MICROWAVE PHOTONICS
Focusing on Performance Improvement

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OUTLINE

- Analog or Digital?
- Some Applications of Microwave Links
- Brief Overview of Intensity Modulation
- Factors Limiting Performance
    - Link Measures
    - COTs Performance
    - Noise
    - Linearity
- SFDR Improvement
    - Noise
    - Linearity
- Electrical and Optical Linearization

Digital or Analog?

- Bulk of fiber optics communications associated with DIGITAL communications
  - Fast switching and low pulse distortion determine link fidelity
- Certain applications not suited to digital:
  - Bandwidth too high to be effectively digitized
  - System complexity better suited toward simpler modulation drive circuitry (size, weight, power constraints)
- Whatever the system, the primary distinction between digital and analog is *linearity*
  - Analog/Microwave links depend upon *low distortion* to achieve high fidelity

DIGITAL = NONLINEAR
ANALOG = LINEAR

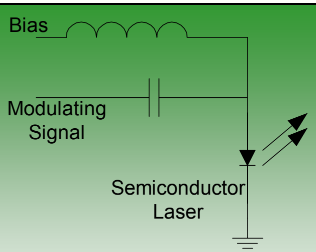
Microwave Link Applications

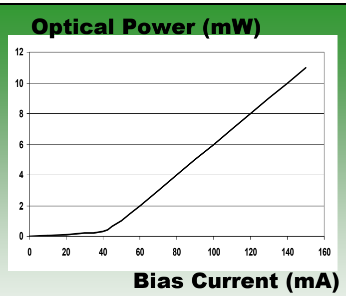
- ***Microwave Link***: "Characterized by an RF Input and an RF Output"
  - Necessarily has a means of modulating and demodulating an optical carrier
- Applications
  - Phased Array Communications and Radar
    - Narrowband RF feeds directly to antenna arrays
    - True Time Delay Beamsteering
  - Antenna and Signal Remoting
    - Direct-RF over longer distances (many km)
    - Reliable alternative to wireless in fixed services
    - Subcarrier-multiplexed digital communications (still analog)
  - Electronic Warfare / SIGINT / ELINT
    - Fiber-Towed Decoys provide >> bandwidth
  - Secure Communications (EMI hard)
    - Connection to passive sensors (listening)
    - Remoting personnel from active sensors (protection)

Intensity Modulation

- Direct Modulation
  - – Microwave Signal is applied directly to a laser diode, along with bias current
- External Modulation
  - – Stable laser source (carrier) modulated by a separate electro/optical component
    - Electro-Optic Modulation
      - – Mach-Zehnder Modulator
    - Electro-Absorption Modulation
      - – Varying absorption of semiconductor

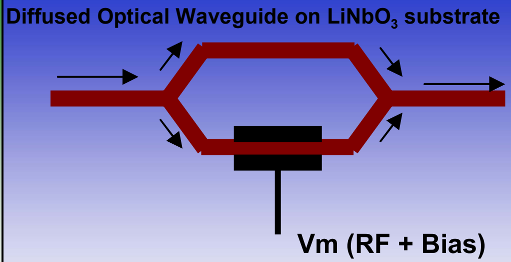
Popular Modulation/Demodulation Techniques

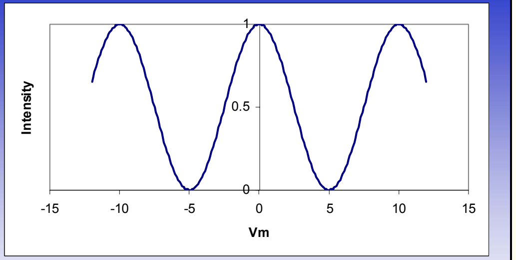




$$P(i_m) = \eta_L (I_L - I_{TH} + i_m)$$

DIRECT MODULATION

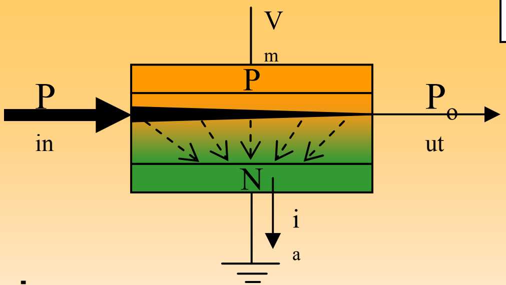


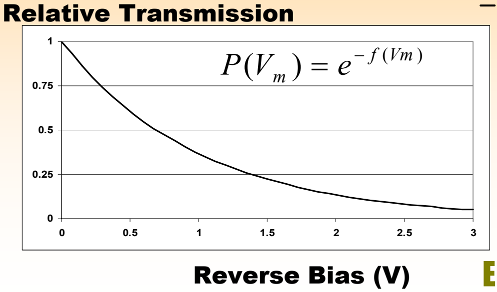


$$P(V_m) = P_m \cos^2 \frac{\pi V_m + \phi}{2V_\pi}$$

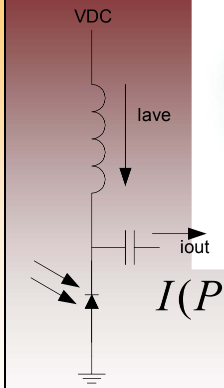
ELECTRO-OPTIC (MZM)

"Quadrature:" $V_m(t) = \frac{V_\pi}{2}[1 + OMI \cdot \cos \omega t]$

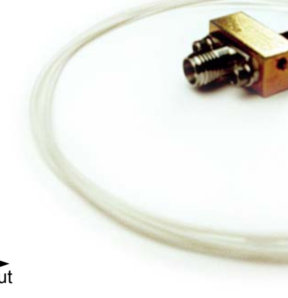


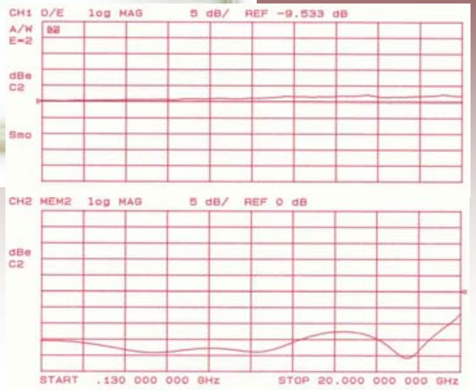


ELECTRO-ABSORPTION



LPL MPR-series Photoreceiver





$$I(P) = R \cdot P$$

PIN PHOTORECEIVER

Modulation Summary

TYPE	COMPLEXITY	SIZE WEIGHT POWER	PRACTICAL MODULATION FREQUENCY	LINEARITY	COST
DIRECT	Low: one optical component (laser)	Lowest	< 12 GHz	Poor 2nd and 3rd-order performance	Lowest
ELECTRO-ABSORPTION	Moderate: requires separate source laser and small modulator	Similar to direct mod	40+ GHz	Poorest Linearity, but may have 2nd and 3rd-order null operating points	Higher, comparable to EOM
ELECTRO-OPTIC (MZM)	Highest: requires source laser, large modulator, plus optical and electrical controls for bias locking	Highest	40+ GHz	Well-defined (sin curve). Operation at quadrature provides 2nd-order null.	Highest

Factors Limiting Performance

- Microwave Launch
  - effectively coupling RF power into the modulating electrodes
  - Input loss reduces gain and increases noise figure
- Inherent Bandwidth
  - high frequency limit determined by device and package reactances
  - smaller devices are faster, but lower dynamic range
- Nonlinearities of Modulating Device
  - Limits dynamic range

Quantitative Link Measures

- Gain
  - Broadband links are lossy
  - Gain Slope / Ripple important to system design
- Noise Figure
  - Generally higher than the link loss
- Third-Order Intercept
  - Intercept of fundamental and 3rd-order IMD curves
- Spur-Free Dynamic Range (SFDR)
  - Power Range over which the intermodulation distortion is below the noise floor

$$SFDR_3 = \frac{2}{3}\left[174 - F + IIP3\right] \quad dB \cdot Hz^{2/3}$$

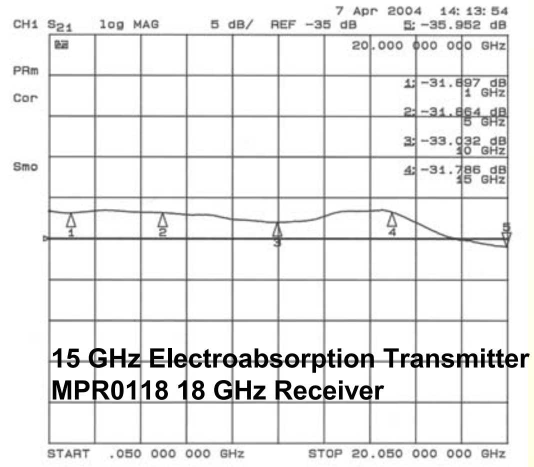
Closing the Link

Typical performance: COTS

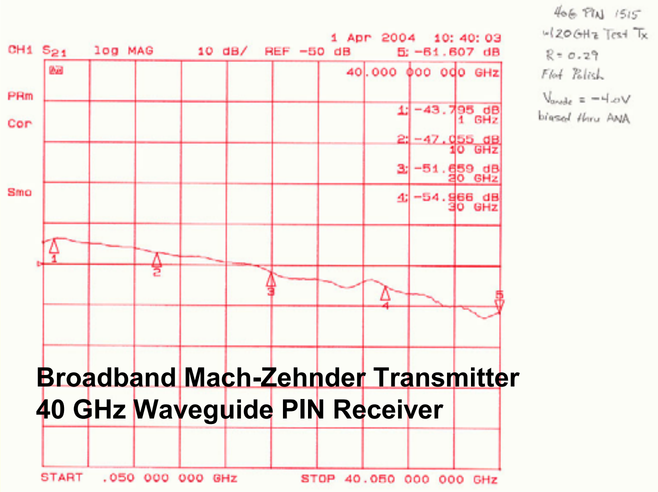
Link Type	Low Freq Gain dB	Operational BW GHz	Slope over BW dB	Input IP3 dBm	Input P1dB dBm	Noise Fig dB	SFDR3 dB Hz^2/3	Optical Budget dB
Direct	**-32**	**3**	**-1**	**36**	**24**	**40**	**113**	**7**
EAM 1	**-35**	**15**	**-3**	**26**	**20**	**40**	**106**	**7**
EOM (Vpi = 5 V)	**-36**	**20**	**-8**	**23**	**15**	**40**	**105**	**8**
EAM 2	**-30**	**30**	**-3**	**18**	**12**	**40**	**101**	**3**

- Performance relative to 0 dBmo incident receiver power (optical budget is equal to typical transmitter optical output power, or the amount of optical attenuation between Tx and Rx).
- Results shown are typical for broadband links to the bandwidth indicated. Narrowband microwave links can achieve proportionately higher performance in gain and DR.
- 1 dB decrease in optical attenuation results in 2 dB increase in RF Gain.
- 1 dB decrease in optical attenuation results in noise figure reduction of from 0 to 2 dB, dependent on RIN, shot, or thermal limited link.

Link Examples

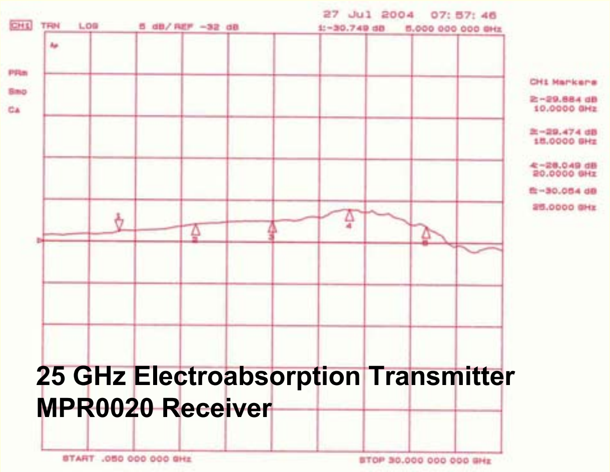


15 GHz Electroabsorption Transmitter
MPR0118 18 GHz Receiver

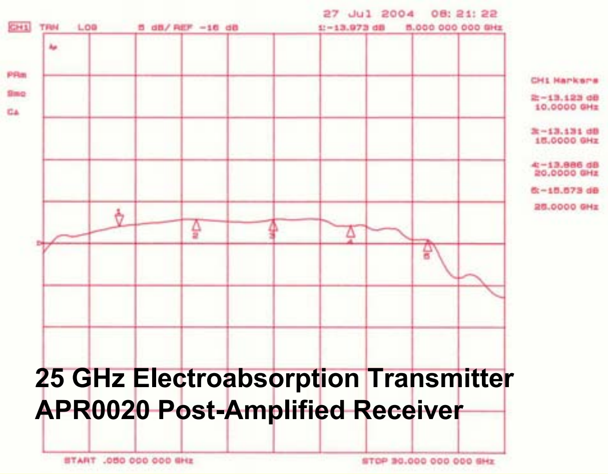


406 PIN 1515
w/20GHz Test Tx
R = 0.29
Flat Polish
V_{anode} = −4.0V
biased thru ANA

Broadband Mach-Zehnder Transmitter
40 GHz Waveguide PIN Receiver



25 GHz Electroabsorption Transmitter
MPR0020 Receiver



25 GHz Electroabsorption Transmitter
APR0020 Post-Amplified Receiver

Performance Improvement

- SFDR is useful quality measure
  - Tells minimum signal levels for interference-free operation

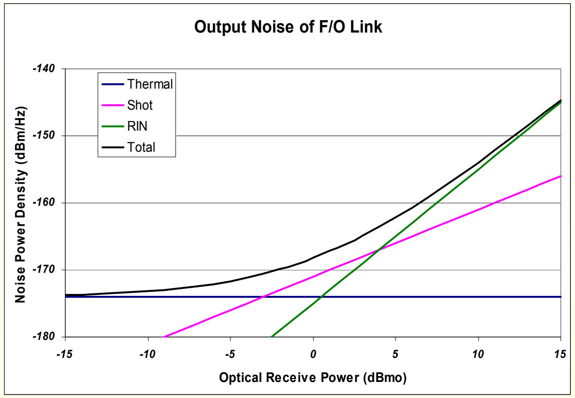
$$SFDR_3 = \frac{2}{3}\left[174 - F + IIP3\right] \qquad dB \cdot Hz^{2/3}$$

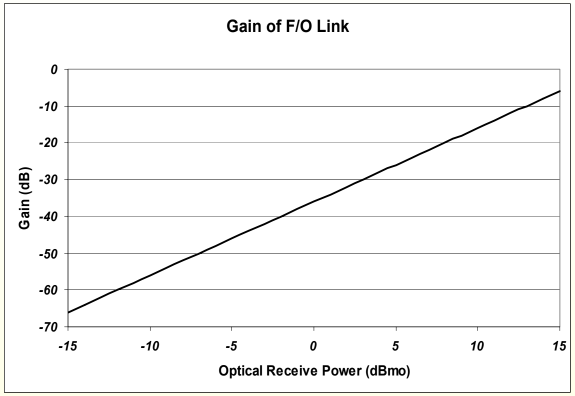
- Avionics platforms are targeting broadband 120 $dB \cdot Hz^{2/3}$
- To improve SFDR must decrease noise figure (F) and/or increase intercept (IP3)
  - 3 dB decrease in F yields 2 dB increase in $SFDR_3$
  - 3 dB increase in IP3 yields 2 dB increase in $SFDR_3$
    - Or, a 3 dB improvement in IMD yields 1 dB $SFDR_3$

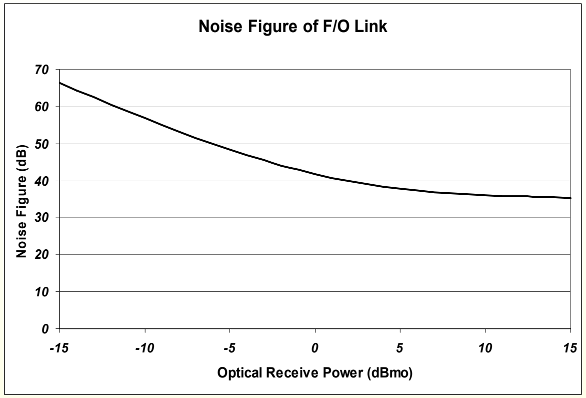
Understanding Link Noise

- Link noise results from 3 sources (if no optical amplifiers)
  - *System Thermal Noise*
    - Low-Level incident optical power (< 0 dBmo)
    - Noise Figure varies 2:1 with optical power
  - *Receiver Shot Noise*
    - Due to random photon arrivals, with quantized energy
    - Mid-Level incident optical (1-3 dBmo)
    - Noise Figure varies 1:1 with optical power
  - *Laser Relative Intensity Noise (RIN)*
    - Due to undesired transitions in the source laser
    - High-Level incident optical (> 4 dBmo)
    - Noise Figure independent of optical power ***and min for the link***

Link Noise







- Total output noise is related to optical received power:
  - 2:1 in RIN region
  - 1:1 in shot region
  - 0 in thermal region

- Gain maintains 2:1 relationship with optical drive (assuming linear receiver)

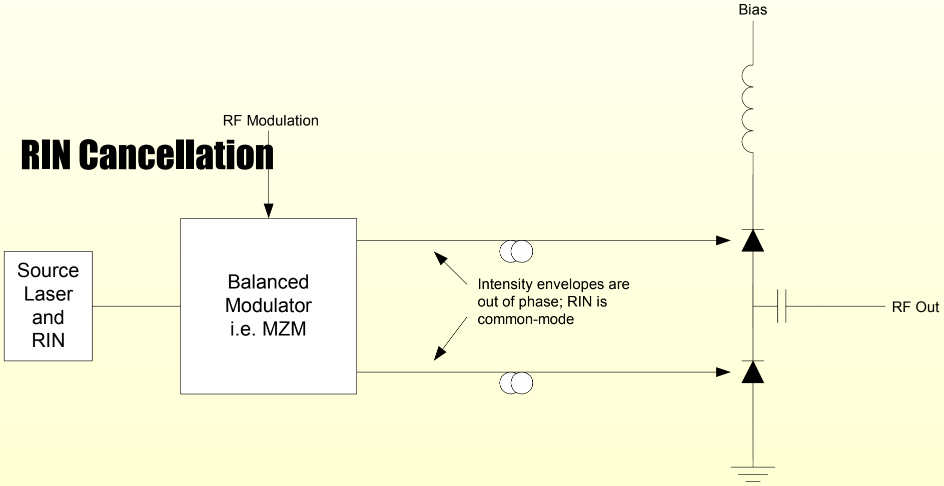
- Resulting noise figure is best at RIN limit
- Minimum value depends on laser RIN noise

Link Noise Figure and Dynamic Range vary with optical power – defined in conjunction with the operational system

Noise Reduction

- Drive the photoreceiver at high optical levels to maintain RIN limit
  - Photoreceiver linearity may be problematic at high optical levels
- Other methods of reducing RIN and shot noise include balanced detection

RIN Cancellation



RIN noise from the laser source is completely cancelled (ideally), as long as optical phase is temporally coherent {Ref 3}.

Result is shot-noise limited performance; increasing optical power can always improve noise figure.

Limitations arise due to:

1) The coherence length of the laser source: the average length over which the optical signal remains coherent. It is limited by the laser linewidth.
2) The ability to maintain constant RF envelope length in dual-fibers over long distances will limit the frequency bandwidth of cancellation

Understanding Linearity

- Sources of nonlinearity:
  - Modulator
    - Even and Odd order distortions caused by nonlinear transfer response
  - Fiber medium (some examples:)
    - Stimulated Brillouin Scattering (SBS) causes nonlinear noise spectrum and reduction in gain at high optical drive levels
    - Four wave mixing causes crosstalk in WDM systems
    - Fiber Dispersion limits the length of transmission at higher frequencies
      - Actually a linear process, but causes gain nulling when AM sidebands cancel
  - Photoreceiver
    - Clipping and intermodulation at high optical levels
- For links of several km or less, at optical levels below ~ 10 mW, modulator nonlinearity dominates

Linearity Improvement

- ***Linearization*** reduces nonlinear distortion; increases dynamic range
  - Techniques include optical, electrical, and combinatorial approaches
    - All necessarily involve additional processing in the form of additional circuitry/components
    - Electrical: aim is to cancel distortion products by providing conjugate distortion inputs
      - Operates in RF domain
      - Predistortion, Feedforward
    - Optical: generally more complex
      - Operates in optical domain – inherently wide-band

Optical & Electro-Optical Linearization

- Dual Series MZM Modulators
  - Proper biasing of series MZM’s may result in linearization of sinusoidal transfer
    - Has been shown to approximate ideal limiter response
    - Inherently wideband
    - Difficult to tune/align
- Feedforward
  - Nonlinear response is sampled (electrically) and re-injected to fundamental path in order to cancel undesired frequency products
    - Limited bandwidth due to need for electrical delay in feedforward path

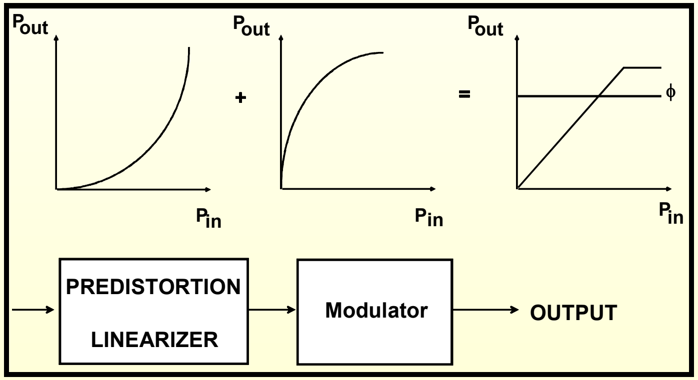
Electrical Predistortion

- Predistortion Linearization has long history in Broadcast Power Amplifiers; SSPAs, TWTAs, Space and Ground Station equipment
  - Generally less complex than optical or combinatorial systems
    - Does not rely on sampled waveforms
    - Bandwidth is the major challenge
  - The aim is to compensate for the gain and phase compression of the nonlinear system by providing a cascaded element function that has the opposite gain and phase characteristic: gain and phase expansion

Electrical Predistortion

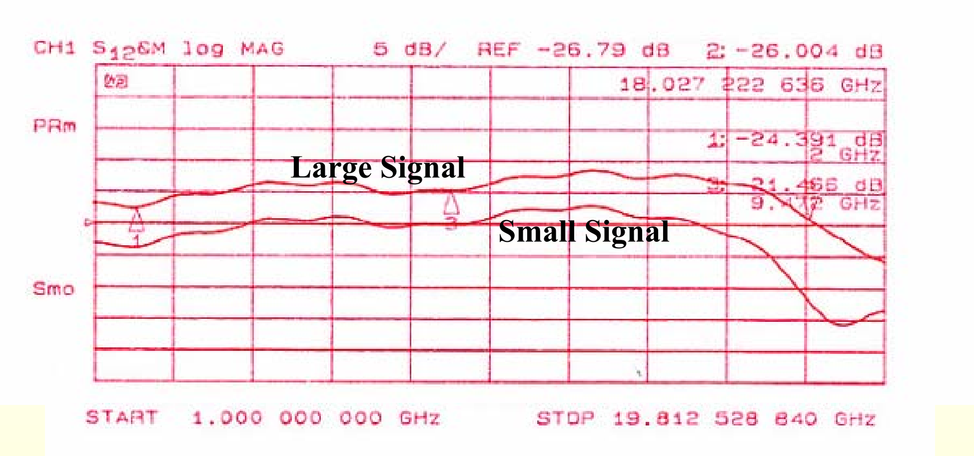
IMPROVED RADIO OVER FIBER PERFORMANCE USING PREDISTORTION LINEARIZATION: OVERVIEW

The performance of hybrid fiber wireless is primarily limited by the distortion introduced by optical modulation. Predistortion linearization eliminates this distortion by generating a function, which has an opposite phase and inverse magnitude to the transfer function of the modulator.



The resulting transfer function approximates an ideal limiter

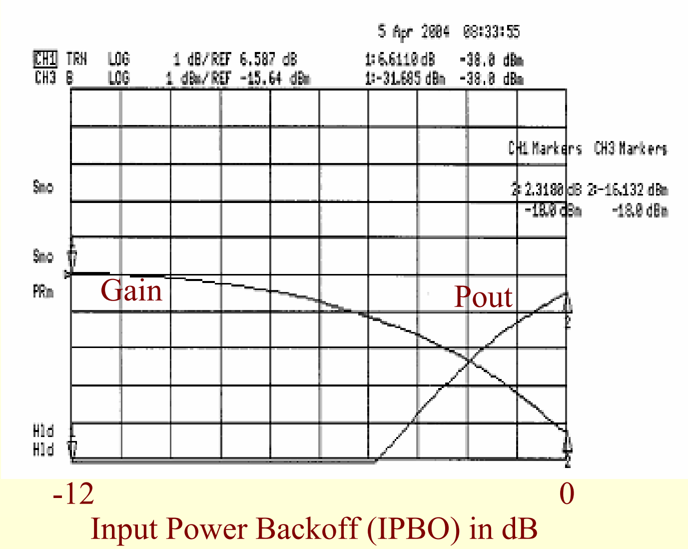
Wideband Predistorter

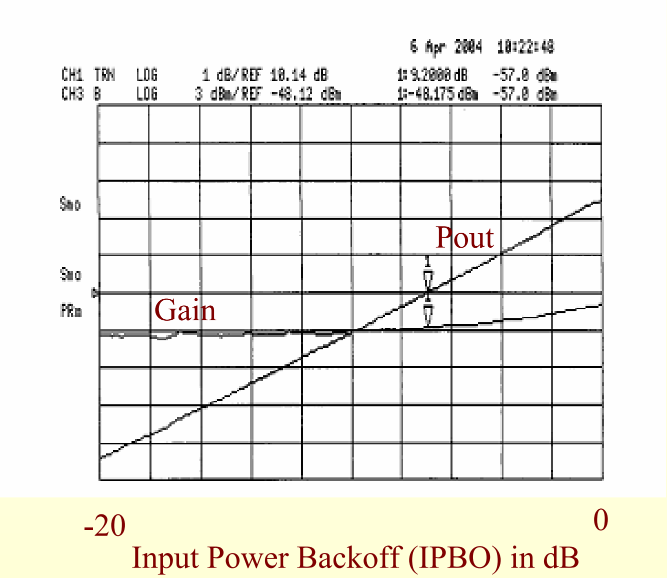


- LPL generic predistorter is very broadband

Predistortion Linearizer Performance

- Linearization Results of EAM Link at 14 GHz



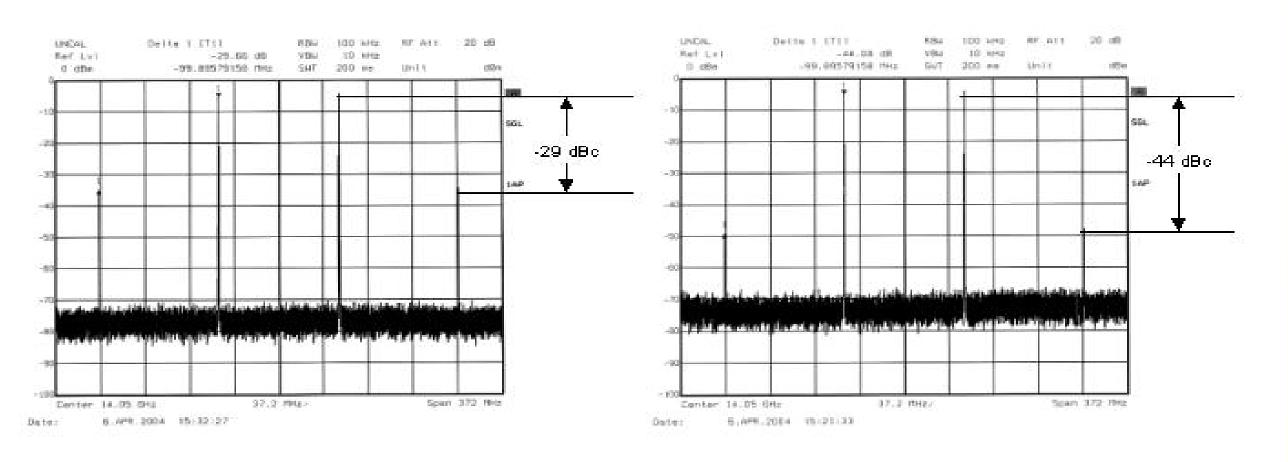


- Non-Linearized
  - 4 dB Gain Compression at Ref. Input Power

- Linearized
  - Predistortion linearizer effectively compensates the gain compression

Predistortion Linearizer Performance

- Intermodulation Distortion Improvement
  - Measured at 6 dB IPBO



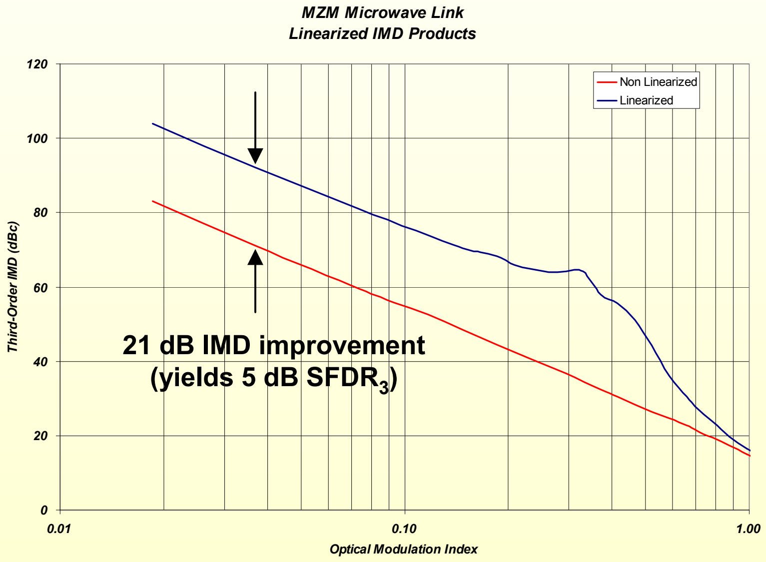
Non-Linearized

Linearized

- 15 dB improvement in IMD equates to 5 dB improvement in SFDR3

MZM Linearization

- Demonstration of IMD improvement from predistorting an MZM link



21 dB IMD improvement
(yields 5 dB SFDR$_3$)

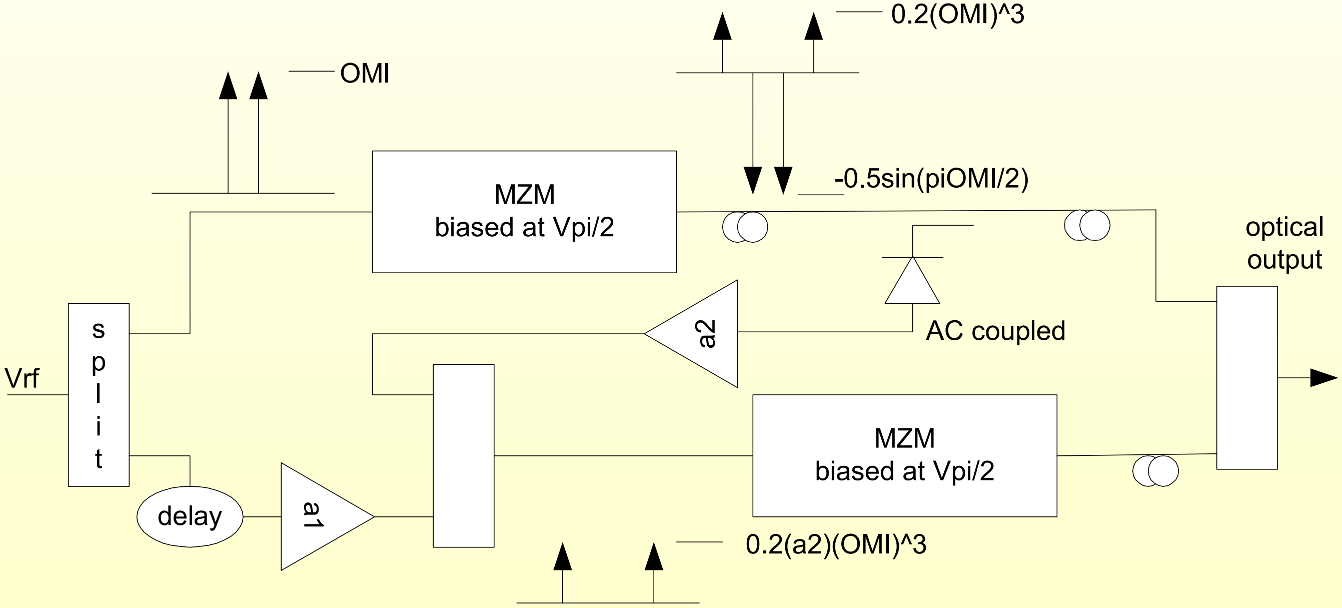
- Results shown at 8 GHz
- Measured improvement of 14 dB (minimum) from 4 to 12 GHz

Hitting the Target

- Starting from COTs-style MZM link with detected power = 0 dBmo and SFDR = 105:
  - Increase detected power to RIN limit
    - Improve F by ~ 6 dB
  - Predistortion linearization
    - Improve IMD by 21 dB (IIP3 by 10.5 dB)
  - Result: SFDR = 105 + 2/3(16.5) = 116
- If system supports RIN cancellation, gain another ~ 10 dB noise figure reduction
  - Result: SFDR = 105 + 2/3(26.5) = 122
- ***120 dB SFDR target within reach using straight-detect analog links***

Optical Linearization Example

- Optical Feedforward Coupled linearization of Mach-Zehnder modulator
  - Third-order cancellation



Description

- First MZM generates distortion products
  - Amplitudes of distorted detected outputs are:

$$V_{fund} = -\frac{1}{2}\sin\left[\frac{\pi \cdot OMI}{2}\right] \qquad V_{IMD} = 0.2 \cdot OMI^3$$

  - 2-tone 3rd-order amplitudes (IMDs) were found by eval. Fourier Series of the output
  - Note that Fundamental and IMD products are always out of phase

- RF signal is delayed and added to the distorted output
  - Level is set to "just cancel" the carriers of the detected signal, leaving just the distortion

- Distortion products are re-modulated, and summed with the first modulator output.
  - Summation must be noncoherent
    - Dual lasers or sufficient delay

Desired Electrical Gains

V1 = Detected MZM1 RF components
V2 = Output from RF coupler
V3 = Detected MZM2 RF components (if there were a detector)

For the Two-Tone RF case:

$$V_1 = -\frac{1}{2}\sin\left(\frac{\pi \cdot OMI}{2}\right)\Bigg|_{f1\&f2} + 0.2 \cdot OMI^3\Big|_{2f1-f2\&2f2-f1}$$

$$V_2 = -\frac{A_2}{2}\sin\left(\frac{\pi \cdot OMI}{2}\right)\Bigg|_{f1\&f2} + A_2 \cdot 0.2 \cdot OMI^3\Big|_{2f1-f2\&2f2-f1} + A_1 \cdot OMI\Big|_{f1\&f2}$$

$$= OMI\left(A_1 - \frac{\pi}{4}A_2\right)\Bigg|_{f1\&f2} + A_2 \cdot 0.2 \cdot OMI^3\Big|_{2f1-f2\&2f2-f1}$$

We want f1&f2 terms of V2 to cancel, so $A_1 = \frac{\pi}{4}A_2$ and then

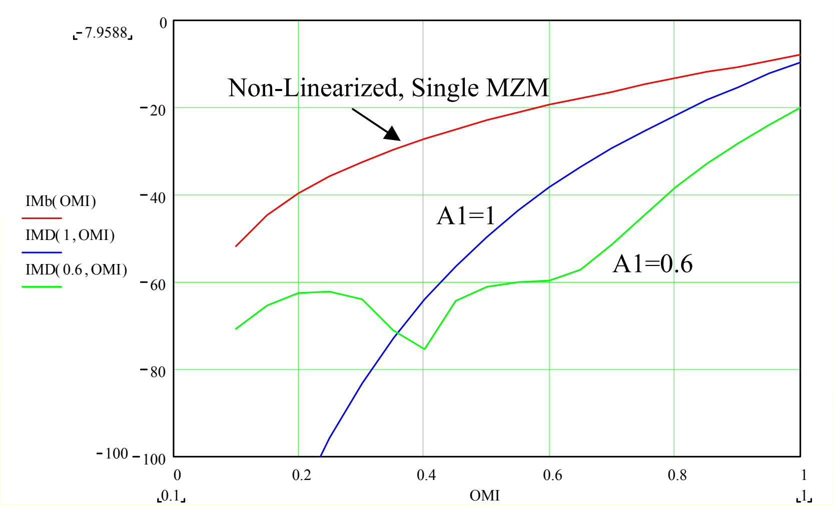
$V_2 = A_2(0.2 \cdot OMI^3) = OMI'$ where OMI' = equivalent per-channel OMI of third-order products into MZM2. Then we get

$$V_3 = -\frac{1}{2}\sin\left(\frac{\pi \cdot OMI'}{2}\right)\Bigg|_{2f1-f2\&2f2-f1} = -\frac{\pi}{4}A_2(0.2 \cdot OMI^3)\Big|_{2f1-f2\&2f2-f1}$$

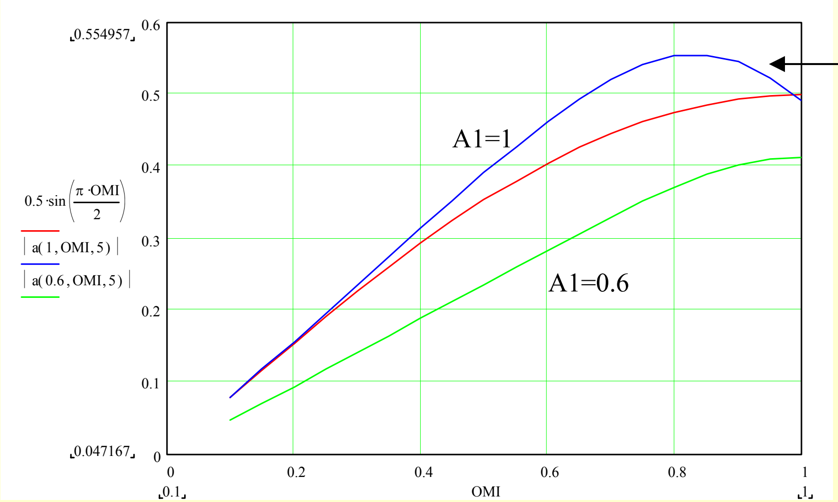
We want $V_3 = -0.2 \cdot OMI^3\Big|_{2f1-f2\&2f2-f1}$ so we set A1 and A2 as follows:

$$A_1 = 1 \qquad A_2 = \frac{4}{\pi}$$

Modeled results with A2 = 4/π



Two-Tone
Third-order IMD

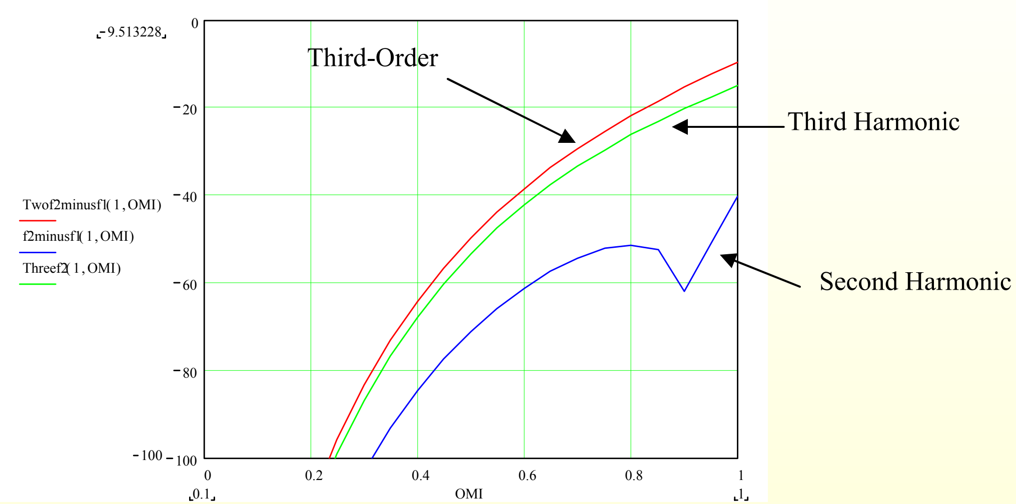


Non-Linearized, Single MZM

Two-Tone
Fundamental Transfer Function

Note: OMI is per-carrier

A2 = 4/π and A1 = 1



Third-Order

Third Harmonic

Second Harmonic

Summary

- Avionics platforms can reap full benefit of fiber optic links with higher dynamic range.
  - EMI immunity
  - Weight Reduction
  - Improved Safety/Maintenance
  - Increased Bandwidth and Flexibility
- SFDR_3 of 120 $dB \cdot Hz^{2/3}$ is achievable
  - Linearized Modulators
  - Reduced Noise Architectures
- Electrical Linearization is viable technique
  - Low cost and complexity
  - Work needed in extending even order correction to multi octaves