APPLICATIONS OF MICROWAVE PHOTONICS
Present Technology and Future Trends

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OUTLINE

- Analog (not Digital)
- Some General Applications
- Microwave Link Overview
  - Intensity Modulation
  - Photoreceivers
  - Link Comparisons
  - Link Noise
- Performance Improvement
  - Electrical Predistortion
  - Optical Linearization Example

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 (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

- Phased Array Communications and Radar
  - Narrowband RF feeds directly to antenna arrays
  - Lower weight, lower complexity
  - True Time Delay beamsteering
- Antenna and Signal Remoting
    - Direct-RF over longer distances (many km)
    - Reliable alternative to wireless in fixed services
- Electronic Warfare / SIGINT / ELINT
  - Fiber-Towed Decoys provide very high bandwidth
  - Secure Comms (EMI hard)
    - Connection to passive sensors (listening)
    - Remoting personnel from active sensors (protection)

Microwave Link

- We mean:

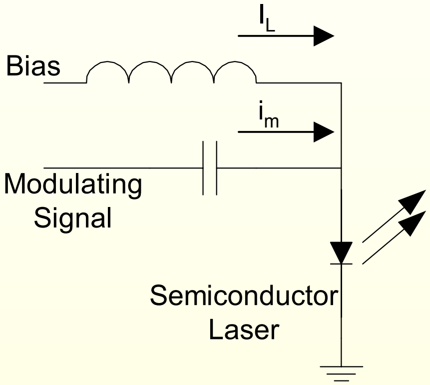
  "Characterized by an RF-input and an RF-output"

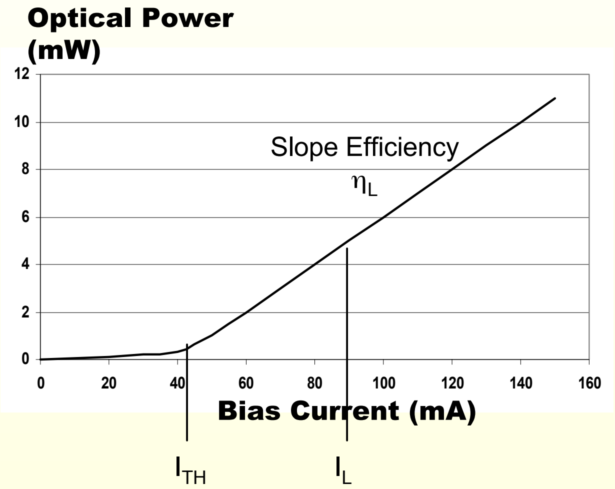
  - Necessarily has a method of *modulating and demodulating an optical carrier*, and some fiber in between
  - Today's technology dominated by:
    - *Intensity modulation* of semiconductor lasers
    - *Photodetection* using PIN or avalanche photodiodes

Intensity Modulation

- Direct
  - Laser diode is modulated directly
- External
  - Laser source drives a separate optical component

Direct Intensity Modulation





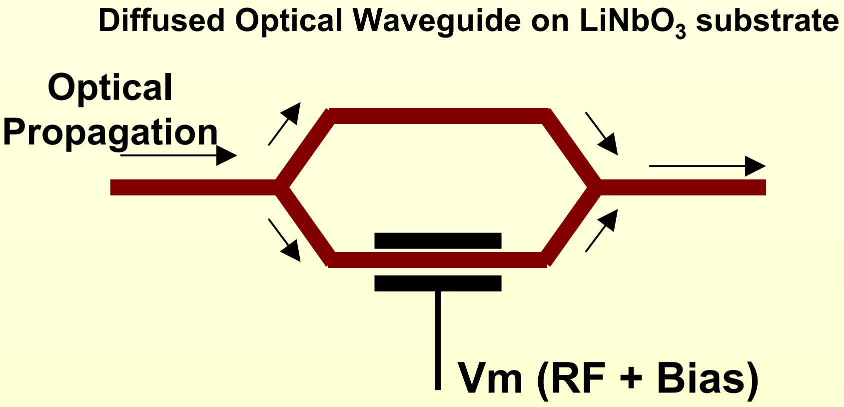
$$P(i_m) = \eta_L (I_L - I_{TH} + i_m)$$

External Modulation

- A CW optical signal is intensity modulated via a field-dependent optical medium
- Microwave modulation speeds can be achieved with 2 major methods:
  - Electro-Optic Modulation
    - Field-dependent change in optical index (electo-optic effect)
  - Electro-Absorption Modulation
    - Field-dependent change in optical attenuation

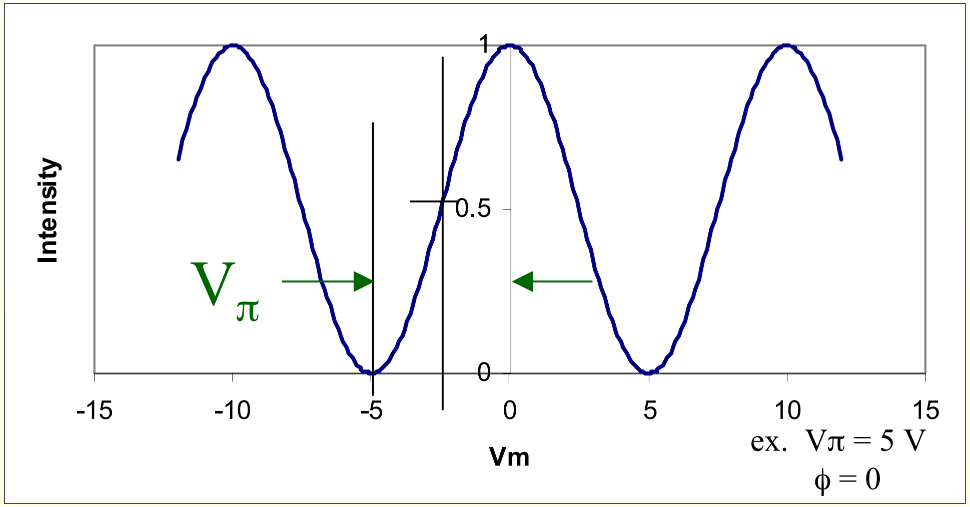
Electro-Optic Modulation

- Index along propagation axis is dependent on applied field (modulating signal)
  - Electro-Optic effect can be realized in Lithium Niobate ($LiNbO_3$), InP, and other crystal structures, i.e. KDP (KH_2PO_4)
  - Mach-Zehnder Modulator



- Propagation constant of the beam in the lower leg is retarded due to transverse electric field – experiences less phase shift.
- Optical intensity (power) is modulated by the applied RF signal

Mach-Zehnder



ex. $V\pi = 5$ V

$\phi = 0$

- **Optical Output power follows $\cos^2$ function**
  - **Caused by adding 2 signals of differing phase**

- **V_π is DC voltage that causes 180° phase rotation**
  - **Depends on crystal physics and electrode length**
  - **Corresponds to "min" and "max" output power**
  - **Digital Modulation: variation between min and max**

- **Analog Modulation: Bias at Quadrature (shown)**
  - **Results in linear intensity modulation**
  - **Slope = 1 at quadrature point**

Optical Output Power:

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

I_m = max output intensity
typically 3 to 4 dB below input

V_m = bias voltage

ϕ = phase offset (shift from origin)

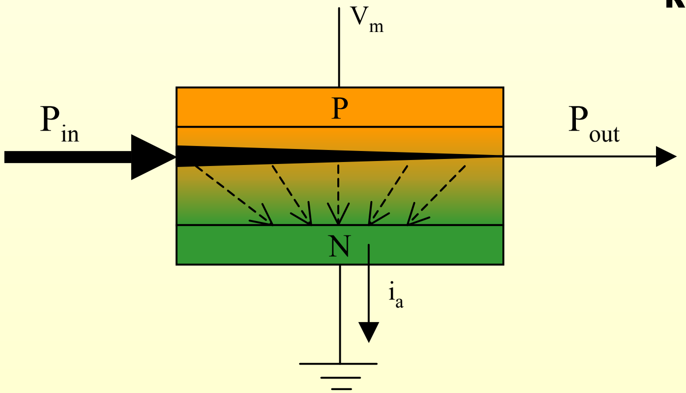
Quadrature Analog CW:

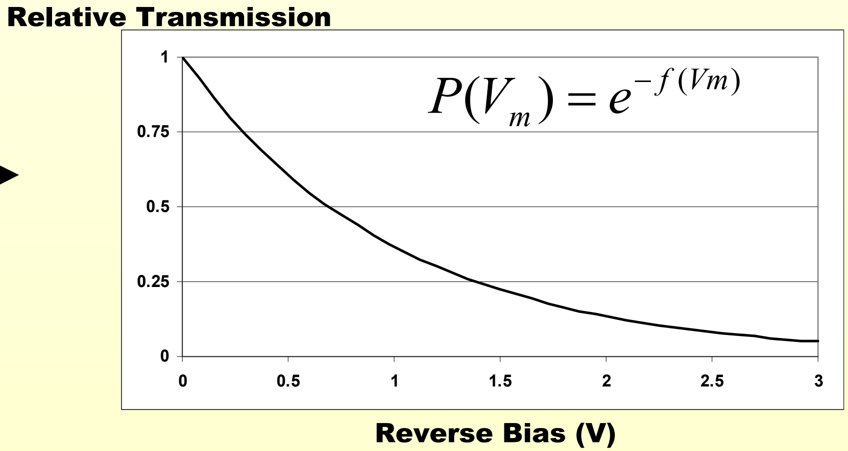
$$V_m(t) = \frac{V_\pi}{2}\left[1 + OMI \cdot \cos \omega t\right]$$

OMI = Optical Modulation Index

Electro-Absorption

- Absorption of optical signal dependent on applied bias
  - Transmission follows exponential relationship with applied field
    - Exponential f(Vm) is dependent on device length, carrier confinement, and instantaneous change in absorption



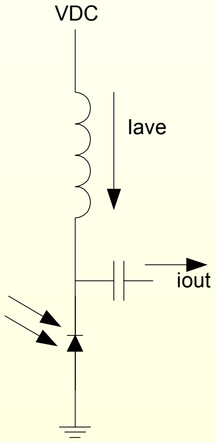


Modulation Summary

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

Photodetection

- P-I-N diodes are most common

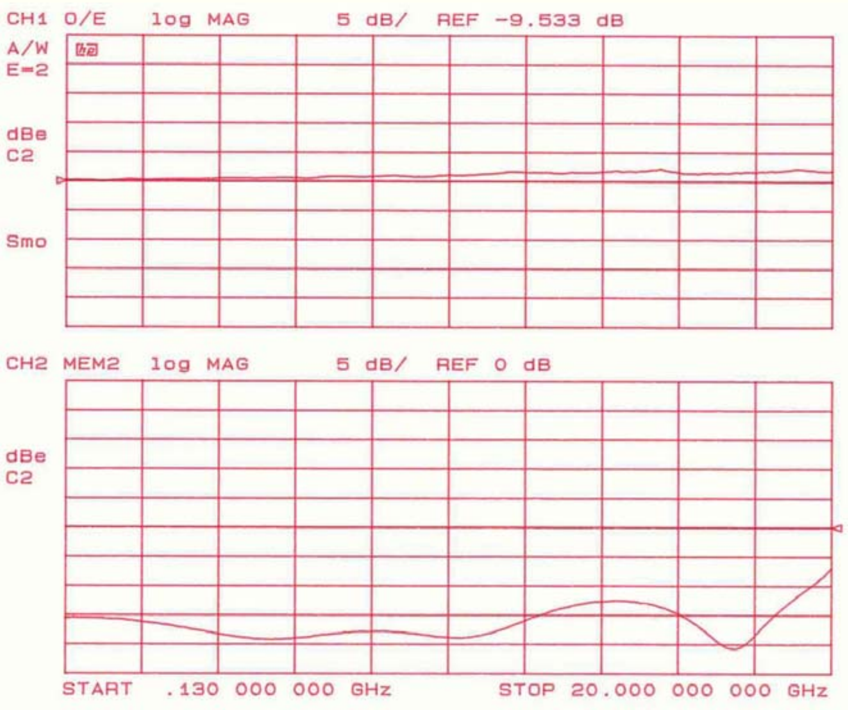


$$I(P) = R \cdot P$$

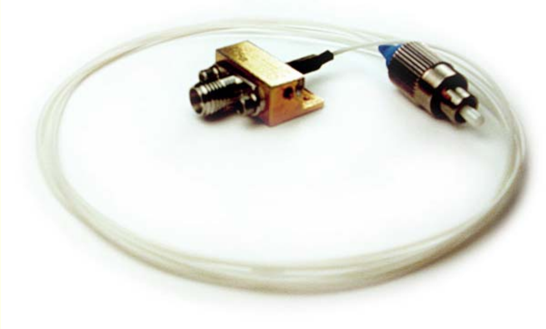
R = responsivity (amps/watt)

  - Intrinsic bandwidth limited by diode capacitance
  - Package and launch considerations may also limit performance
    - 25 GHz bandwidth from lateral PIN
    - 50+ GHz from waveguide PIN

Photoreceiver Response



O/E Response and Return Loss of MPR0020 photoreceiver



MPR-series Photoreceiver

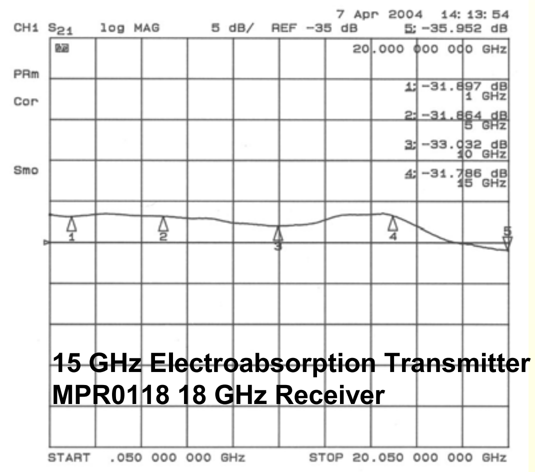
Closing the Link

- Typical performance

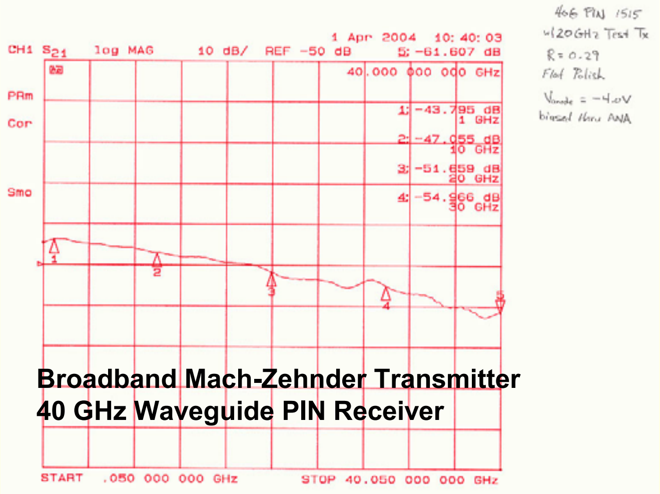
Link Type	Low Freq Gain dB	Operational BW GHz	Slope over BW dB	Input IP3 dBm	Noise Fig dB	SFDR3 dB Hz^2/3	Optical Budget dB
Direct	**-32**	**3**	**-1**	**36**	**40**	**113**	**7**
EAM 1	**-35**	**15**	**-3**	**23**	**40**	**105**	**7**
EOM (Vpi = 5 V)	**-36**	**20**	**-8**	**23**	**40**	**105**	**8**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

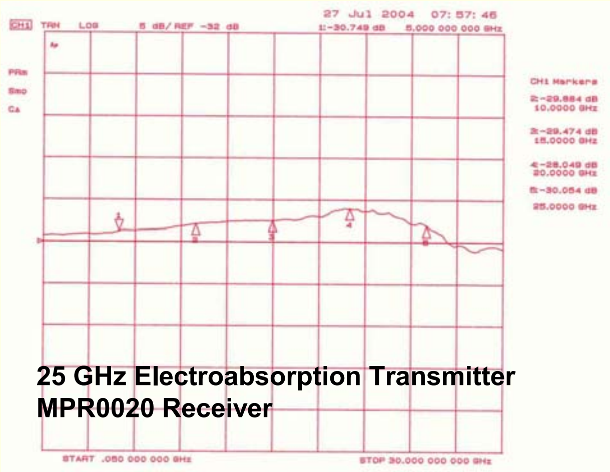
Link Examples



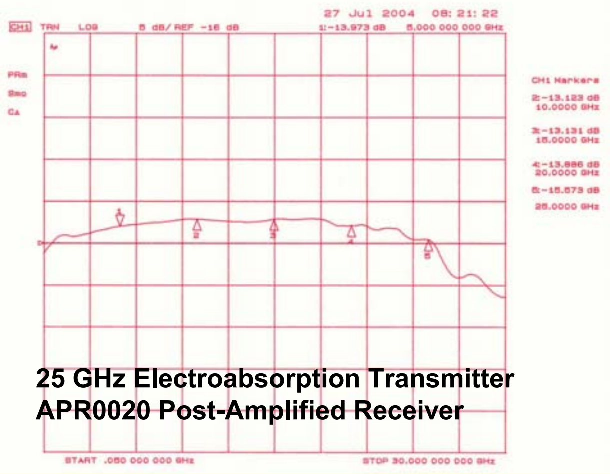
15 GHz Electroabsorption Transmitter
MPR0118 18 GHz Receiver



Broadband Mach-Zehnder Transmitter
40 GHz Waveguide PIN Receiver



25 GHz Electroabsorption Transmitter
MPR0020 Receiver

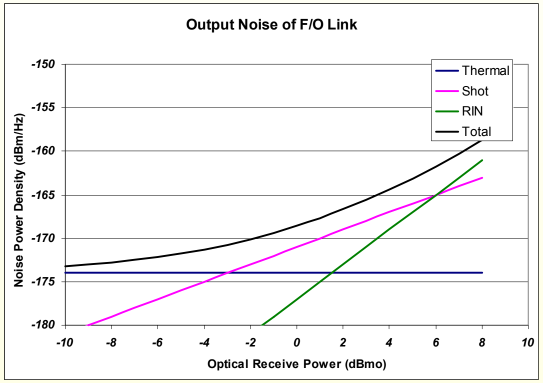


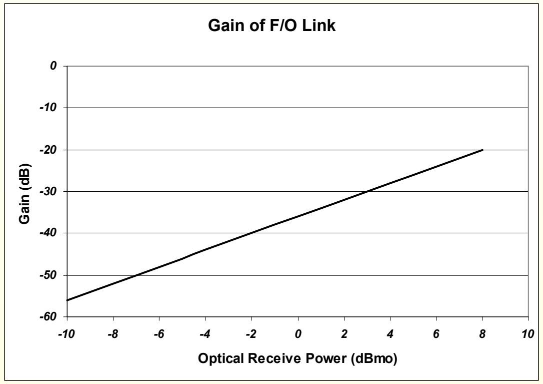
25 GHz Electroabsorption Transmitter
APR0020 Post-Amplified Receiver

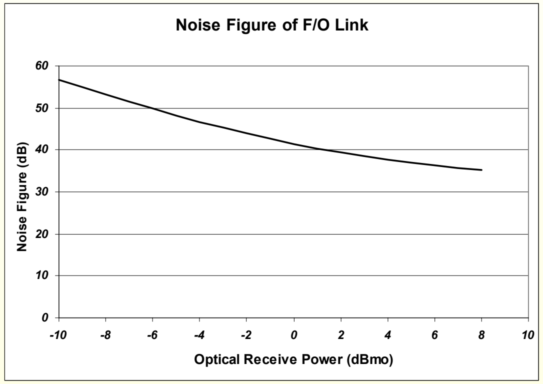
Modulation Summary

- Performance Limiting Factors
  - Linear Factors
    - Microwave Launch
      - Laser diode and EAM diode are low-impedance
        - Fano’s Rule
        - Packaging
      - MZM functionality dependent on interaction length of optic and electric fields
        - Traveling-Wave Launch with RF termination is inherently inefficient
    - Inherent Bandwidth
      - Limited by device capacitances; smaller devices = lower power
    - Noise
  - Nonlinear Factors
    - Intermodulation Distortion

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 link 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

Performance Requirements

- Communications
  - Multi-carrier, complex waveforms, moderate dynamic range, high bandwidth
    - Requires very high linearity, lower drive levels
- Radar
  - Mostly single-carrier, simple waveforms, lower dynamic range, lower bandwidth
    - Requires moderate linearity, can drive to higher levels
    - Distinction between transmit and receive side
- EW
  - Ultra-wide bandwidth drives need for high dynamic range

- Improvements in SFDR will broaden application opportunities for microwave fiber optics

Performance Improvement

- Linearization Techniques
  - Linearization improves nonlinear distortion; increases dynamic range
  - Major techniques under study include optical, electrical, and combinatorial approaches
    - 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

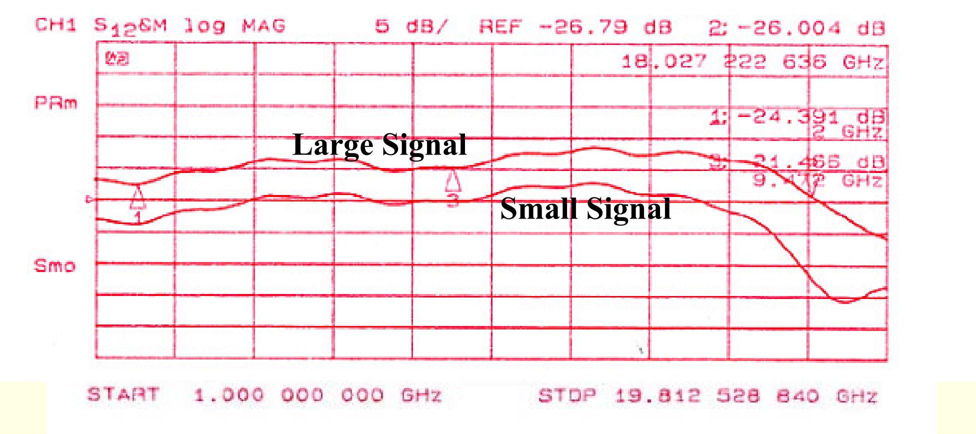
Electrical Predistortion

- Predistortion Linearization has long history in broadcast power amplifiers; SSPAs, TWTAs, klystrons, space and ground station equipment
  - Generally much less complexity 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

The Multi-Octave Problem

- Predistorter tends to generate 2nd- and 3rd-order nonlinearities
  - 2nd-order terms may tend to worsen performance for > octave bandwidth
    - Even terms not in the proper phase to cancel
- Ongoing effort to develop predistorters that generate only 3rd-order components and operate over multi-octave bandwidth

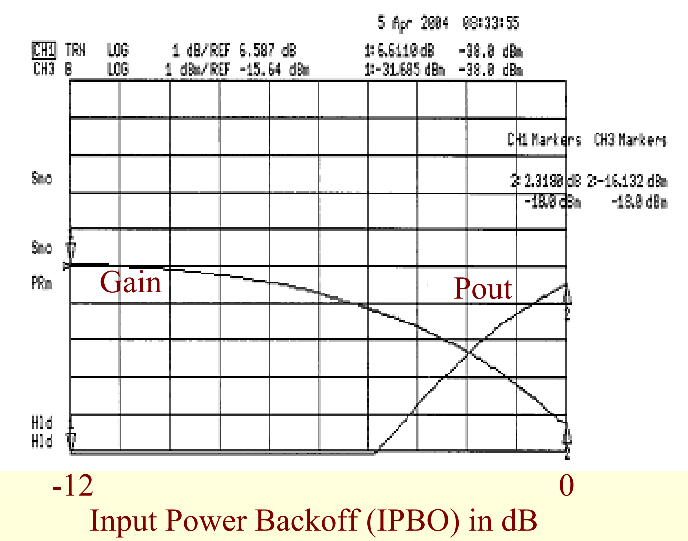
Wideband Predistorter

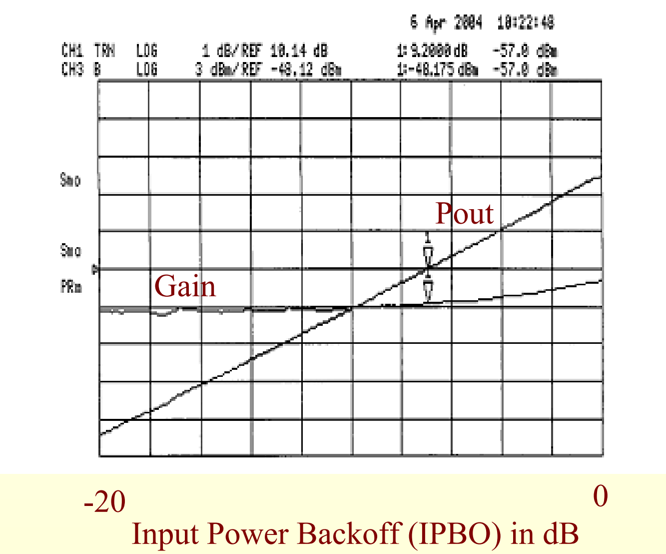


- Broadband performance from generic predistorter element
  - Generates both even and odd nonlinear terms

Predistortion Linearizer Performance

- Linearization Results of EAM Link at 14 GHz



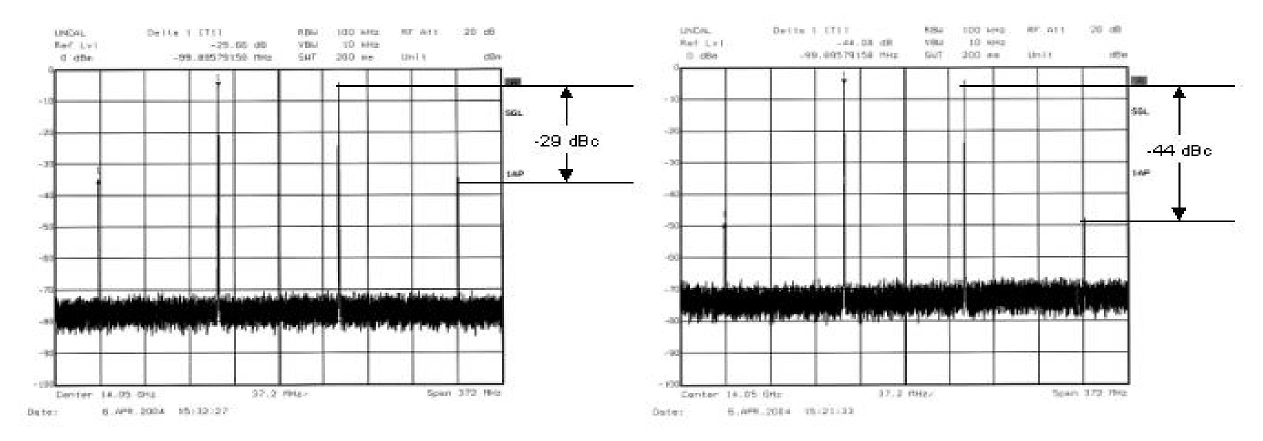


- Non-Linearized
  - 4 dB gain compression at reference input power (saturation)

- Linearized
  - Predistortion linearizer effectively compensates the gain compression

Predistortion Linearizer Performance

- Intermodulation Distortion Improvement
  - Measured at 6 dB IPBO



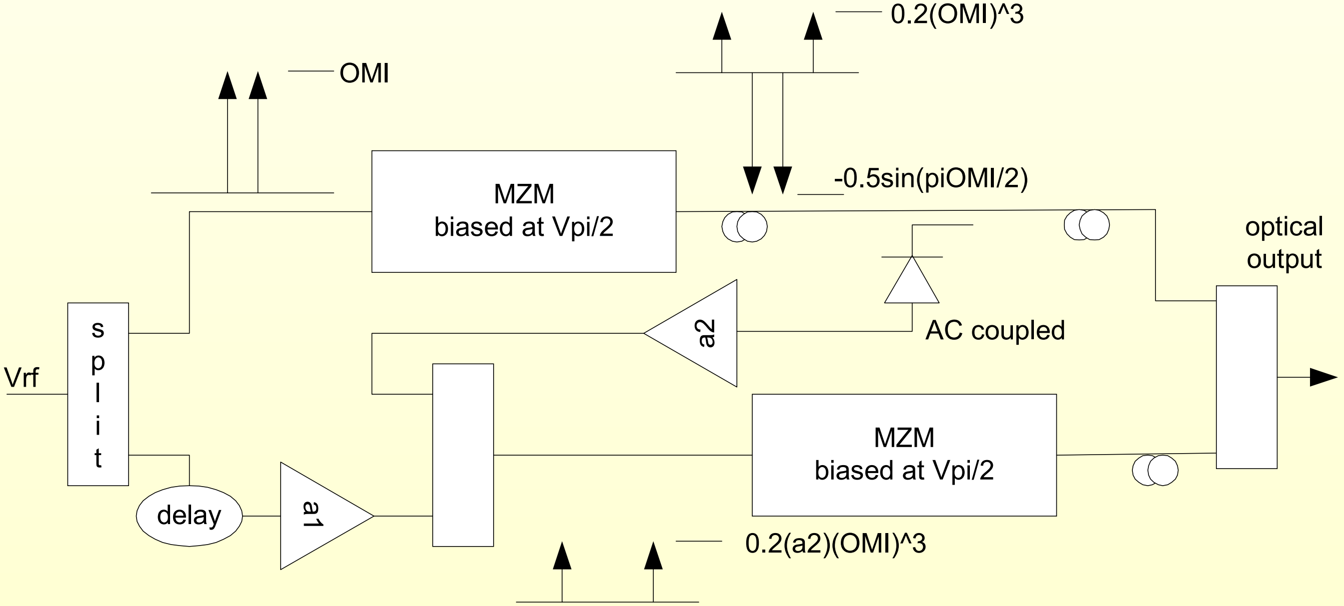
Non-Linearized

Linearized

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

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

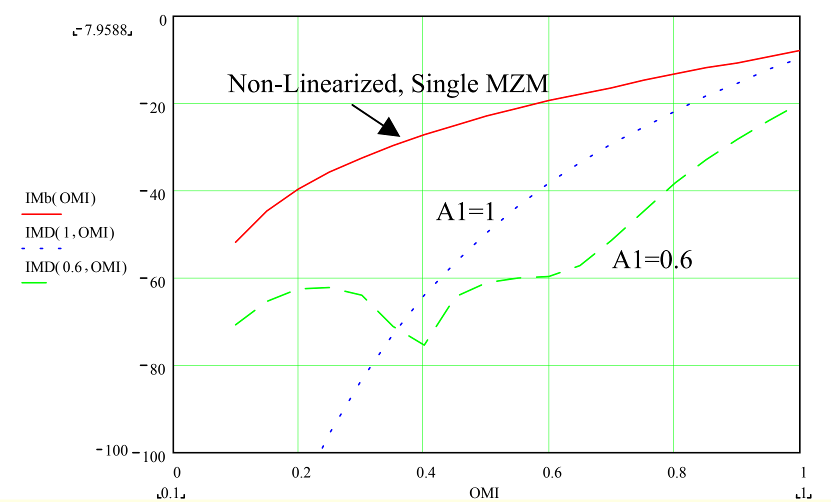
$V_2 = A_2(0.2 \cdot OMI^3) = OMI'$ where OMI’ = equivalent per-channel OMI of third-order products into MZM2. Then we get

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

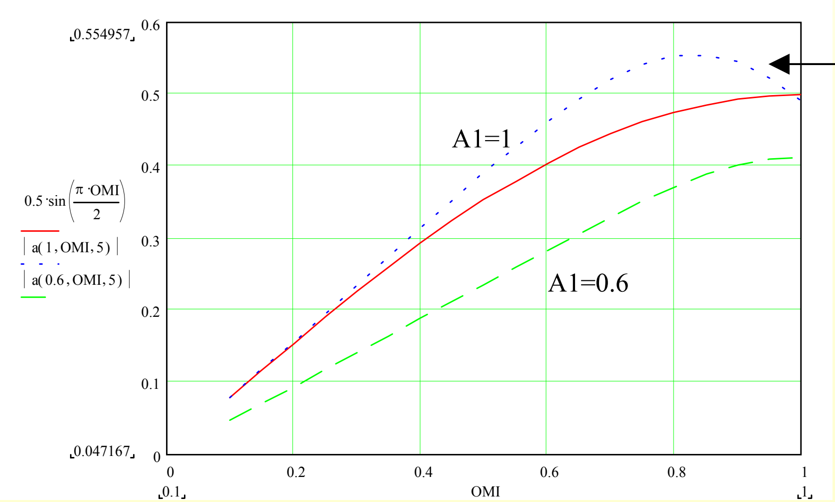
We want $V_3 = -0.2 \cdot OMI^3\Big|_{2f1-f2\&2f2-f1}$ so we set A1 and A2 as follows:

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

Modeled results with A2 = 4/π



Two-tone
Third-order IMD

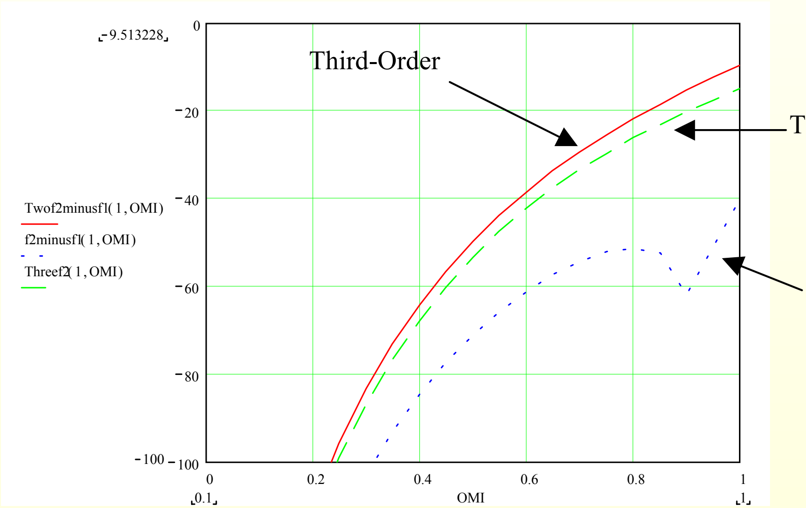


Non-Linearized, Single MZM

Two-Tone
Fundamental Transfer Function

Note: OMI is per-carrier

$A2 = 4/\pi$ and $A1 = 1$



Third-Order

Third Harmonic

Second Harmonic