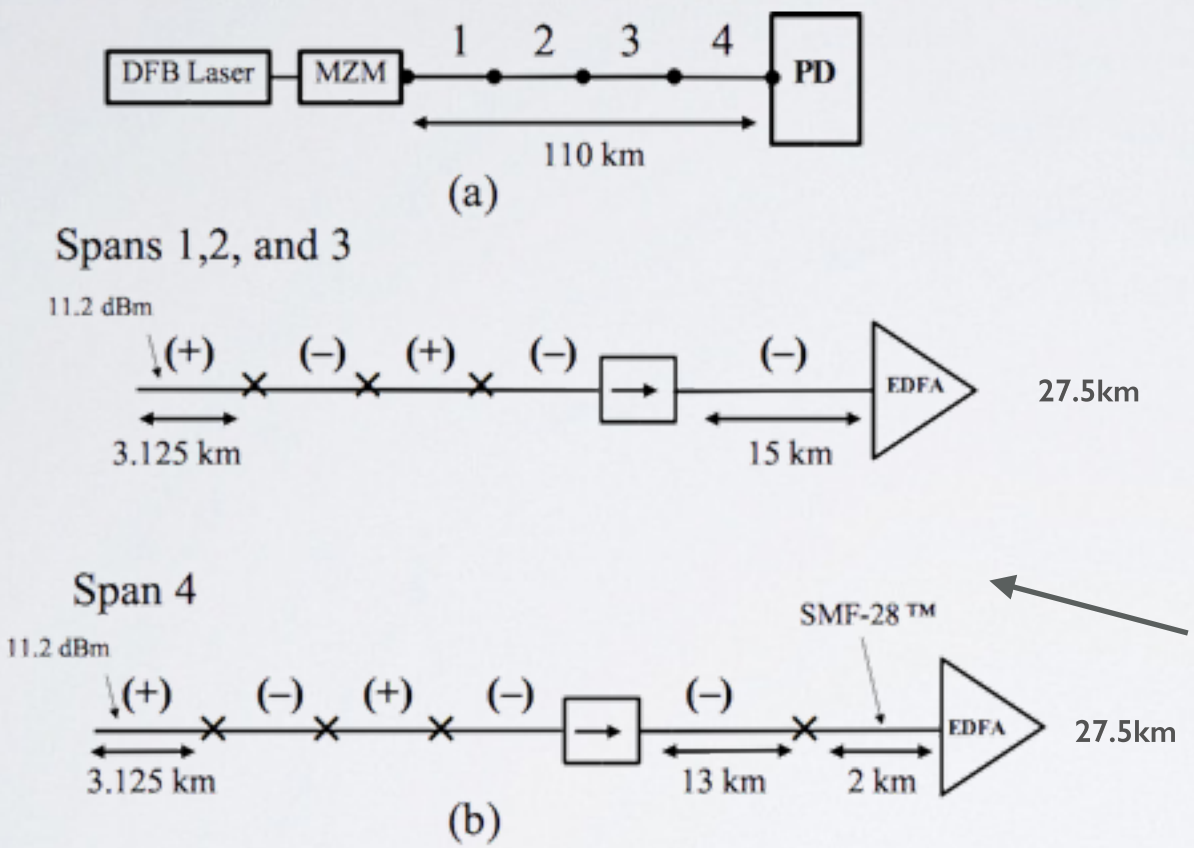
$$P_{th} \approx 21 \frac{A_{eff}}{g_B L_{eff}} \qquad (12)$$

$$L_{eff} = (1 - e^{-\alpha L}) / \alpha \qquad (13)$$

Long Haul Link Design

Optical Noise Figure and SBS depends on optical amplifier placement



(+) Positive dispersion shifted fiber
(–) Negative dispersion shifted fiber

TOTAL DISPERSION = 8ps/nm
FIRST NULL = 395 GHz
TOTAL LENGTH = 110 km

- EDFA at launch
  - ✅ Min. NF_{opt}
  - ❎ Max. P_{opt} and SBS
- EDFA at end
  - ✅ Reduced SBS
  - ❎ Poor NF_{opt}
- **Distributed amplification**
  - ✅ **Reasonable compromise**
  - ✅ **Spacing to keep P_{opt} below SBS threshold**

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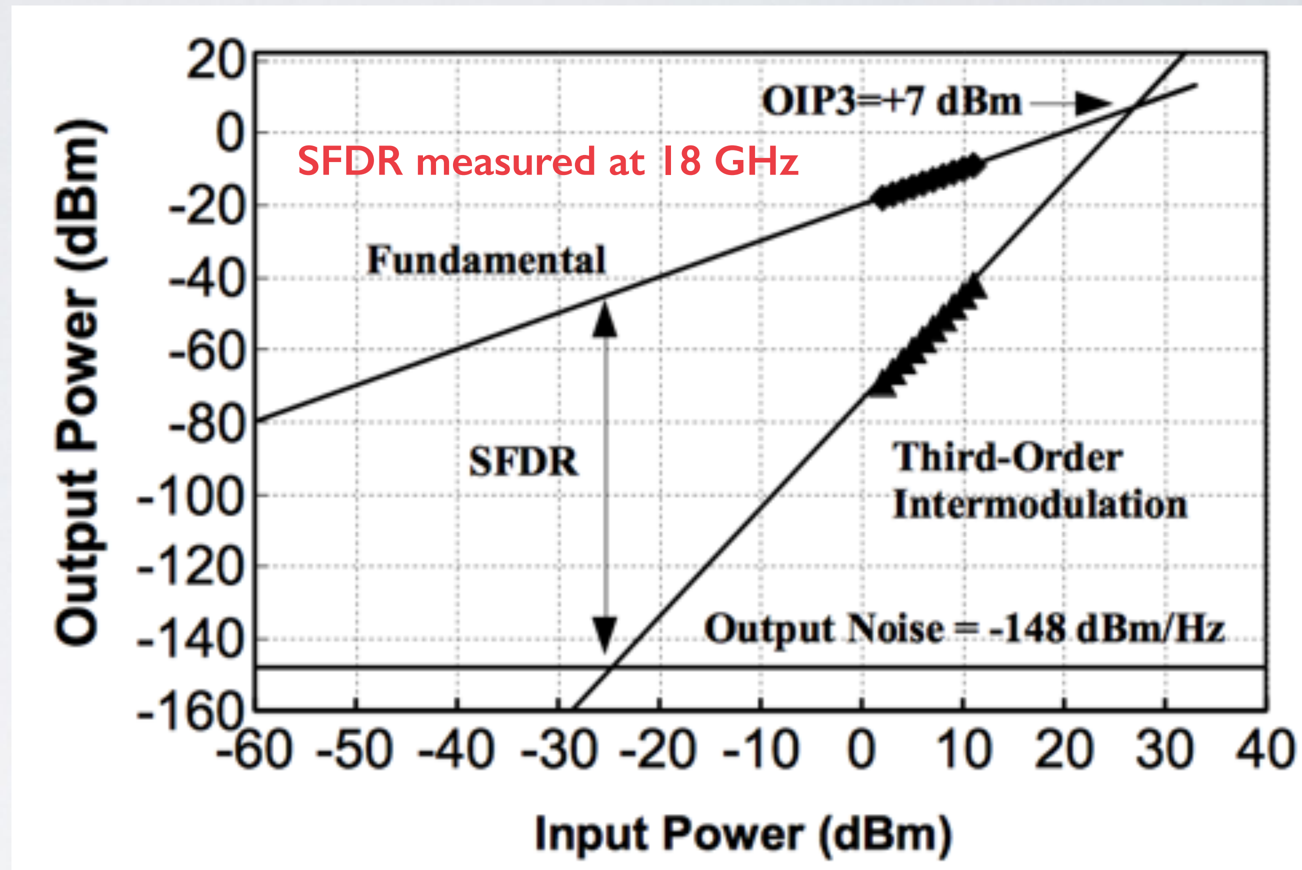
Remember, SBS = Stimulated Brillouin Scattering

RESULTS: Excellent Dynamic Range performance over 110 km!

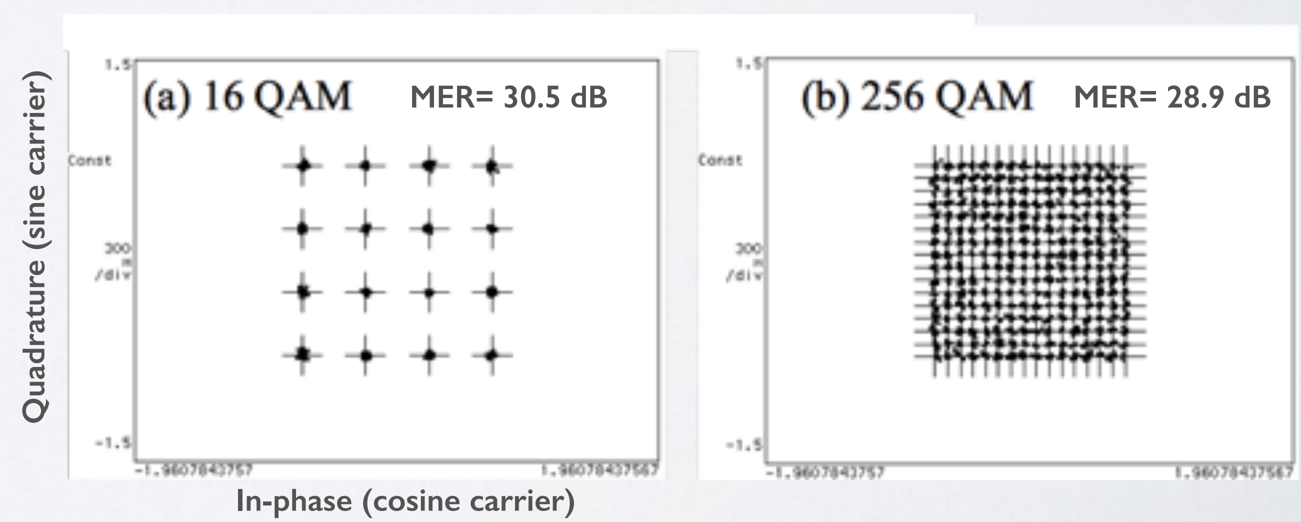
- ✅ SFDR: 103 dBHz$^{2/3}$
- Dynamic Range is critical for multi-carrier RF applications & AM-based modulation formats
- Sufficient for 256-QAM signal with ~30dB MER



Measured Constellations

Typical of digital TV (CATV) and cable modem signal constellations.

16-QAM encodes 4 bits/symbol & 256-QAM encodes 8 bits/symbol



5 MSymb/s @ 2 GHz

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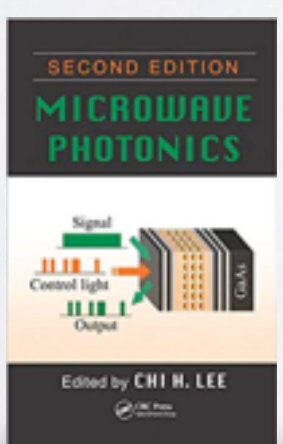
CONCLUSION

"Thank you for your time"

- Radio over Fiber can provide low-loss & high dynamic range RF links over 110 km or more!
- Simple RF link equations: Gain, Noise Figure, Dynamic Range.
- Distributed optical amplification enables long-haul links.
- Dynamic Range is limited primarily by modulator linearity, Brillouin scattering, and optical noise from spontaneous emission.

Learn More Here....

Download this talk: RedMountainRadio.com



Eric E. Funk, Vincent J. Urick, and Frank Bucholtz, "High Dynamic Range 100-km Digital Radio-Over-Fiber Links." in *Microwave Photonics*, Ed. Chi H. Lee, New York: CRC Press, 2006, Ch. 6.

Vincent J. Urick, Frank Bucholtz, and **Eric Funk**, "High Dynamic Range 100-km Digital Radio-Over-Fiber Links." in *Microwave Photonics*, 2nd Ed., Ed. Chi H. Lee, New York: CRC Press, 2013, Ch. 6.

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