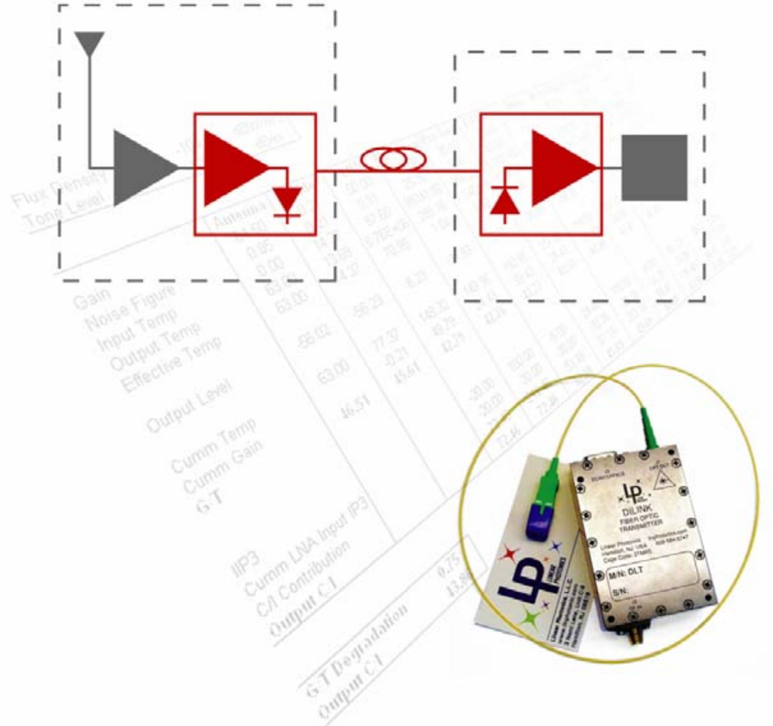

# LINEAR MICROWAVE FIBER OPTIC LINK SYSTEM DESIGN


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IEEE MTT-S International Microwave Symposium

3 - 8 June 2007 Honolulu, Hawaii

IMS2007 IEEE MTT-S


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# Microwave Fiber Optic (F/O) Link Analysis

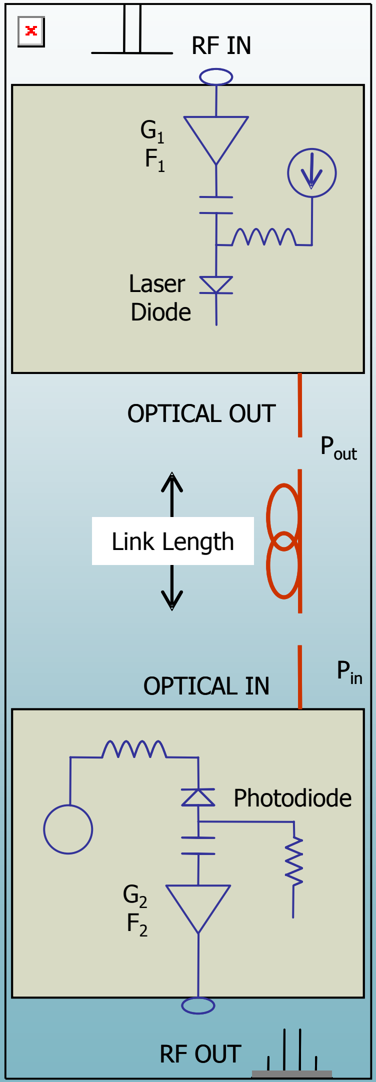
Microwave (linear) F/O Links used for point-to-point communications

- Antenna remoting
- Sensors
- Radio-over-Fiber

1. We present a new method for quickly determining the system impact of a F/O Link
   - GAIN
   - NOISE
   - LINEARITY
2. We demonstrate a linearization method for improved F/O Link linearity

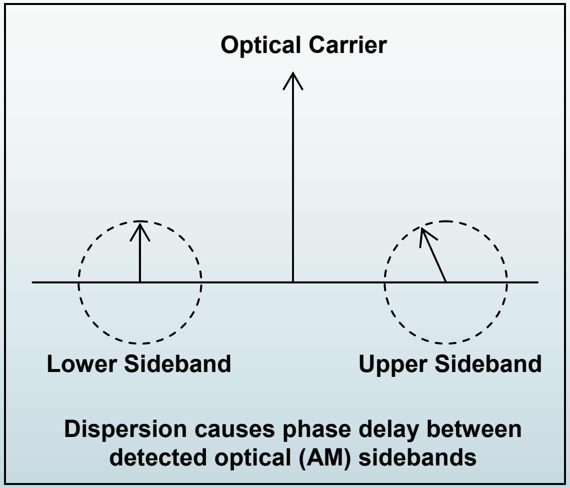
# Brief Overview of DM Links

- Directly-Modulated (DM) Fiber Optic Links
  - Transmitter: RF pre-amplification, biasing, and matching to low-impedance laser diode
    - Output is Intensity Modulated
    - Modulation Efficiency = ratio of peak output modulation envelope to peak microwave input current
  - Receiver: PIN photodiode, matching from high-impedance diode, RF post-amplification
    - Responsivity = ratio of generated current to incident light intensity
    - PIN diode performs direct envelope detection



# Brief Overview: Fiber and Optical Medium

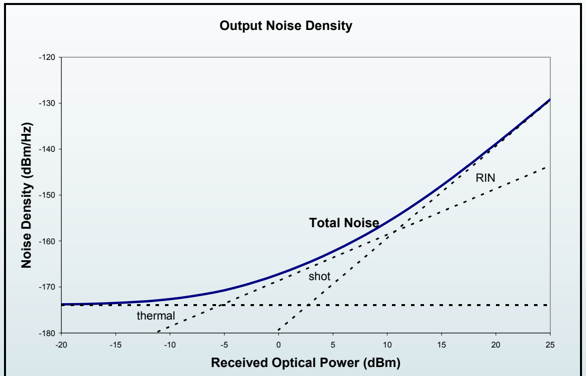
- Propagation Loss in Optical Medium
  - Fiber is (almost) lossless, compared to coax
    - 9 μm single-mode ~ 0.25 dB/km at 1550 or 0.4 at 1310
  - Connectors, splices, switches, splitters add loss
- Chromatic Dispersion
  - Upper and Lower sidebands arrive at different times
  - Generally not a concern for < 10 km and < 4 GHz



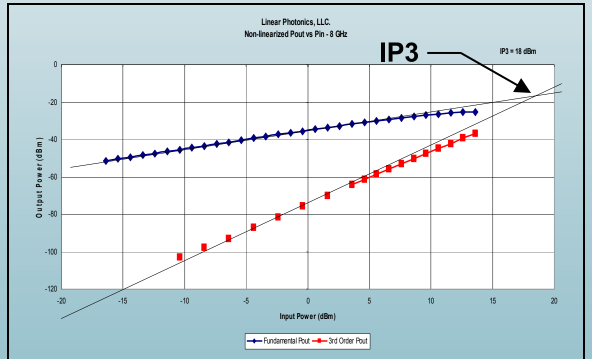

- Fiber Nonlinearities
  - Items to be aware of, but generally not a concern for single-wavelength with <10 mW optical power:
    - Stimulated Brillouin Scattering (SBS)
      - Backscattering effect leading to high noise and nonlinear power transfer
    - Stimulated Raman Scattering (SRS)
      - Can lead to degenerative optical gain when optical power is very high
    - Four-Wave Mixing (FWM) and Cross-Phase Modulation (XPM)
      - Intermodulation distortion and cross-talk in WDM systems (multiple optical wavelengths)
    - Self-Phase Modulation (SPM)
      - Leads to nonlinear group delay

# System Parameters using DiLink

- End-to-End Gain
  - DiLink gain is typically 0 or 15 dB
    - Fully temperature-compensated, referenced to 0 dB OL
  - ***End-to-End gain is lower by twice the optical loss***
- Noise
  - Three primary Sources: Laser (RIN), Shot, Thermal
  - ***Output noise level depends on optical power at the receiver***
- Third-order Linearity
  - IP3 is intersection of 1st and 3rd order transfer lines
  - Contributors: Laser, Receiver, RF Amplifiers
    - Transmitter: Fixed IP3
    - Receiver: IP3 decreases with higher optical receive power (photoreceiver and amps driven harder)
  - ***Overall: depends on optical loss***




**Output noise density is the result of 3 primary sources: RIN, Shot, Thermal**




**Third-order Intercept is the (imaginary) intersection of 1st and 3rd order output**

**By defining the link properly, the 3 primary system parameters depend only on optical loss**

# System Equations

- Standard Link Definitions (available for DiLink)
  - $G_{ref}$ — End-to-End Link Gain with no optical loss (dB)
  - $C_{th}$ — Thermal noise constant (dBm/Hz)
  - $C_{shot}$ — Shot noise constant (dBm/Hz)
  - $C_{rin}$ — RIN noise constant (dBm/Hz)
  - $IIP_{eq}$ — Equivalent Input Intercept (dBm)
  - $OIP_{eq}$ — Equivalent Output Intercept (dBm)
- From these, the "Black Box" System Parameters:

**Link Gain, $G_L$**

$$G_L(dB) = G_{ref} - 2 \cdot OL$$

**Link Noise Figure, F and Output Noise Power Density, $N_{out}$**

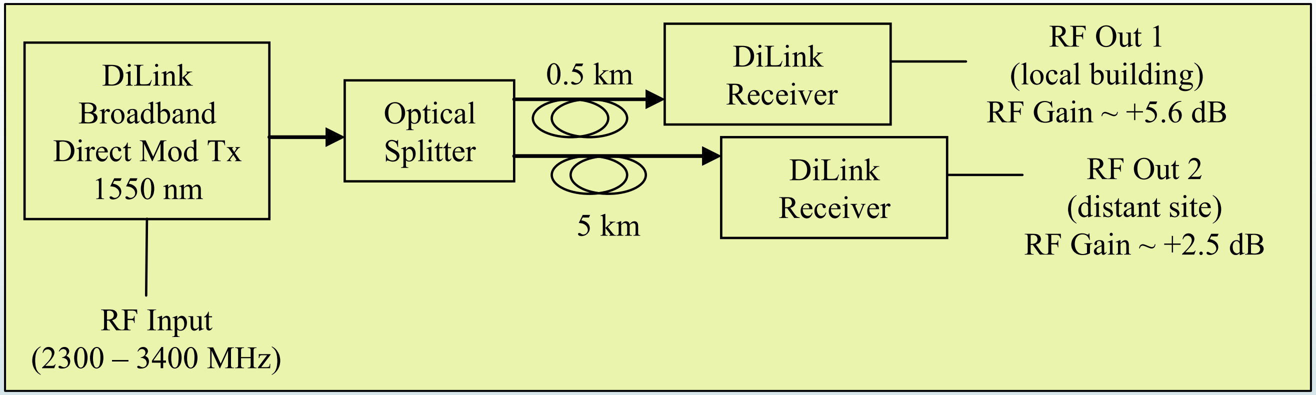
$$F(dB) = N_{out}(dBm/Hz) + 174 - G_L(dB)$$

$$N_{out} = 10\log\left[10^{\frac{c_{th}}{10}} + 10^{\frac{c_{shot}-OL}{10}} + 10^{\frac{c_{rin}-2OL}{10}}\right]$$

**Link Input Intercept, $IIP_3$**

$$IIP_3(dBm) = 10\log\left[\frac{10^{\frac{OIP_{eq}+IIP_{eq}}{10}}}{10^{\frac{OIP_{eq}}{10}} + 10^{\frac{IIP_{eq}+G_L}{10}}}\right]$$

# Example




DiLink DLT5N81 / DLR5N81 standard definitions

| | |
|---|---|
| $G_{ref}$ | 15 dB |
| $C_{th}$ | -139.9 dBm/Hz |
| $C_{shot}$ | -144 dBm/Hz |
| $C_{rin}$ | -139 dBm/Hz |
| $IIP_{eq}$ | 13.6 dBm |
| $OIP_{eq}$ | 27.0 dBm |

**SYSTEM-LEVEL END-TO-END LINK PARAMETERS**

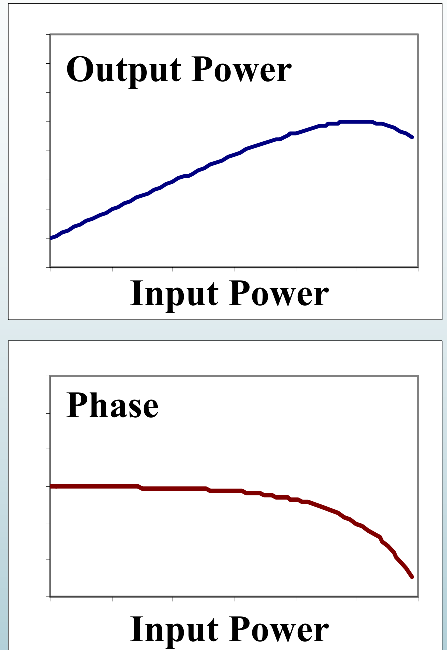
| PARAMETER | PATH 1 | PATH 2 |
|---|---|---|
| Optical Loss | 4.7 dB | 6.25 dB |
| Link Gain | +5.6 dB | +2.5 dB |
| Link Noise Figure | 29.5 dB | 33.3 dB |
| Link Input 3rd order Intercept | 12.9 dBm | 13.3 dBm |
| Other Parameters Derived from above: | | |
| Link Noise Temperature | $26 \cdot 10^3$ K | $62 \cdot 10^3$ K |
| Third-order SFDR | 104.9 $dB \cdot Hz^{2/3}$ | 103.3 $dB \cdot Hz^{2/3}$ |

# Linearity Improvement

- Linearization: Methods of improving the linearity of a nonlinear network
  - Predistortion Linearization is one technique
    - Employs a nonlinear element in the microwave signal path
    - Operates at instantaneous microwave rate
      - Not limited by delay as in feedback or feedforward approach
      - Not limited by overly complicated component-count
      - Limited primarily by microwave matching, preamplifiers, etc.
- Linearizer Technology, Inc. (Linear Photonics' sister company) has been manufacturing linearizers and linearized networks for > 15 yrs
  - Technology is readily applied to fiber optic networks

**Linearizer Technology, Inc.**

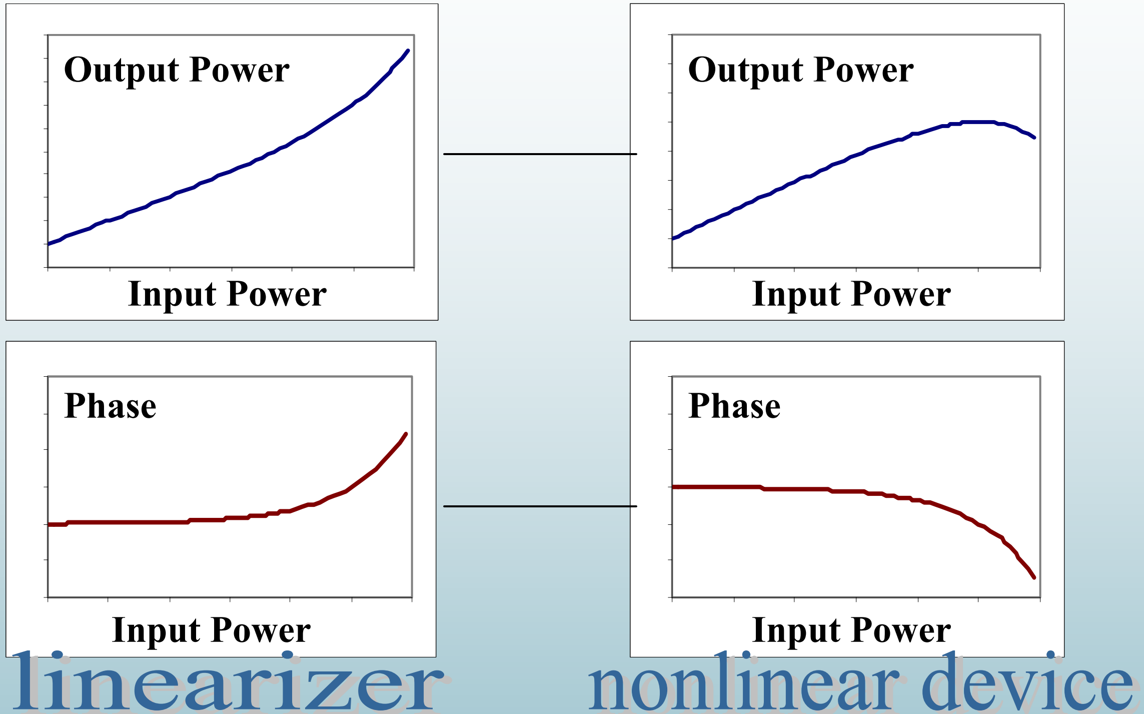
# Predistortion Linearization




nonlinear device

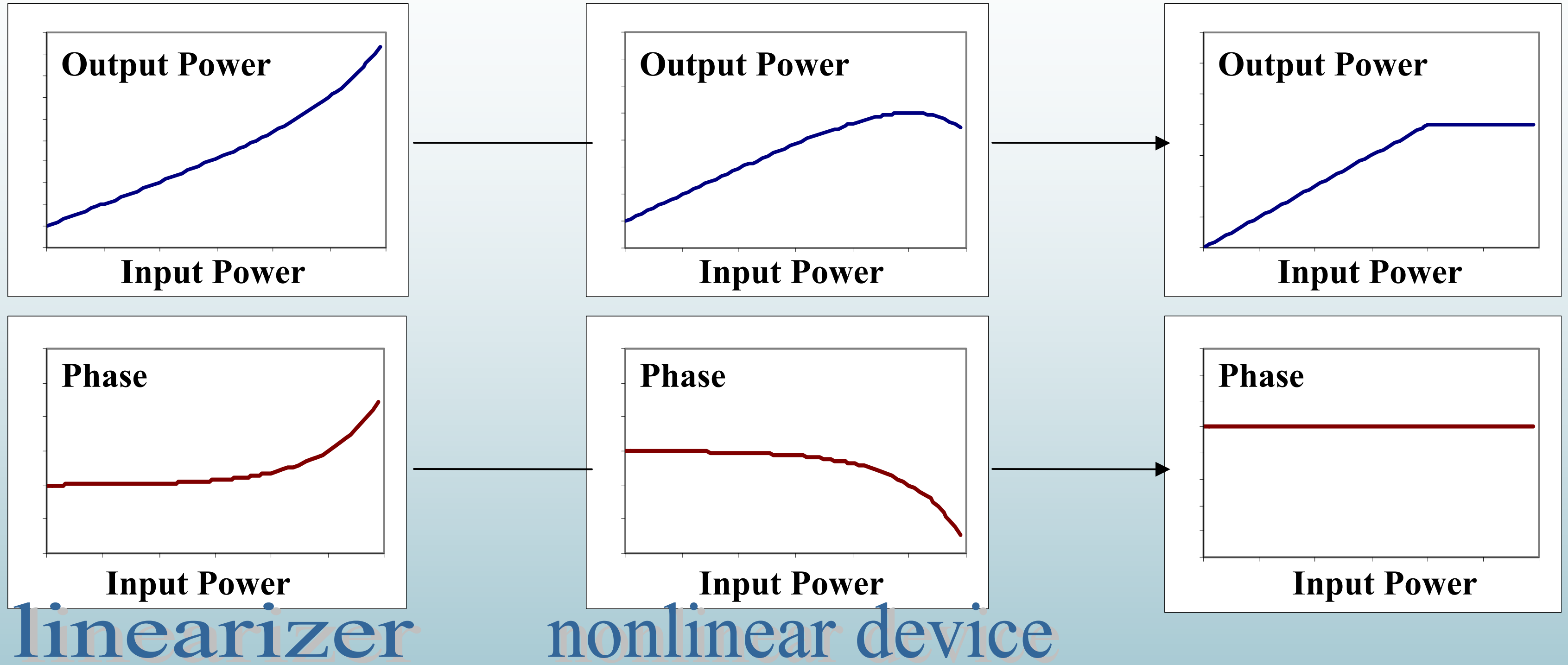
- Nonlinear Device exhibits Gain and Phase Compression

# Predistortion Linearization




- Nonlinear Device exhibits Gain and Phase Compression
- Precede it with another nonlinear device that exhibits gain and phase expansion, in conjugate with the device to be linearized (the **linearizer**)

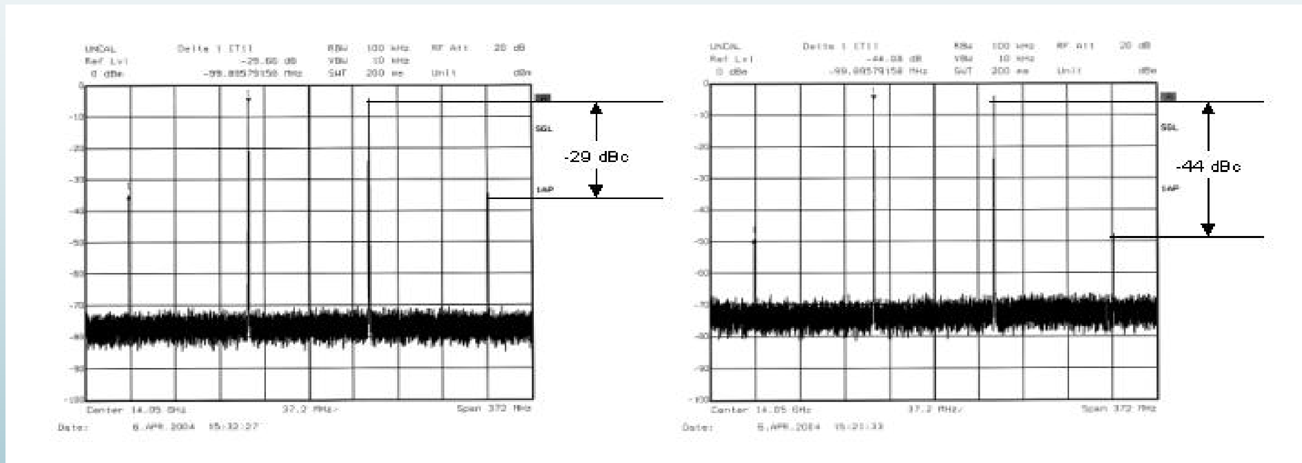
# Predistortion Linearization




- Nonlinear Device exhibits Gain and Phase Compression
- Precede it with another nonlinear device that exhibits gain and phase expansion, in conjugate with the device to be linearized (the **linearizer**)
- The desired outcome is an **ideal limiter**
  - The linearity of an ideal limiter cannot be improved

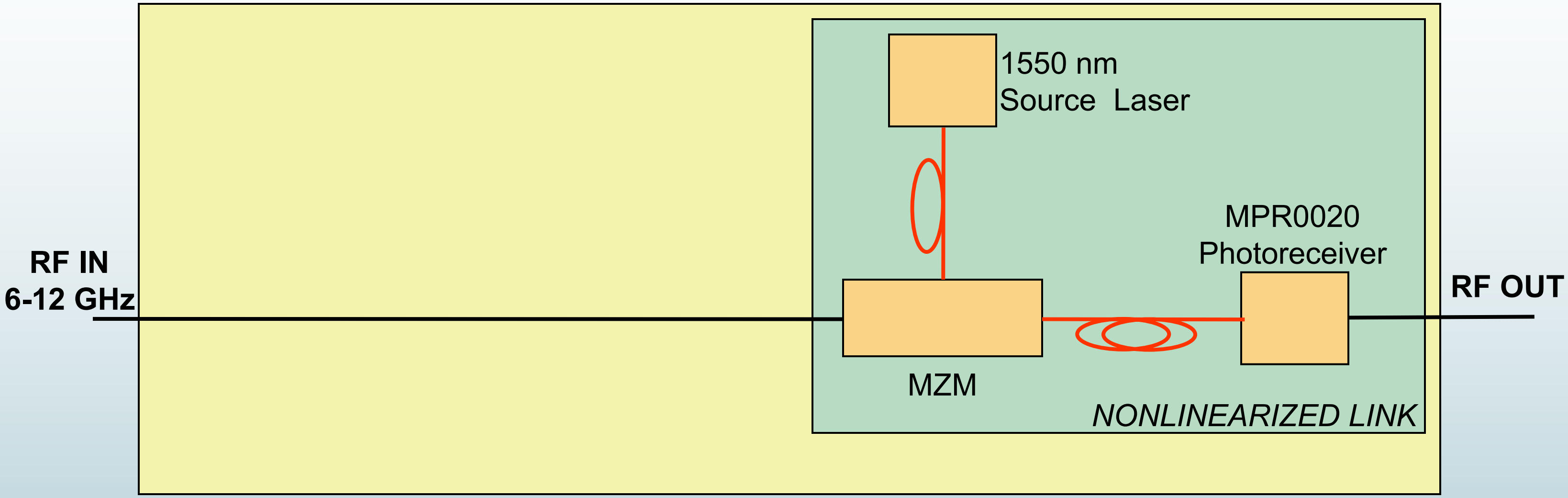
# Predistortion Linearization

- Result is reduction in IMD:



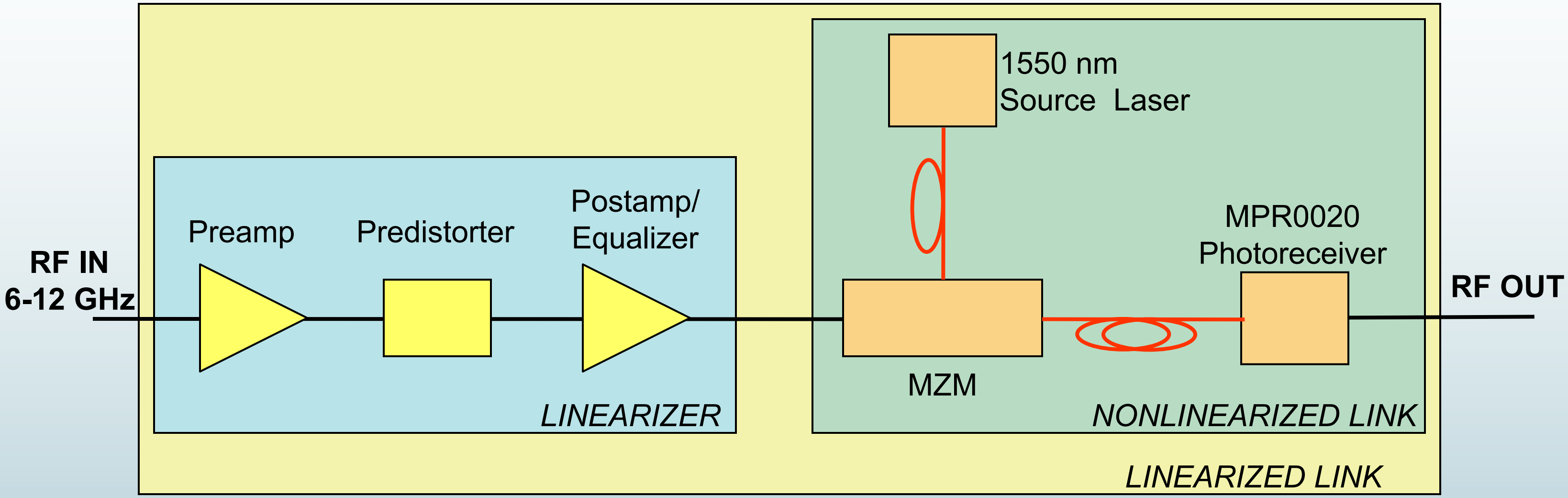

- SFDR is impacted 1:3 (dB) with IMD

# Microwave Link Linearization



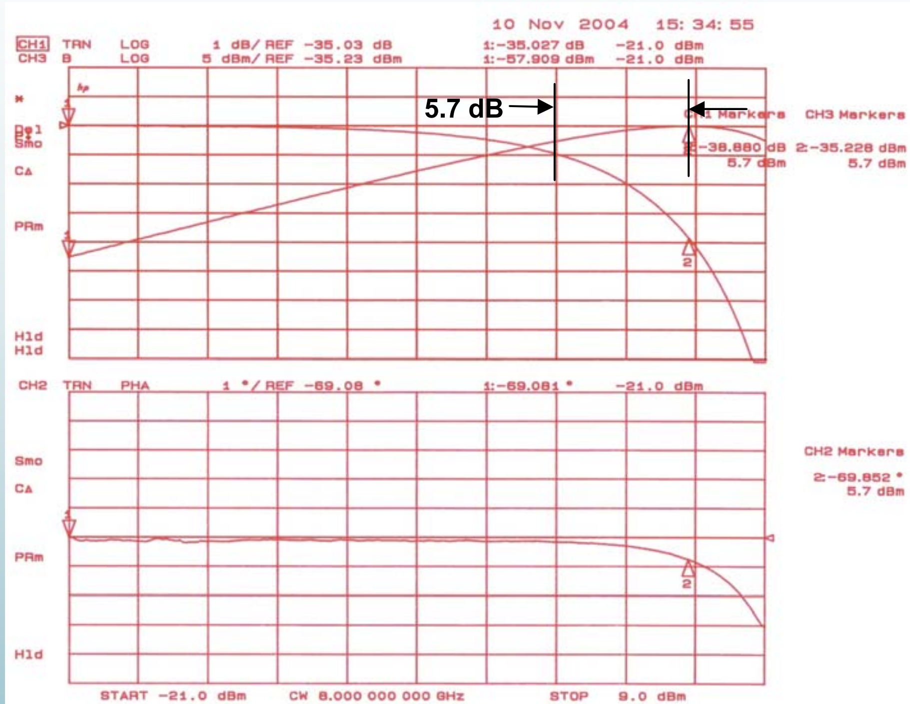

- Nonlinearized MZM Link:
  - Commercial Mach-Zehnder Modulator biased at quadrature
  - 20 GHz flat receiver driven at 0 dBmo

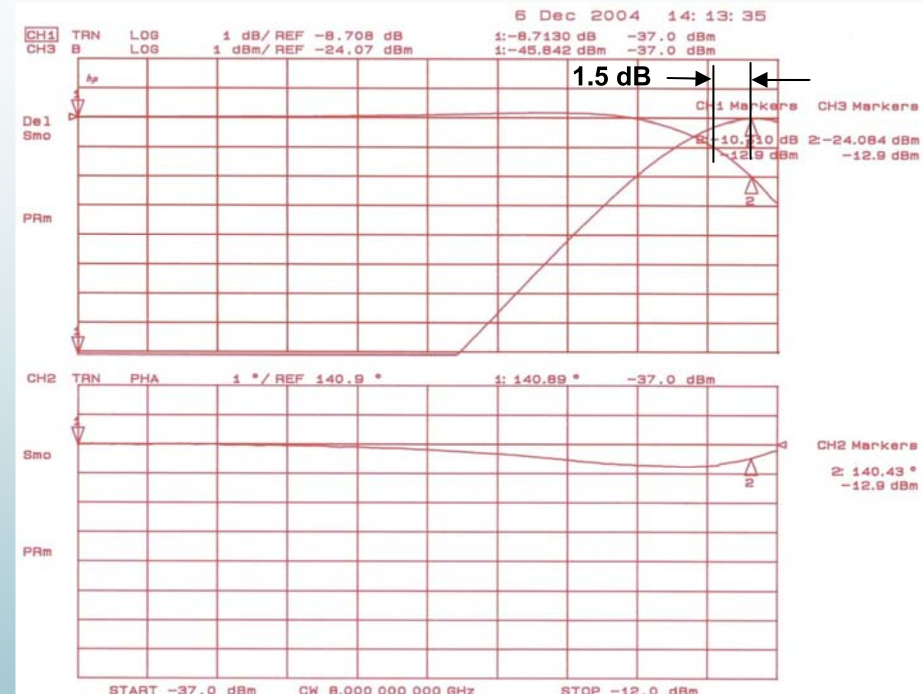
# Microwave Link Linearization




- Nonlinearized MZM Link:
  - Commercial modulator biased at quadrature
  - 20 GHz flat receiver driven at 0 dBmo
- Linearizer:
  - Includes broadband gain stages
  - Predistorter is single-chip GaAs circuit (proprietary design)
    - Signal levels adjusted to match gain expansion of predistorter to gain compression of MZM
  - Postamp stage includes slope equalizer to match levels over frequency

# Results: Gain and Phase Transfer




**Non linearized @ 8 GHz**

P1 dB is 5.7 dB from saturation

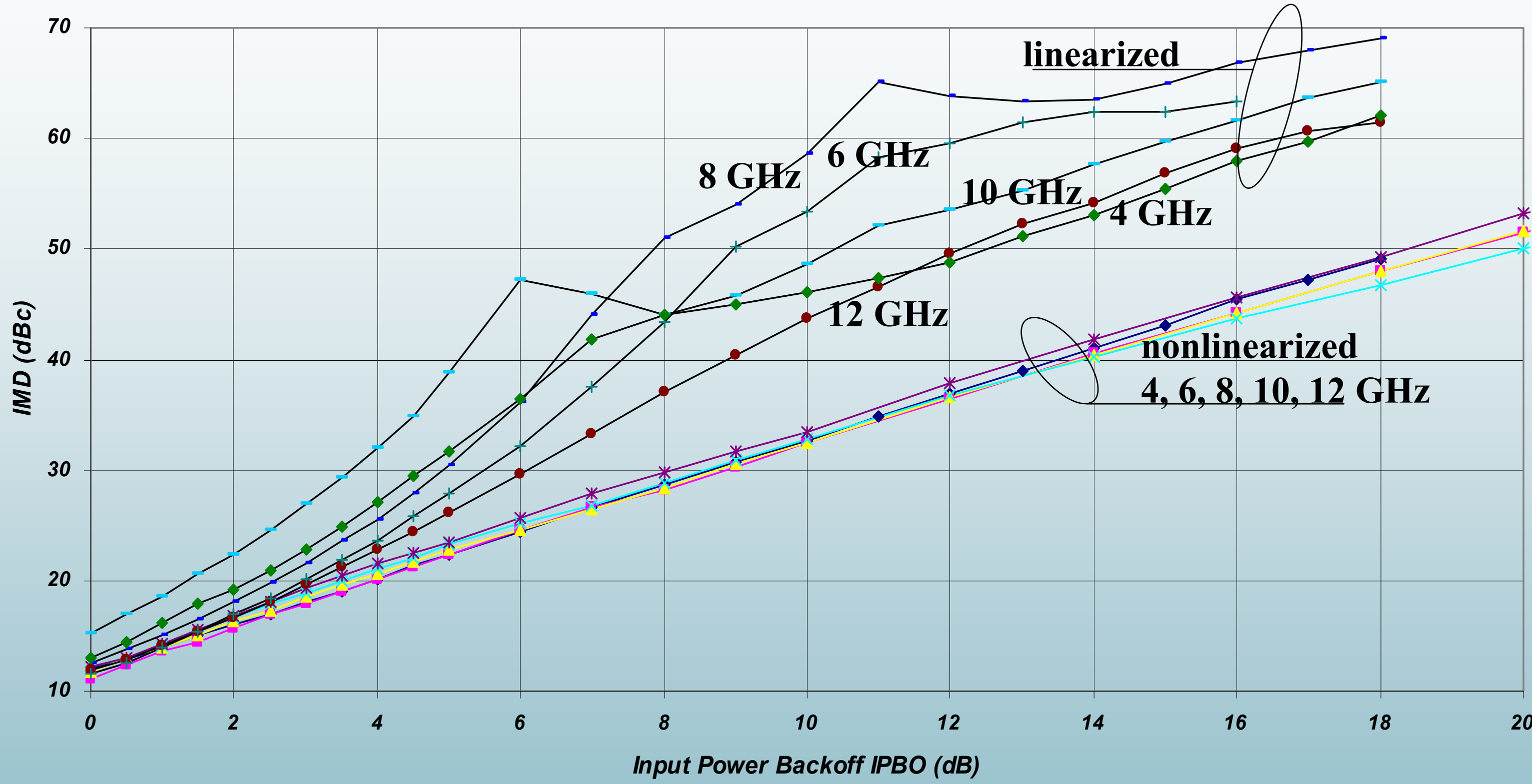
Phase compression rapidly above sat

**Linearized @ 8 GHz**

P1 dB is 1.5 dB from saturation

Phase nonlinearity held to < 1° past sat

# IMD Improvement



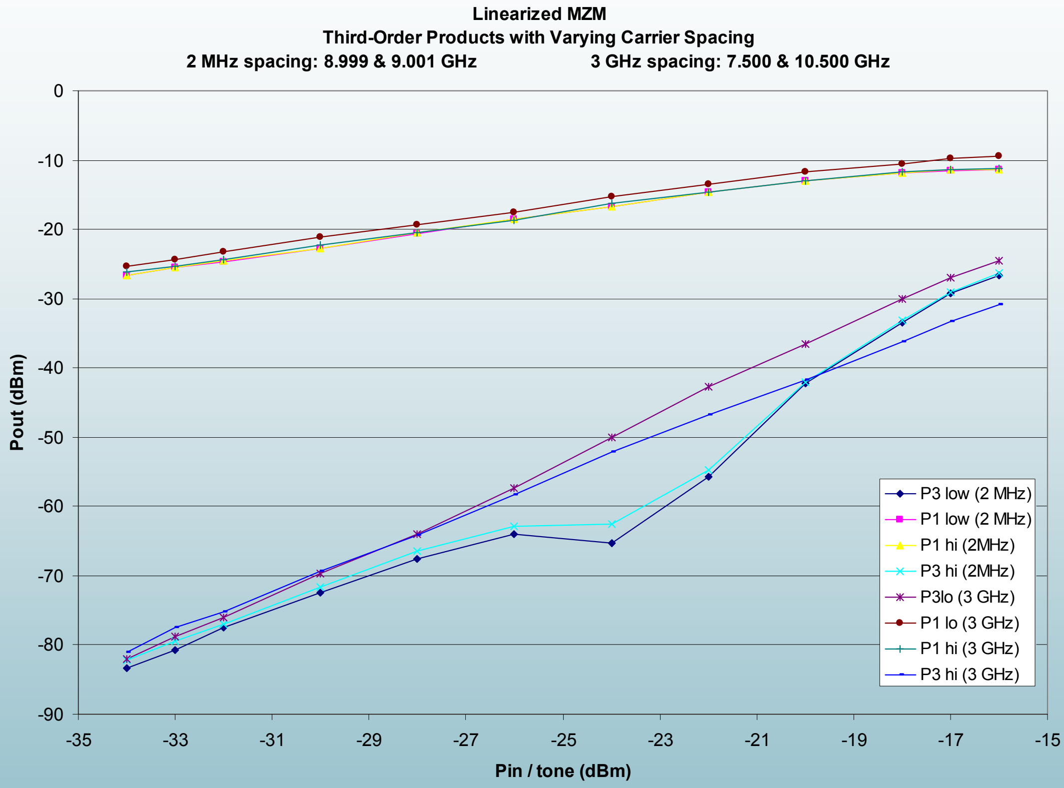

- Broadband correction for input drive below ~ 5 dB from saturation
  - 5 dB IPBO is about 65% Optical Modulation Index (OMI)

# IMD / IIP3 / SFDR

| Frequency (GHz) | IMD Improvement (dB) | IIP3 Improvement (dBm) | $SFDR_3$ Improvement ($dB \cdot Hz^{2/3}$) |
|---|---|---|---|
| 4 | 13.3 | 6.65 | 4.4 |
| 6 | 20.0 | 10.0 | 6.7 |
| 8 | 23.6 | 11.8 | 7.9 |
| 10 | 17.9 | 8.95 | 6.0 |
| 12 | 12.3 | 6.15 | 4.1 |

# Correction Bandwidth

- Two-tone IMD measured with span of 2 MHz and 3 GHz
  - Centered at 9 GHz




**Linearizer is effective over full octave instantaneous bandwidth**

# Summary

- A proper set of link definitions allows rapid calculation of system-level performance, i.e. Gain, Noise, Linearity.
  - LPL DiLink-series Fiber Optic Links provide fully defined operational parameters intended for System Engineers
- A broadband linearized link has been demonstrated with improved SFDR
  - Improvement of 7.9 dB at 8 GHz
  - Instantaneous correction over multioctave bandwidth

**THANK YOU!**

**Copies of this presentation are available at Booth 429**