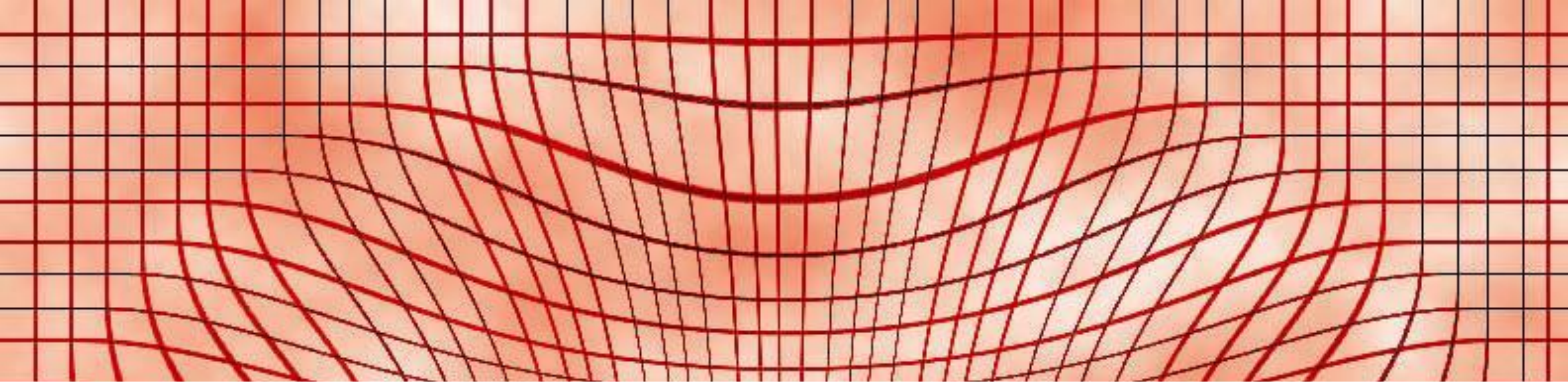
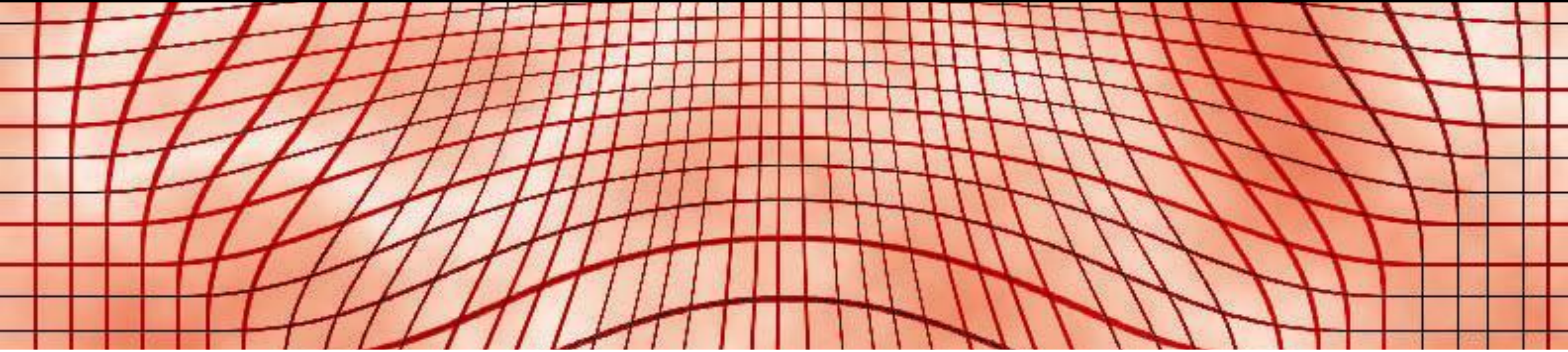


LINEARIZATION:

REDUCING DISTORTION IN POWER AMPLIFIERS



BY: DR. ALLEN KATZ, APRIL 2009

OUTLINE

- WHY LINEARIZE
- TYPES OF LINEARIZERS
- THEORY/IDEAL LIMITER
- PREDISTORTION LINEARIZERS
- PHOTONIC LINEARIZERS
- PERFORMANCE EVALUATION
- RESULTS
- MEMORY EFFECTS
- CONCLUSIONS

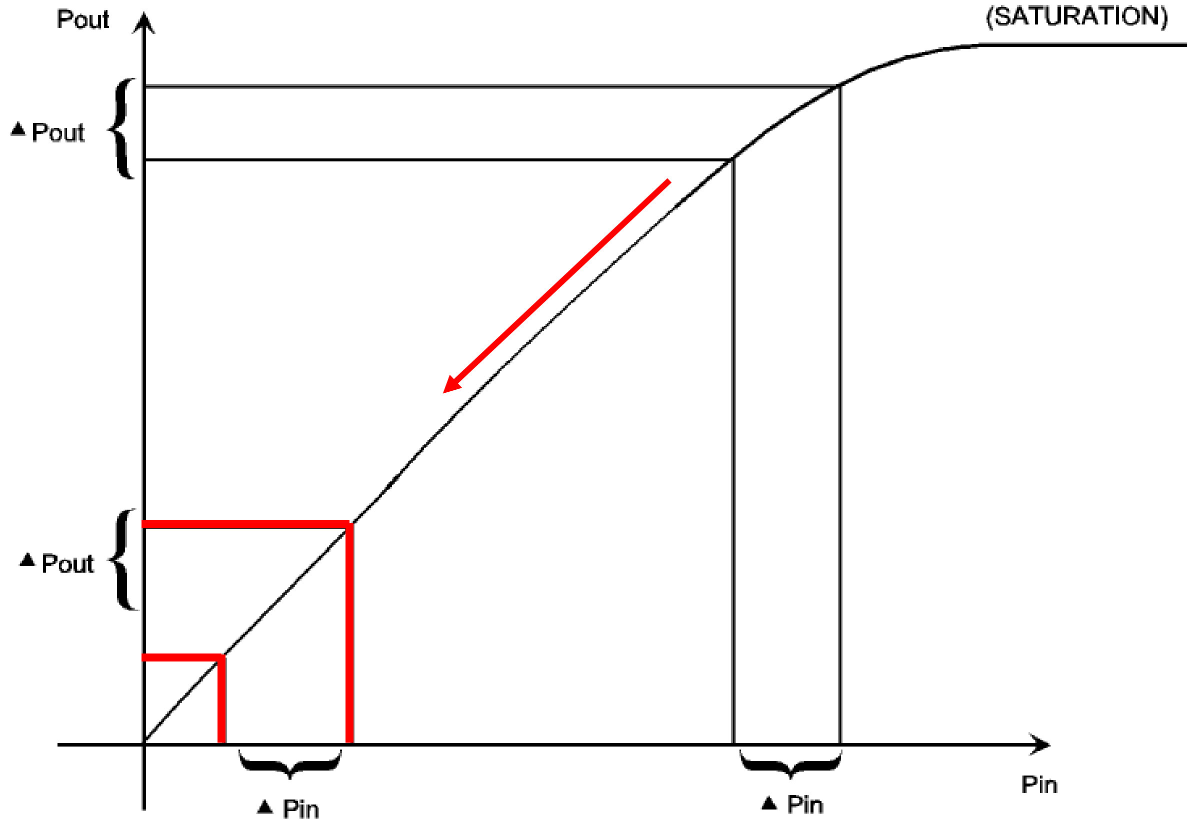
IN PAST MOST AMPS USED FOR SC FM MOD SIGNALS

- NL PRODUCTS ELIMINATED WITH LP FILTER
-OPERATER AT SATURATION (MAX PWR & EFF)

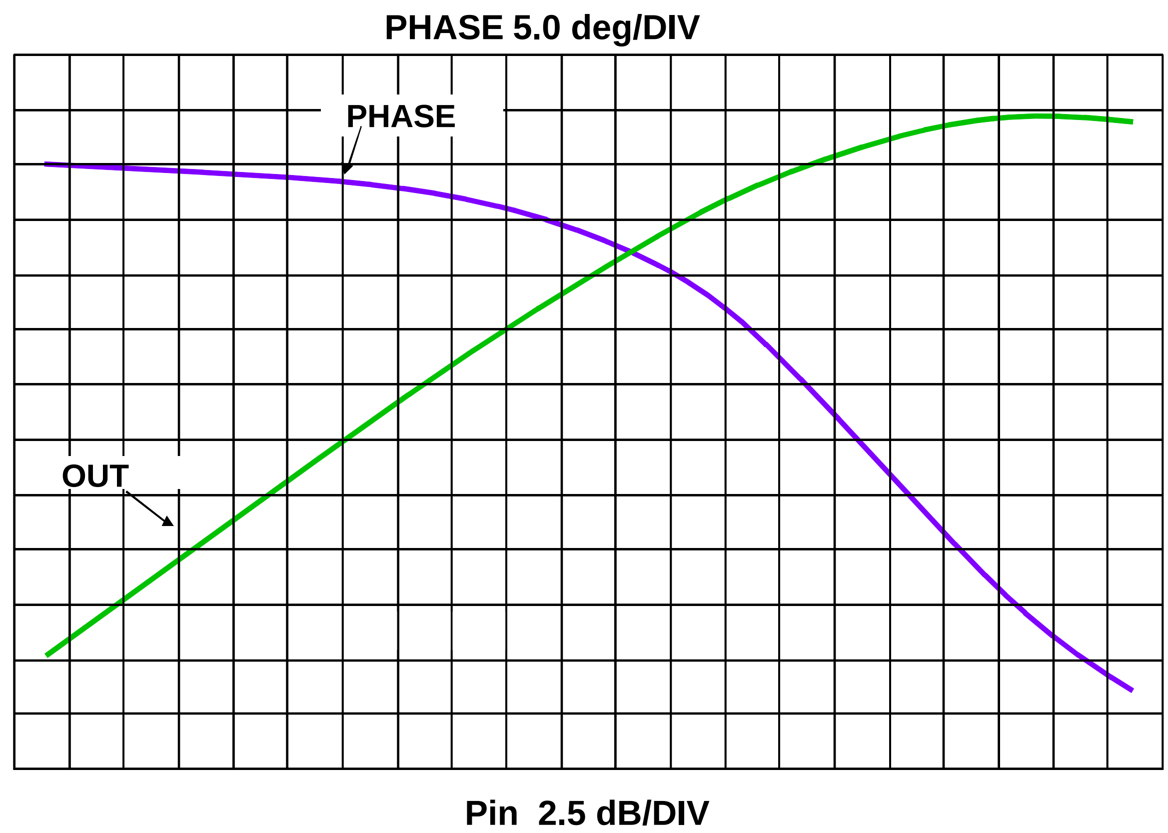
TODAY MULTI-CARRIER AND COMPLEX MODULATED SIGNALS COMMON
WHEN MORE THAN ONE CARRIER - DISTORTION PRODUCED (IM)

TO REDUCE DISTORTION TO AN ACCEPTABLE LEVEL

-MUST OPERATE AMPLIFIER AT REDUCED POWER LEVEL (BACKOFF FROM SATURATION)



DISTORTION ALSO PRODUCED BY CHANGE IN PHASE WITH POWER LEVEL



$$A_c \cos(\omega_c t + M \cos[\omega_m t]) = A_c \sum_{n=-\infty}^{n=\infty} J_n(M) \cos([\omega_c + n\omega_m]t)$$

FOR A DIGITALLY MODULATED CARRIER DISTORTION PRODUCES SPECTRAL REGROWTH

LINEARIZATION --

SYSTEMATIC PROCEDURE FOR REDUCING DISTORTIONS

USUALLY EXTRA COMPONENTS ADDED TO AN AMPLIFIER

WHEN CONFIGURED IN A SUBASSMBLY OR *BOX* KNOWN AS A **LINEARIZER**

THREE COMMON FORMS:

1) FEEDFORWARD
2) FEEDBACK
3) PREDISTORTION

+ TECHNIQUES TO IMPROVE EFFICIENCY USING NL PAs

CHOICE OF LINEARIZATION

- LEVEL OF LINEARITY (DISTORTION REDUCTION) NEEDED.
- BANDWIDTH REQUIRED (SIGNAL AND OPERATIONAL).
- COST/COMPLEXITY CONSTRAINTS.

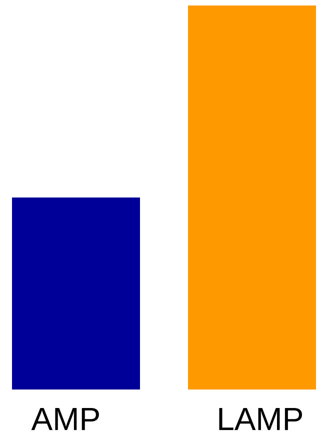
LINEARIZERS HAVE BEEN USED WITH

- TWTAs and KLYSTRONS
- BIPOLAR SSPAs (CLASS A, AB, B)
- FET SSPAs (GaAs, MOS, LDMOS)
- PHOTONIC (DIRECT, MZM, PIN)

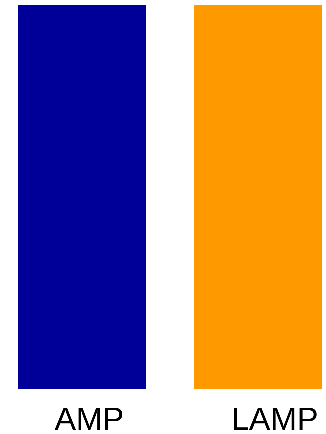
LINEARIZERS ALLOW HPAs TO OPERATE CLOSER TO SAT

Greater Ouput Power

POWER OUT

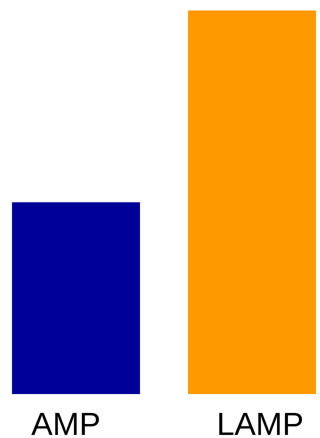


“SAME” Distortion

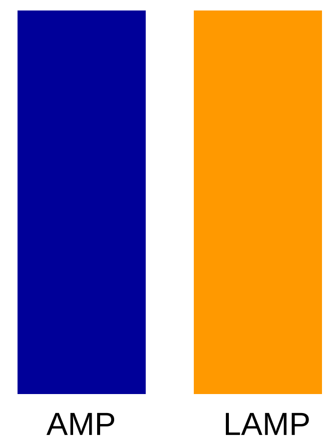


Greater Efficiency

Efficiency



“SAME” Distortion



FIRST RULE:

YOU CAN'T LINEARIZE AN AMPLIFIER THAT IS ALREADY LINEAR!

WANT TO OPTIMIZE EFFICIENCY AND SATURATED POWER, NOT LINEARITY

EXCELLENT RESULTS CAN BE OBTAINED WITH CLASS A-B AND B AMPS BOTH FET AND BIPOLAR

IDEAL AMPLIFIER CHARACTERISTIC

WANT CONSTANT GAIN AND PHASE

IMPROVEMENT DEPENDS ON ACCEPTABLE DIST LEVEL

SATELLITE --

- IMD PRODUCTS ADD TO THERMAL NOISE
  IF C/I = CNR THEN CNR DEGRADES BY 3 dB

- WANT C/I > CNR + 10 dB FOR NEGLIGIBLE DEG. (< .5 dB)
  IF CNR = 16 dB THEN C/I = 26 dB

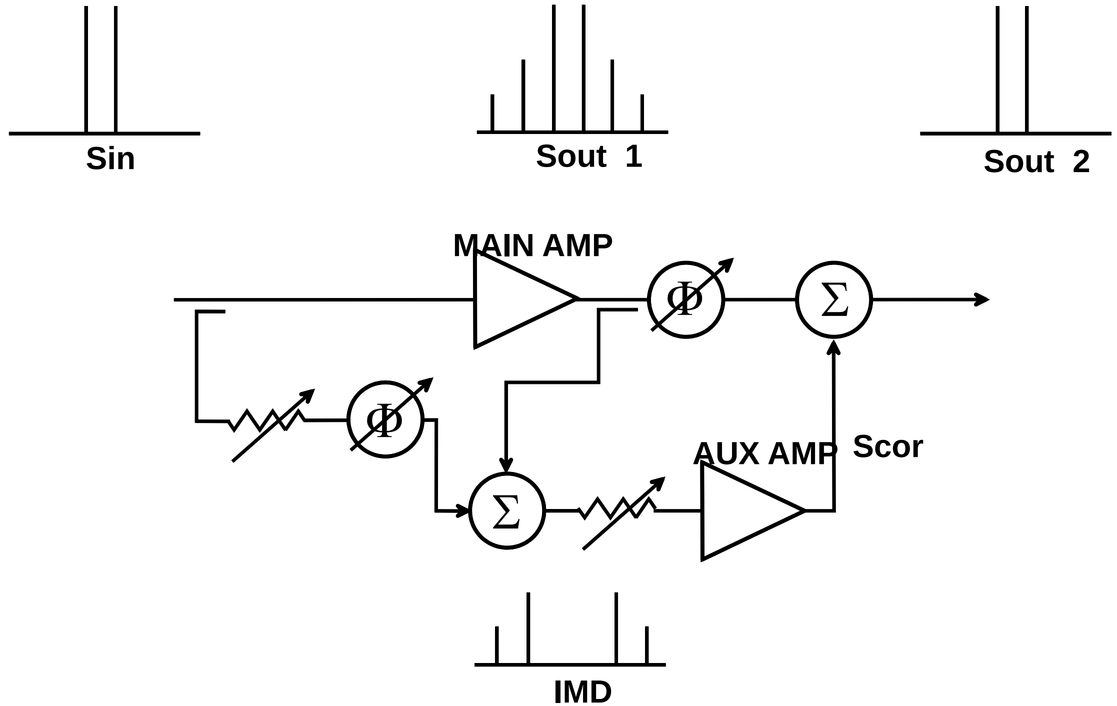
- IF C/I = CNR + 6 THEN CNR = CNR DEG. BY 1 dB

CELLULAR --

- INTERFERENCE FROM TX TO ADJACENT RX A PROBLEM --
  CAN NEED C/I > 35 ~ 70 dB.

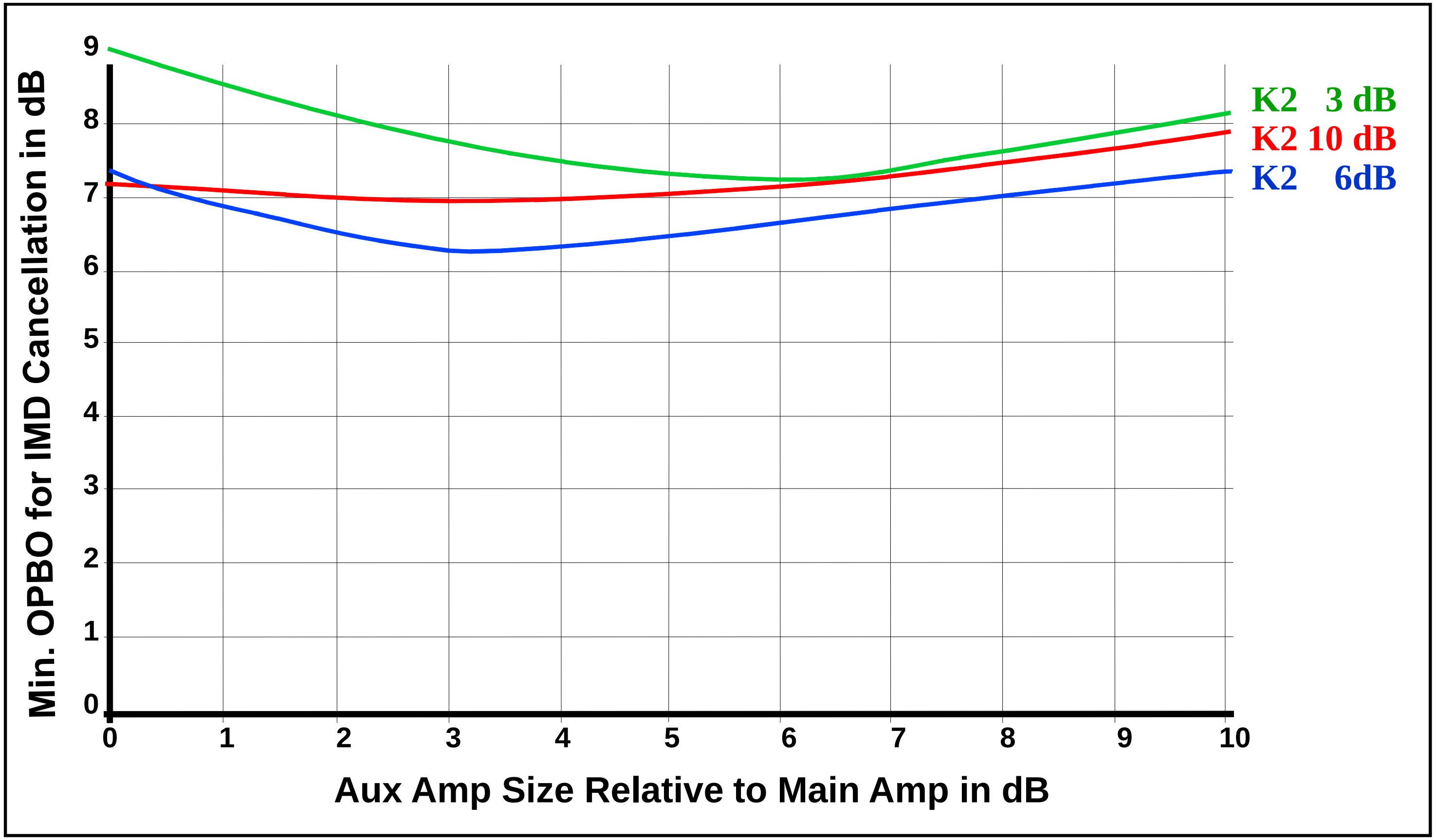
- FOR DIGITAL MOD, 16QAM … 8PSK NEED HIGH C/I TO
  KEEP BER DOWN.

FEEDFORWARD



- RELATIVELY COMPLEX
- NOT WORKABLE AS STAND-ALONE UNIT
- NOT EFFECTIVE FOR OPBOs < 6 dB
- MOST USEFUL FOR VERY HIGH LINEARITY APPLICATIONS

MINIMUM FEEDFORWARD OPBO FOR IMD CANCELATION (20 dB)



DEPENDS ON: **1) AUX AMP SIZE,**

2) OUTPUT COUPLER COEF.

FEEDBACK LINEARIZATION

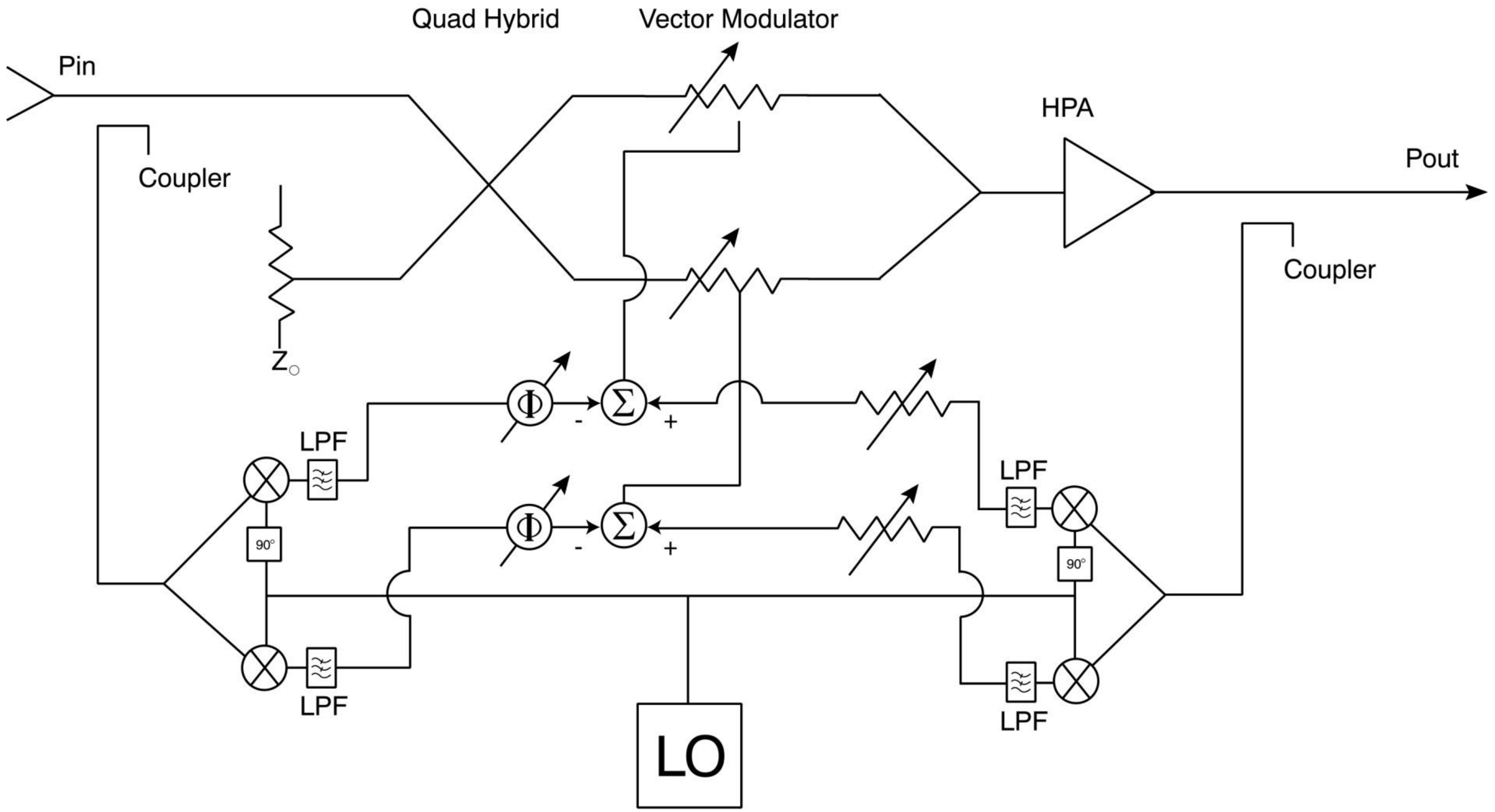
***FEEDBACK (NETWORK)**

- NARROW BAND
- STABILITY PROB
- REDUCED GAIN
- DIFF TO ADJ

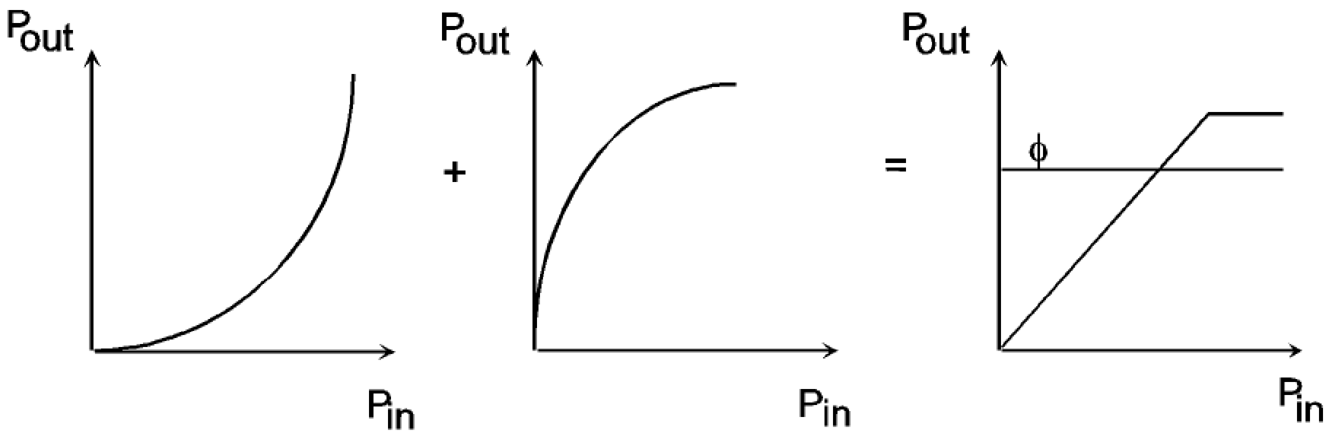
***INDIRECT FEEDBACK**

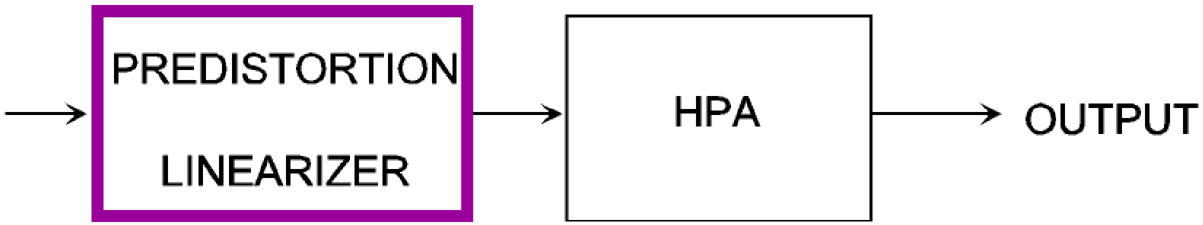
-OPERATES ON ENVELOPE
-VERY LIMITED BW $< 1/(4\Delta t_S)$
-CAN BE POLAR OR CARTESIAN

CARTESIAN FEEDBACK ELIMINATES THE NEED FOR PHASE CORRECTION CIRCUITRY



PREDISTORTION





- RELATIVELY SIMPLE CIRCUITRY
- EASILY IMPLEMENTED AS A STAND-ALONE UNIT
- WIDE BAND (>20% – MULTI OCT/GHz BW ACHIEVED)
- MOST POPULAR FOR MICRO/MILLIMETER WAVE

LINEARIZER GAIN DEPENDS ON INPUT TO HPA

- THE GAIN OF THE LINEARIZER (GL) MUST INCREASE BY THE SAME AMOUNT THE HPA's GAIN (GA) DECREASES.

- $$GL(P_{outL}) - GL_{ss} = -[GA(P_{inA}) - GA_{ss}] \quad \Big|_{P_{outL} = P_{inA}}$$

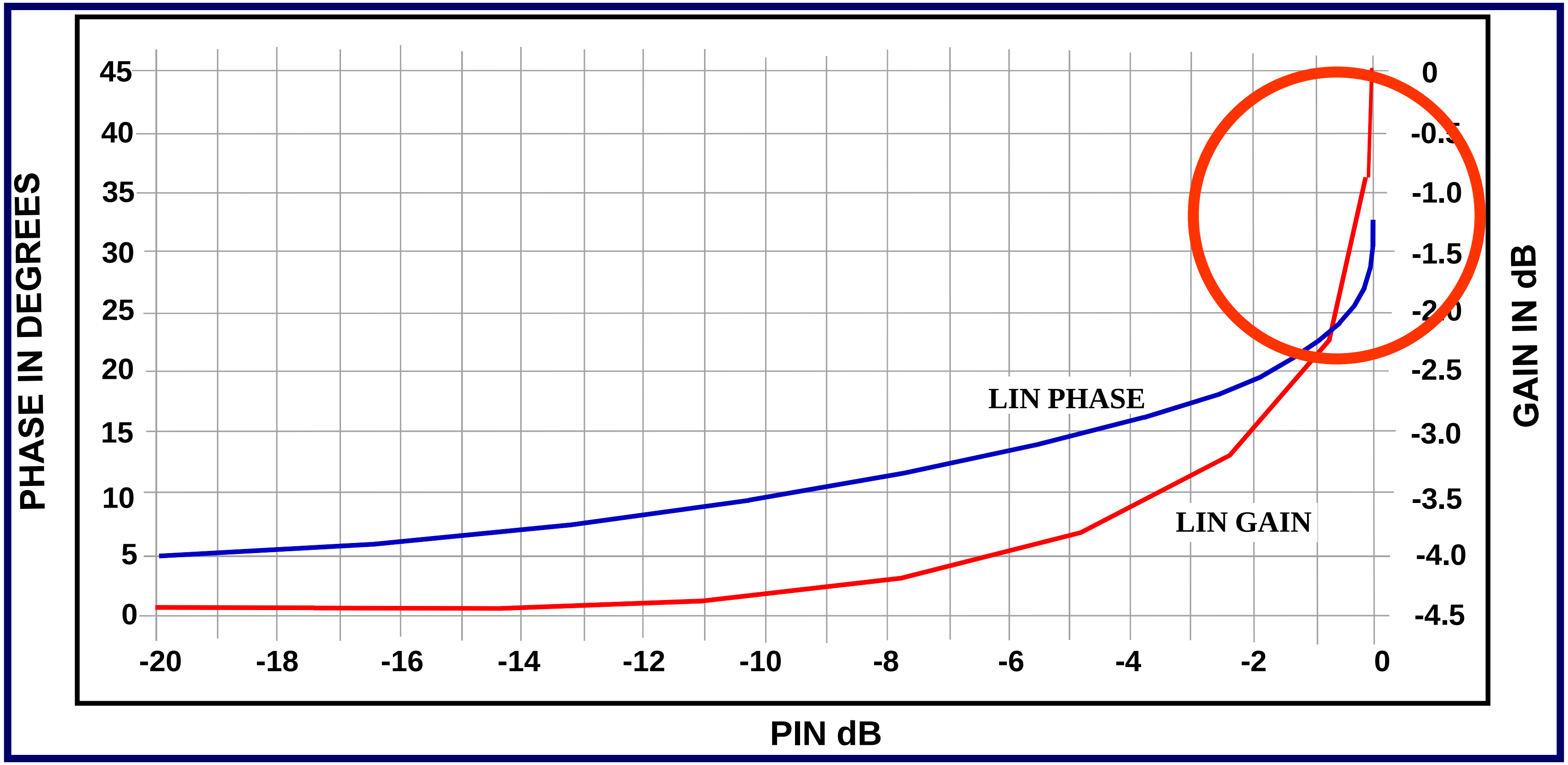
- $$\Phi L(P_{outL}) - \Phi L_{ss} = -[\Phi A(P_{inA}) - \Phi A_{ss}] \quad \Big|_{P_{outL} = P_{inA}}$$

- $$GL(P_{inL}) = GL_{ss} + GA_{ss} - GA(P_{inL} + GL(P_{inL}))$$

- $$\Phi L(P_{inL}) = \Phi L_{ss} + \Phi A_{ss} - \Phi A(P_{inL} + GL(P_{inL}))$$

- **ΦL DEPENDS ON THE GL AND CANNOT BE SET IDENPENDENTLY**

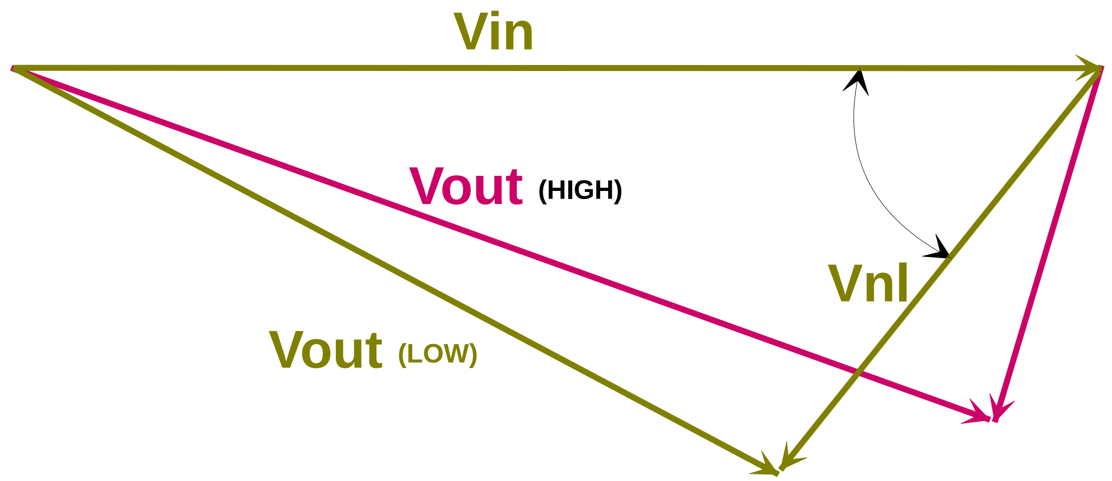
AN IDEAL LINEARIZER MUST PROVIDE A GAIN EXPANSION THAT APPROACHES INFINITY NEAR SATURATION



$$dG/dP \Rightarrow \infty \text{ as } P_{in} \Rightarrow Sat$$

FORMS OF PREDISTORTION LINEARIZERS

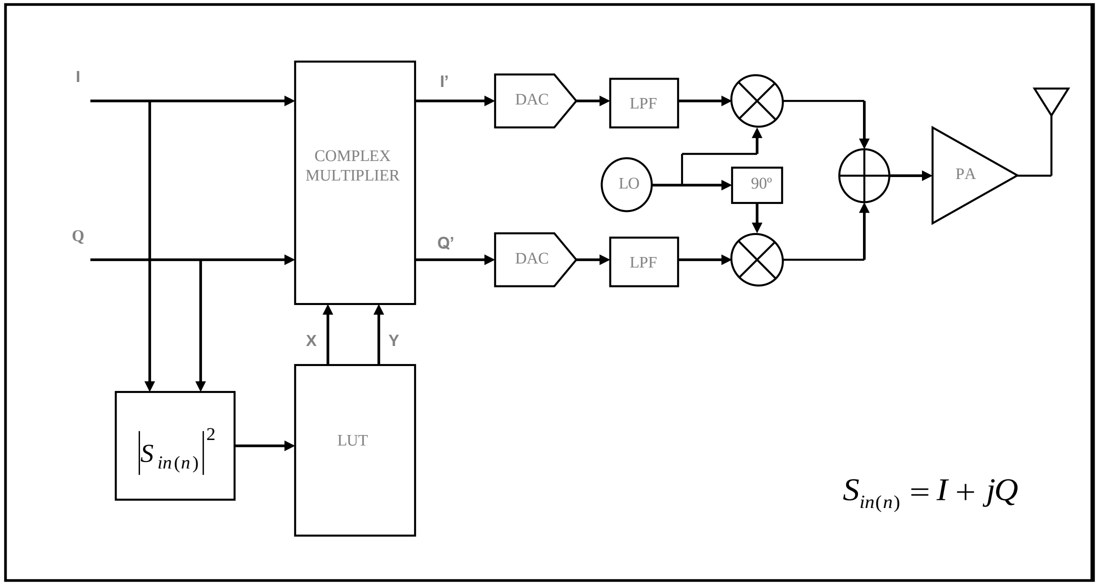
1. TRANSMISSION



2. REFLECTIVE

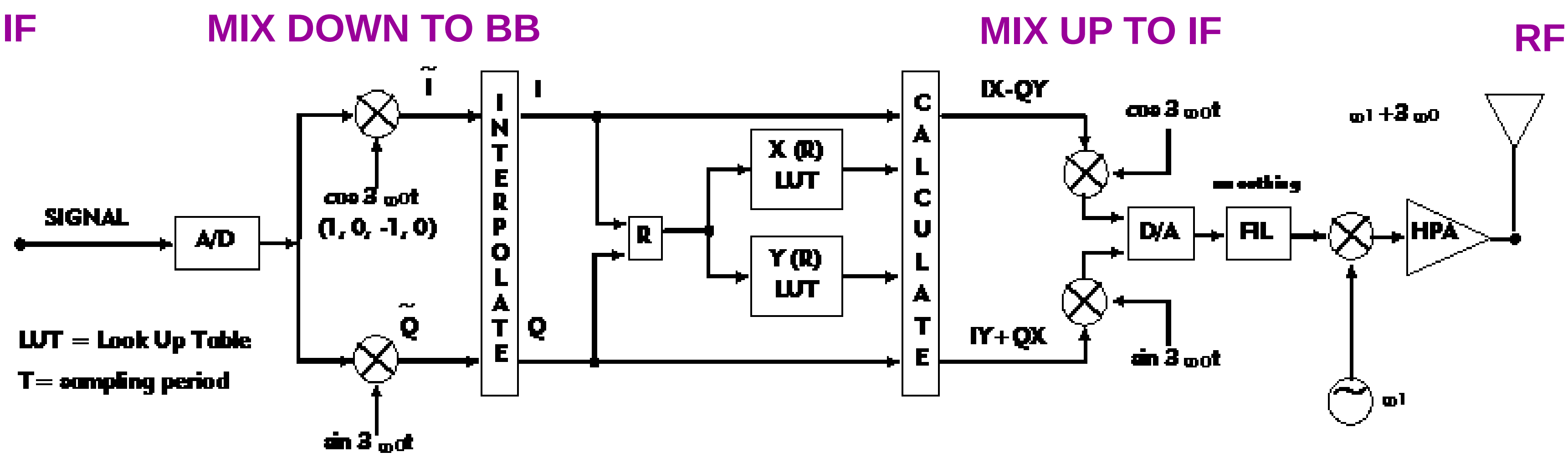
3. IN LINE

BASIC DSP PREDISTORTION (PD) LINEARIZER



- Every input level has a corresponding output level
- Correction (mag & phase) in look up tables (LUT) depends on input level
- LUT often adaptively updated for slow changes over time

DIGITAL PREDISTORTION



- CAN PRODUCE CURVES OF ANY SHAPE
- NORMALLY PROCESS AT BASEBAND
- CAN USE EITHER G AND Φ OR I AND Q
- MUST SAMPLE AT > 2 X CORRECTION BW FOR G AND Φ
- BUT ONLY > CORRECTION BW FOR I AND Q
- CORRECTION BW (CBW) >> 3 x BW OF SIGNAL
- MUST USE MANY BITS FOR HIGH CANCELATION (<6 dB/)

DIGITAL ADAPTIVE PREDISTORTION

CORRECTION BW MUST BE >> SIGNAL BW

DIGITAL ADAPTIVE PREDISTORTION

ADAPTIVE SYSTEMS CORRECT AT << ENVELOPE RATE

DIGITAL PREDISTORTION

- **ADVANTAGES:**

  * ACCURATE CORRECTION OVER WIDE DYNAMIC RANGE AND FOR IRREGULAR NON MONOTONIC CHARACTERISTICS
  * EASY TO MODIFY AND UPDATE
  * SIMPLE TO IMPLEMENT AS ADAPTIVE SYSTEM

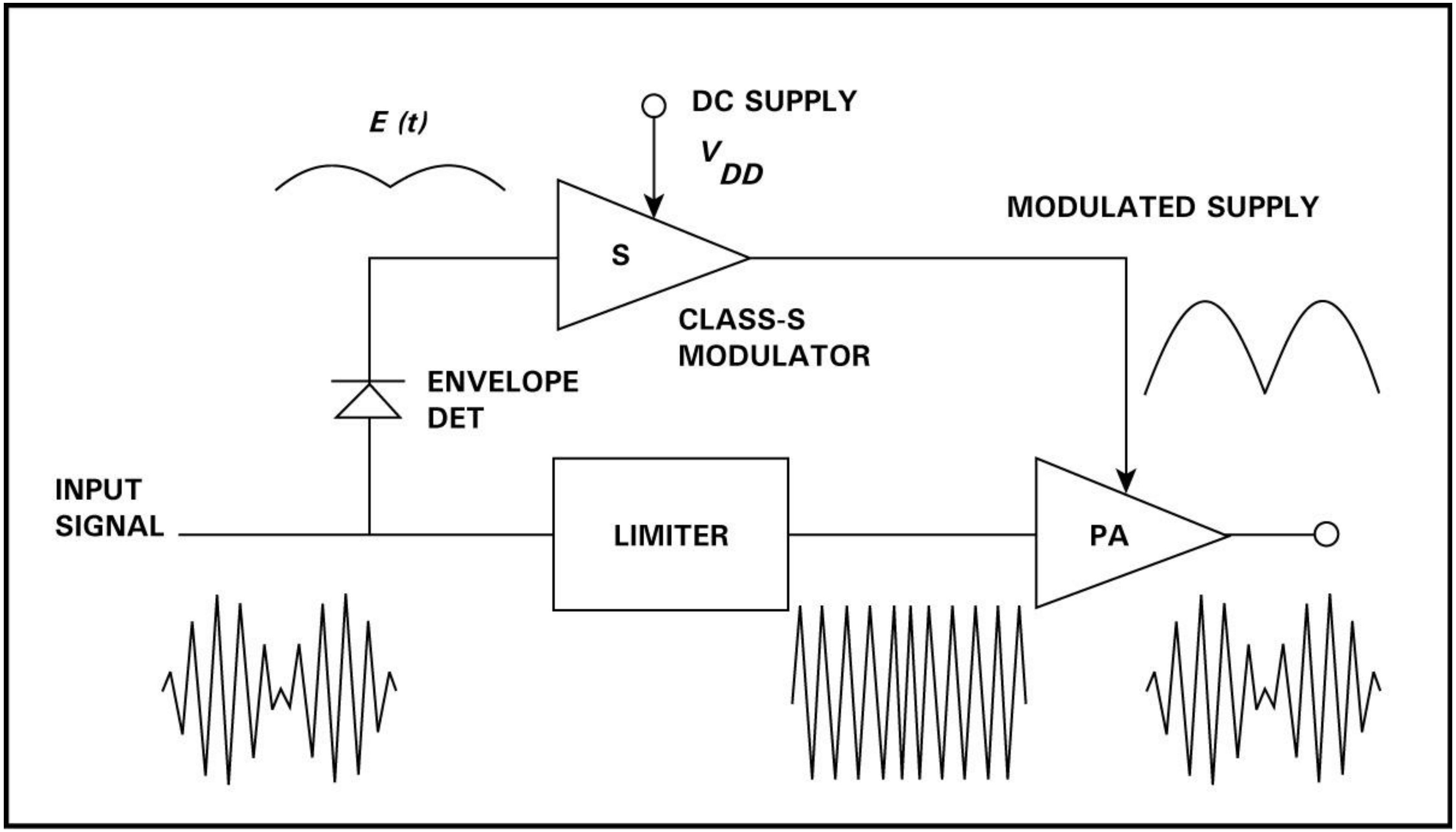
- **DISADVANTAGES:**

  * CORRECTION BANDWIDTH LIMITED BY SAMPLING RATE: SR = CBW = N X BW
  * COST CAN BE HIGHER THAN ANALOG
  * POWER CONSUMPTION CAN BE HIGH
  * WIDE BW SYSTEMS DIFFICULT TO IMPLEMENT

TECHNIQUES TO IMPROVE EFFICIENCY USING NL PAs

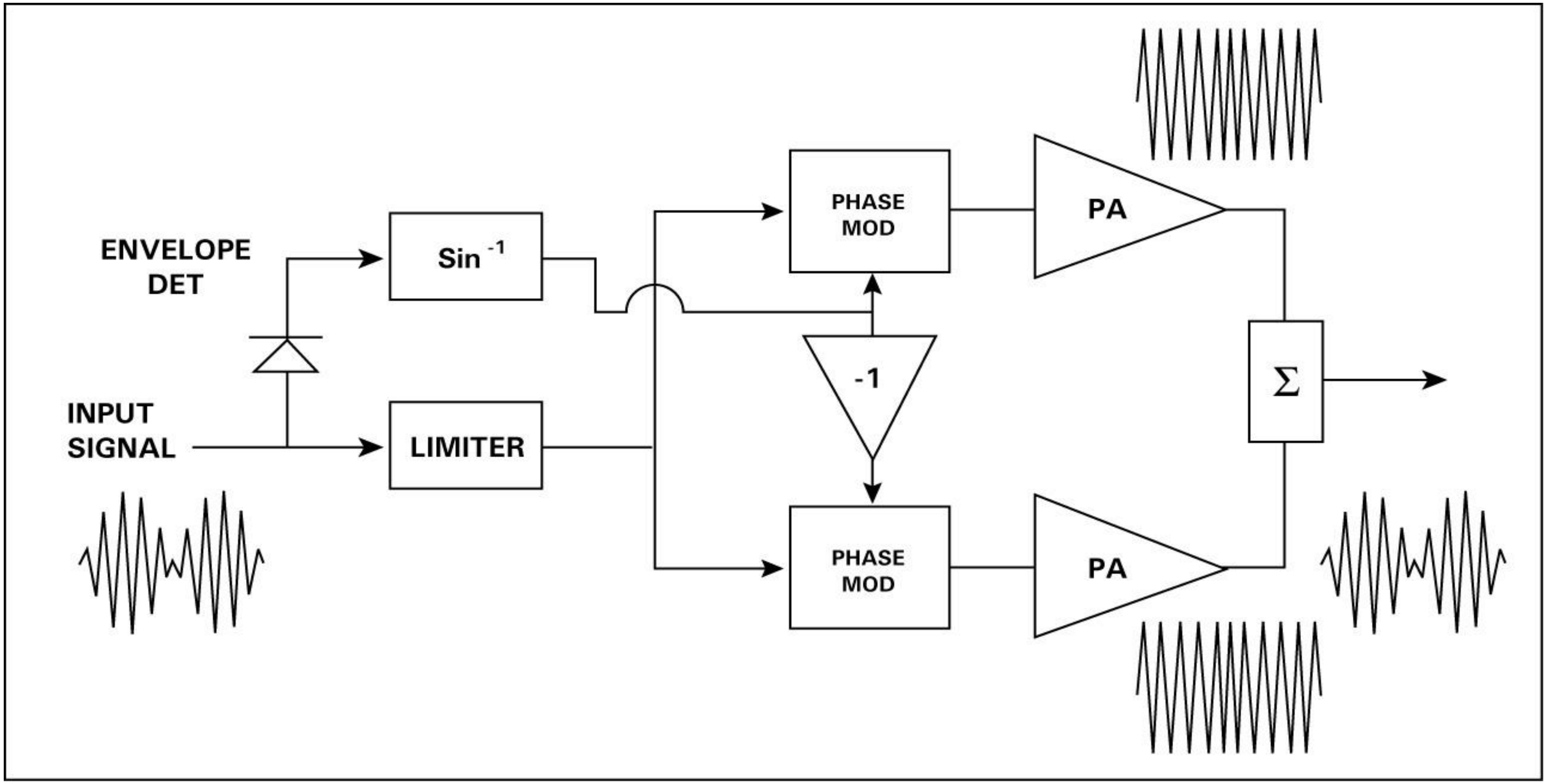
- MANY WAYS TO ACCOMPLISH.
- CLASSICAL “KHAN METHOD” DEMODS ENVELOPE AND LIMITS SIGNAL. THEN REMODULATES AT OUTPUT PA.
- LINC SYSTEMS USE OBTAIN LINEAR AMPLIFICATION BY COMBINING TWO NON-LINEAR PAs.
- LOAD MODULATION AND OUTPHASING (DOHERTY – ONE EXAMPLE)

EER – ENVELOPE ELIMINATION AND RESTORATION



IF ELIMINATE ENVELOPE, SIGNAL CAN BE AMPLIFIED IN NL PA OPERATED AT OR NEAR SATURATION.

LINC – LINEAR AMPLIFICATION WITH NON-LINEAR COMPONENTS



CAN OBTAIN ANY AMPLITUDE FROM THE SUM OF 2 CONSTANT AMPLITUDE SIGNALS OF VARIABLE PHASE

PERFORMANCE EVALUATION

MAGNITUDE & PHASE IMPORTANT INDICATORS OF PERFORMANCE

**** OBTAIN WITH POWER SWEEP**

SEPARATION OF 1 dB COMPRESSION AND SATURATION PROVIDES GAGE FOR COMPARISON

C/I (CARRIER TO IMD) MEASUREMENT

- MANY DIFFERENT STANDARDS MAKE COMPARISON DIF.

- DATA USUALLY PRESENTED REL TO BACKOFF FROM SAT.

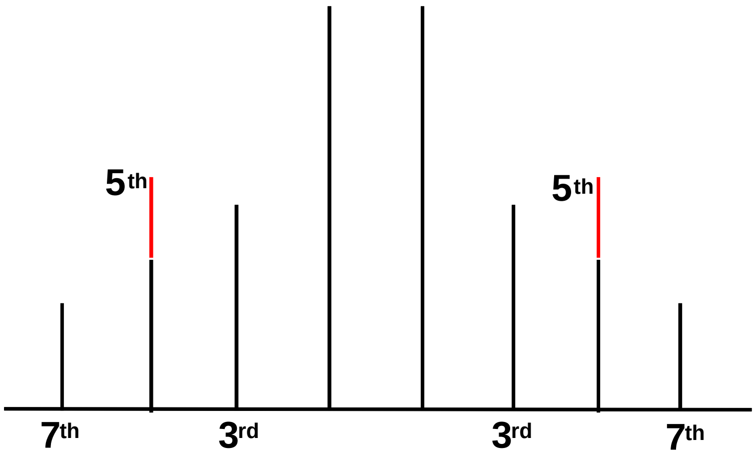
- SAT POINT SHOULD BE SINGLE CARRIER SAT.
  2 CARRIER SAT ABT 1 dB LOWER, NOISE ABT 1.5 dB.

- CAN NOT USE COMPRESSION POINT FOR REFERENCE.
  1 dB = SAT - D

- BOTH IPBO AND OPBO USED … IPBO CAN BE MISLEADING.
  BEST TO REFER TO OPBO
  - OUTPUT LEVEL IS WHAT'S IMPORTANT!

OFTEN RESULTS PRESENTED FOR C/I3 ONLY

With Linearizers, not uncommon for 5th order terms to be greater than 3rds or of same order

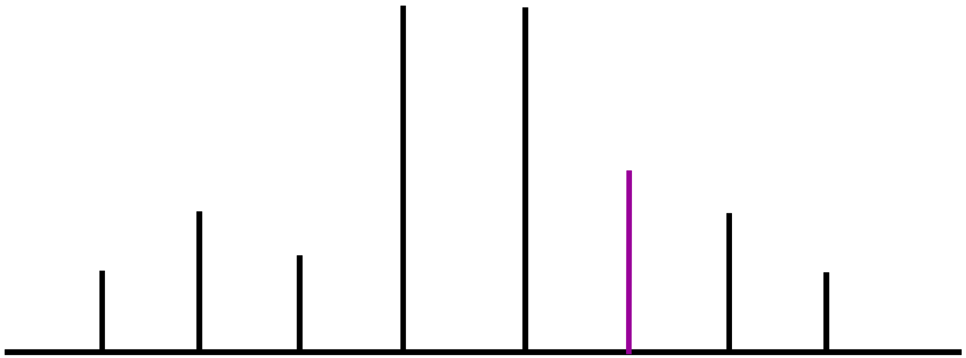


$$C/I\ total = C/\Sigma\sqrt{I3^2 + I5^2 + I7^2 + \ldots}$$

Total C/I preferred to C/I3

C/Imin is a good compromise

IMD TERMS CAN BE NON-SYMMETRICAL

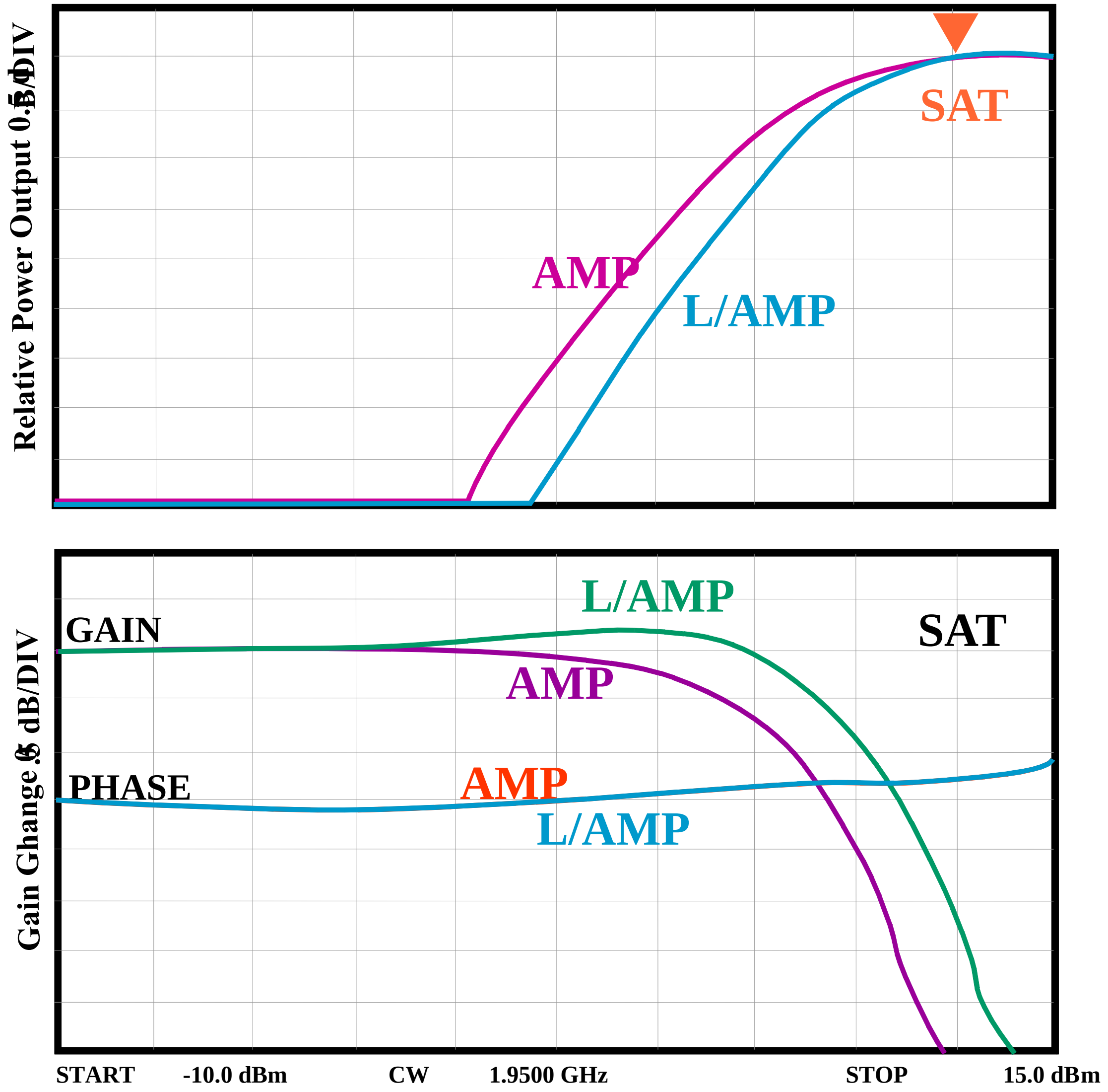


DUE TO *MEMORY EFFECTS* (AM/AM AND AM/PM)

UPPER & LOW ODD ORDER AM/AM TERMS IN PHASE

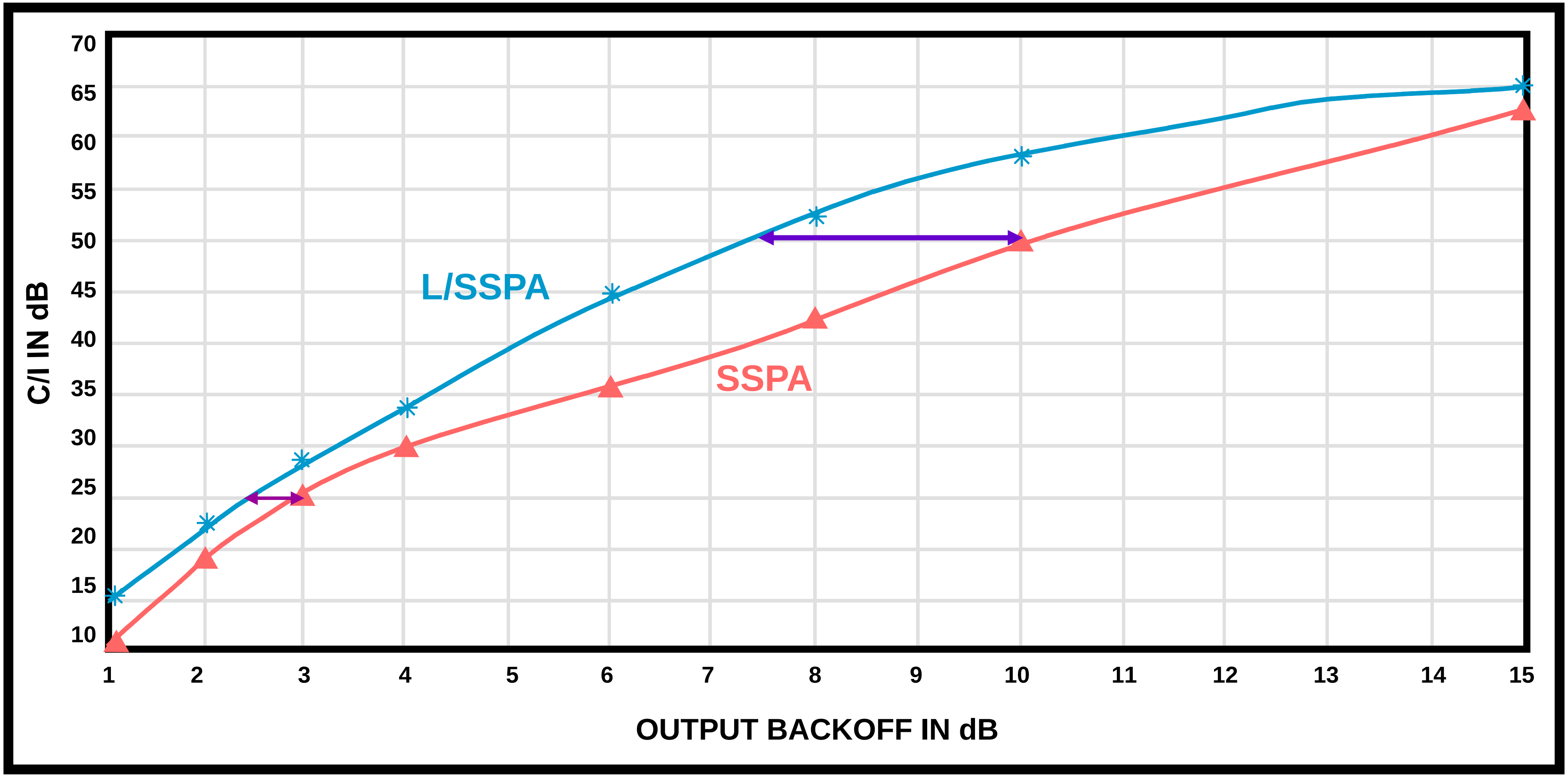
UPPER & LOW ODD ORDER AM/PM TERMS OUT OF PHASE

A LINEARIZER IMPROVES LINEARITY OF A CLASS A SSPA



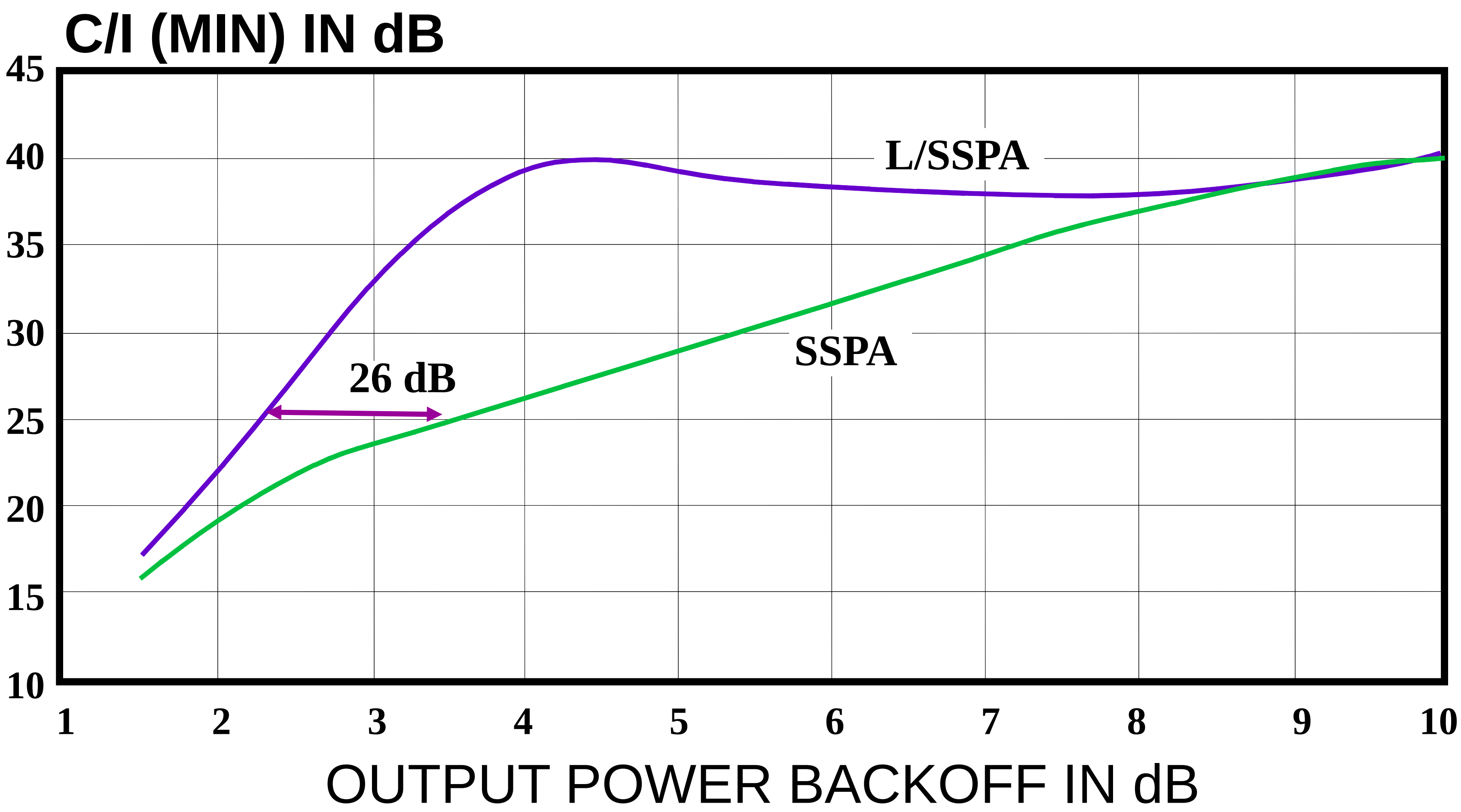
LINEARIZATION OF A CLASS A SSPA PROVIDES ONLY

A 0.5 dB POWER INCREASE FOR A C/I OF 26 dB, BUT A 2.5 dB POWER INCREASE FOR A C/I OF 50 dB

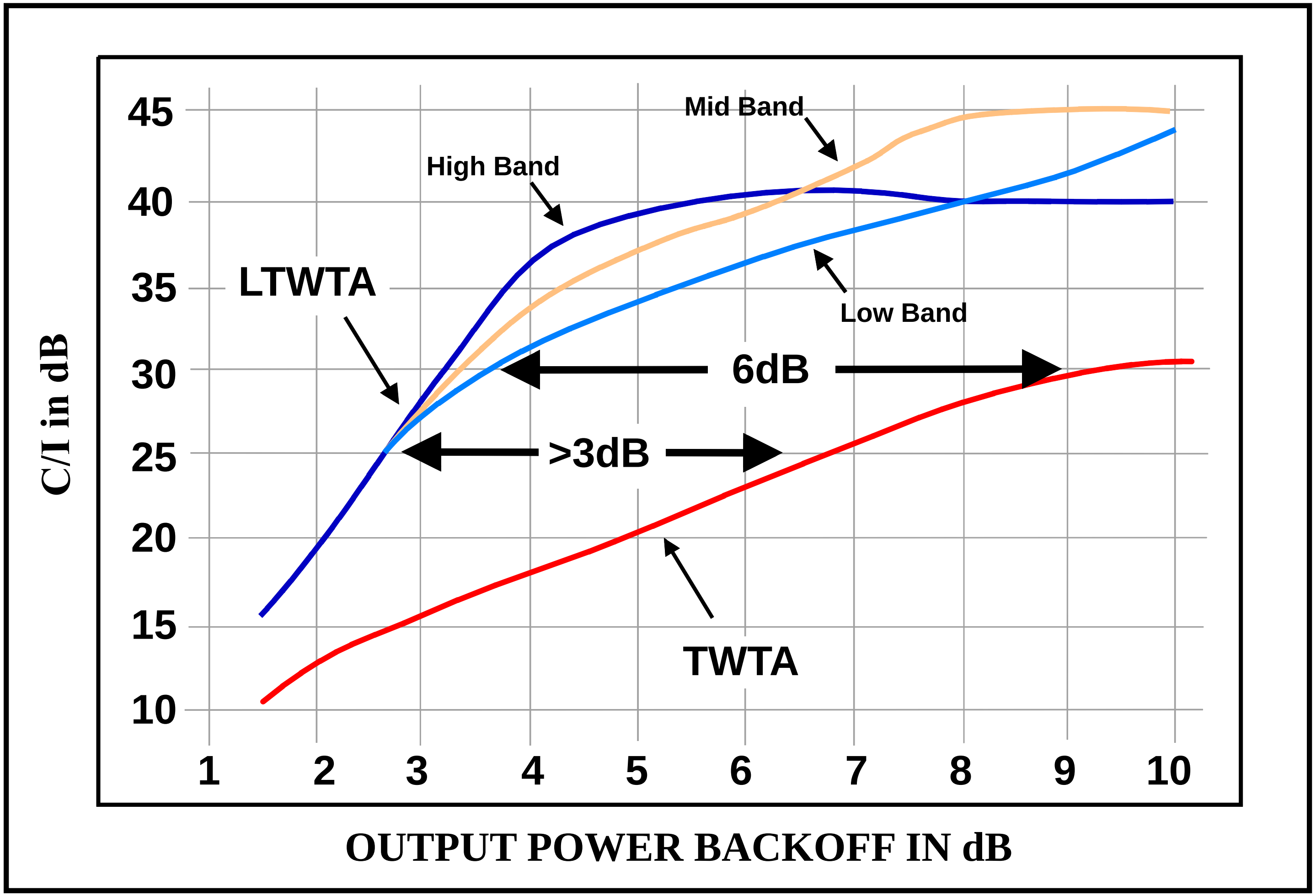


LINEARIZATION OF LESS LINEAR CLASS AB SSPA

PROVIDES > 1.5 dB POWER INCREASE FOR C/I OF 26 dB.



WITH A TWTA A C/I = 26 dB CAN OBTAIN > 3 dB POWER INCREASE



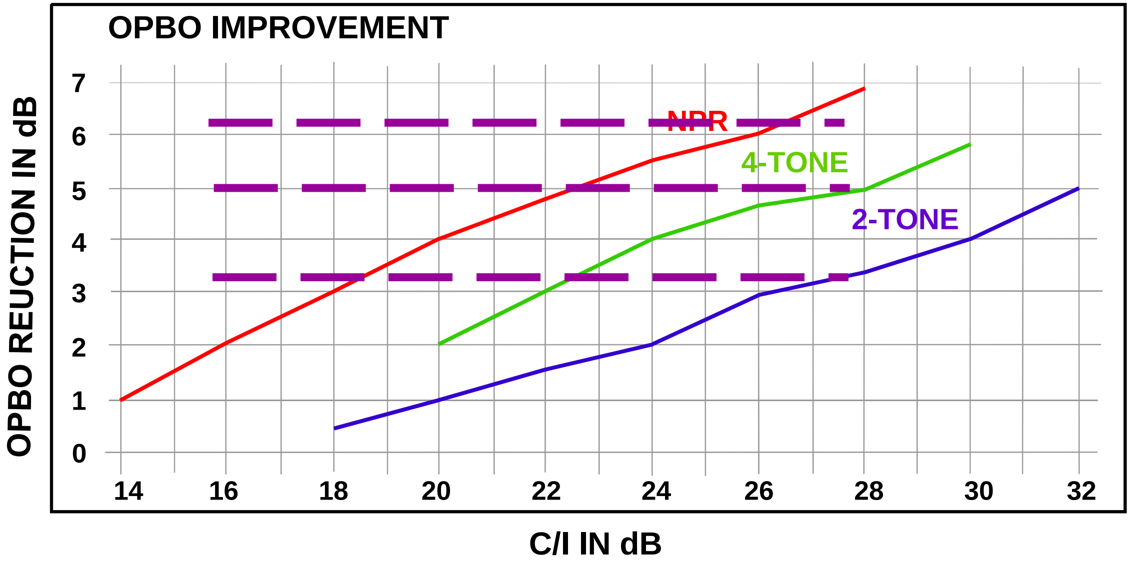
WITH MULTIPLE CARRIERS THE IMPROVEMENT IS EVEN GREATER!

MULTIPLE CARRIERS (N>2)

- EXERCISE OVER RANGE   Ppk = 2NPav

- NO SIMPLE RELATIONSHIP BETWEEN C/I FOR 2 AND N CARRIER CASE

- GREATER IMPROVEMENT
(REDUCTION IN OPBO) FOR A GIVEN C/I AS N INCREASES

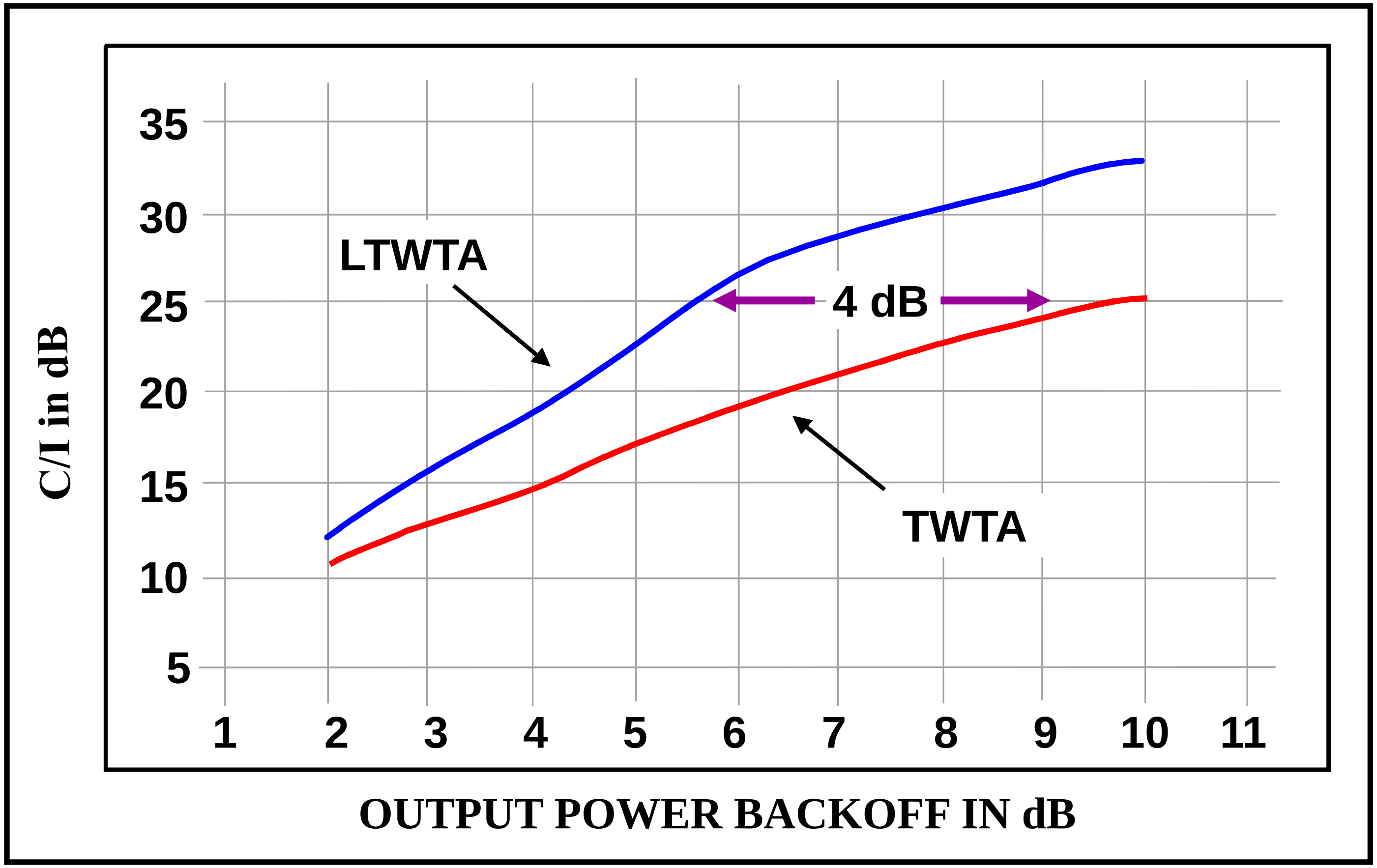


NPR - NOISE POWER RATIO

MEASURE OF N-CARRIER C/I

WANT DEPTH OF GENERATOR NOTCH > 10 dB BELOW NPR OF INTEREST

NPR PREDICTS AMPLIFIER PERFORMANCE WITH MANY CARRIERS

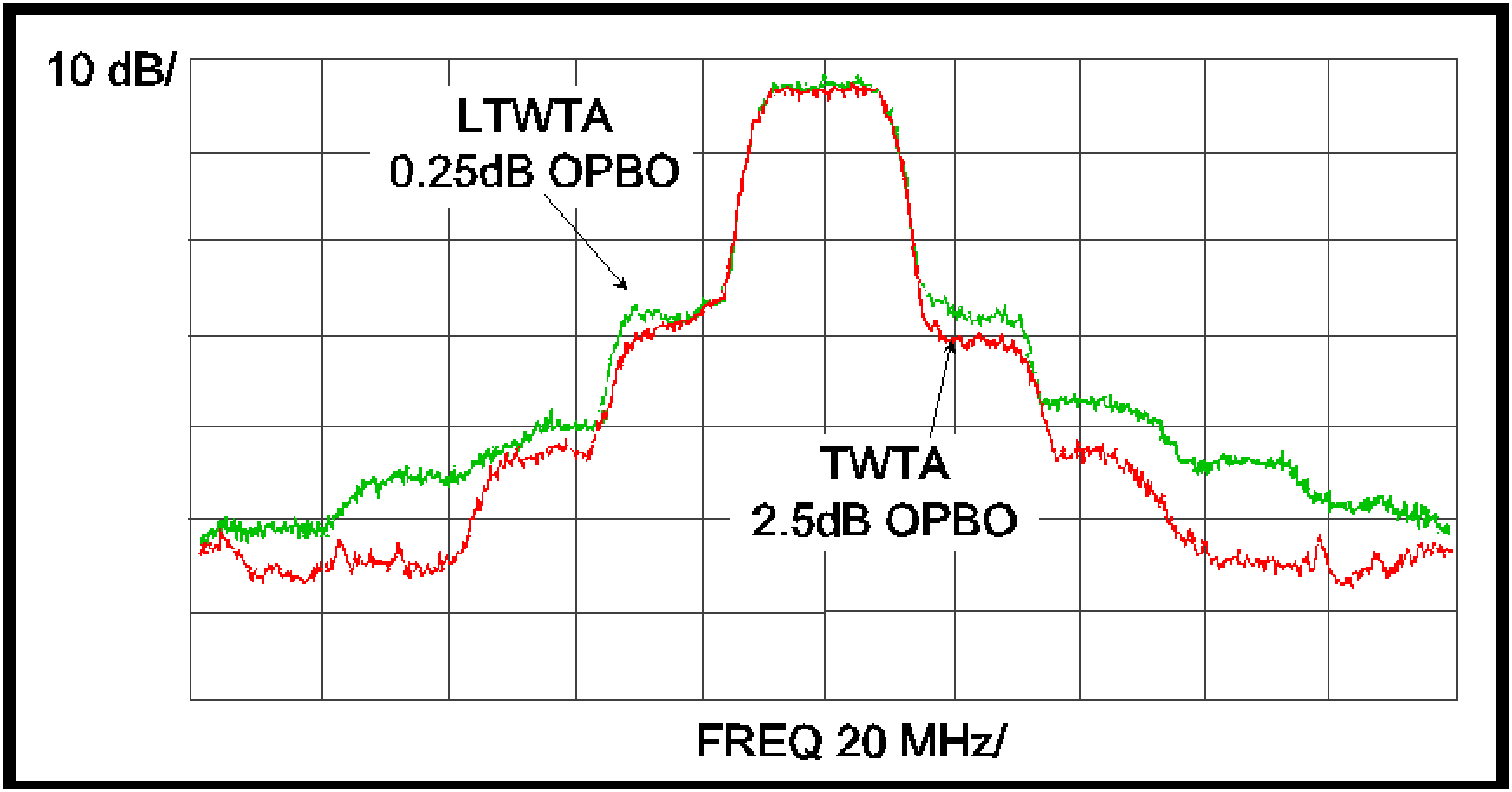


FOR C/I = 25 dB OBTAIN ALMOST 6 dB INCREASE IN POWER.

NPR OF CLASS AB SSPA

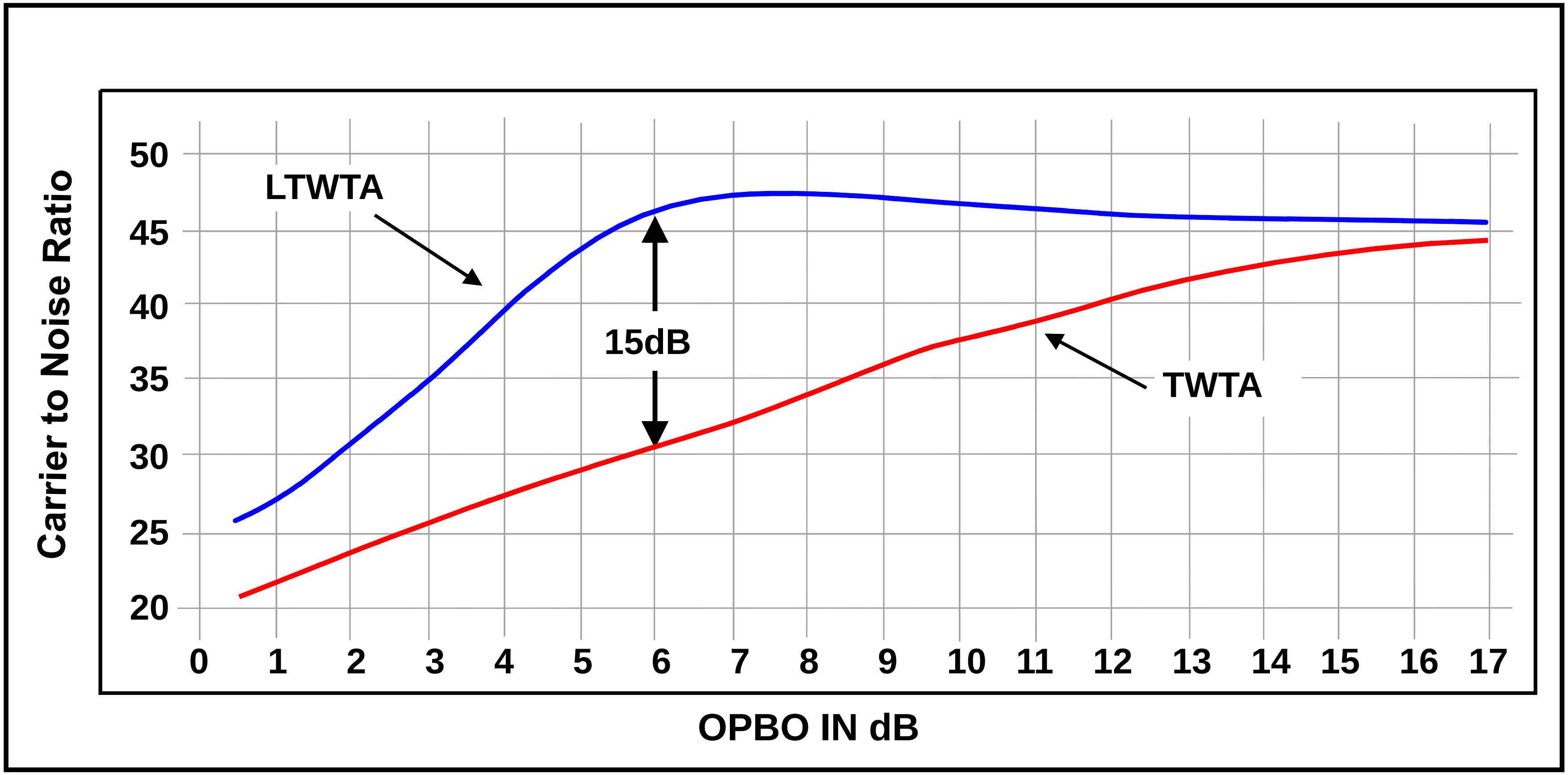
PROVIDES SIGNIFICANT REDUCTION IN SPECTRUM

EVEN NEAR SAT



> 2 dB POWER INCREASE

REDUCTION IN SPECTRAL REGROWTH PROVIDED BY LINEARIZATION OF A TWTA



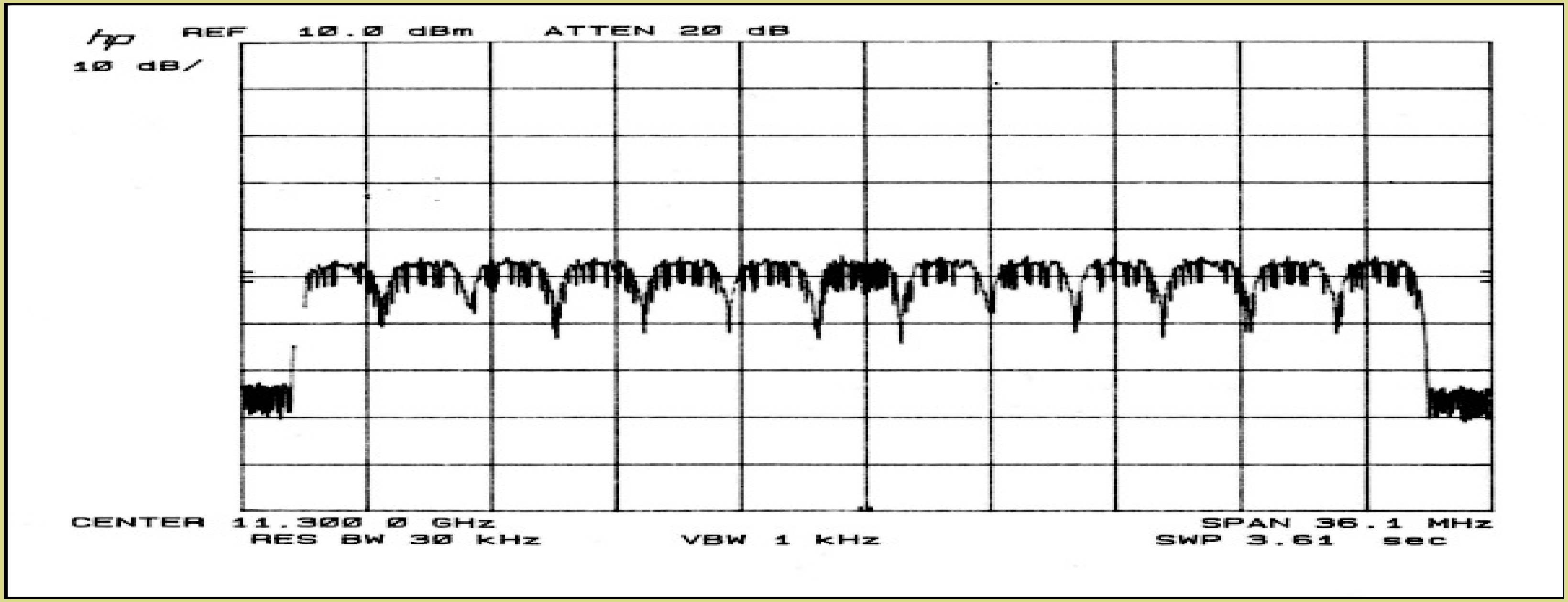
ETSI STANDARDS

- THE EUROPEAN TELECOMMUNICATIONS STANDARDS INSITUTE (ETSI) HAS PRODUCED STANDARDS FOR THE TRANSMISSION OF MPEG-2 TRANSPORT STREAMS OVER SATELLITES USING BEM.
  - QPSK (EN 300 421)
  - 8PSK and 16QAM (EN 301 210).
- PROVIDES A MECHANISM FOR ENCAPSULATING INTERNET PROTOCOL (IP) DATAGRAMS WITHIN A DIGITAL VIDEO BROADCAST (DVB) WAVEFORM (EN 301 192).
- PROVIDES AN OPEN FRAMEWORK FOR DELIVERING INTERNET SERVICES OVER SATELLITE.

THE COLLEGE OF NEW JERSEY

MULTI-CARRIER QAM

- A TYPICAL DVB QAM SIGNAL REQUIRES ABOUT 2 MHz OF BW.



- A STANDARD 36 MHz SATELLITE TRANSPONDER CAN ACCOMMODATE AT LEAST 12 16QAM FDM SIGNALS.

- THIS FORMAT GREATLY INCREASES THROUGHPUT AND REVENUE AND IS IDEAL FOR INTERNET VIA SATELLITE.

MULTI-CARRIER QAM

- IMD IS THE MAJOR PROBLEM. IT LIMITS THE BIT ERROR RATE (BER) OF DIGITAL SIGNAL.

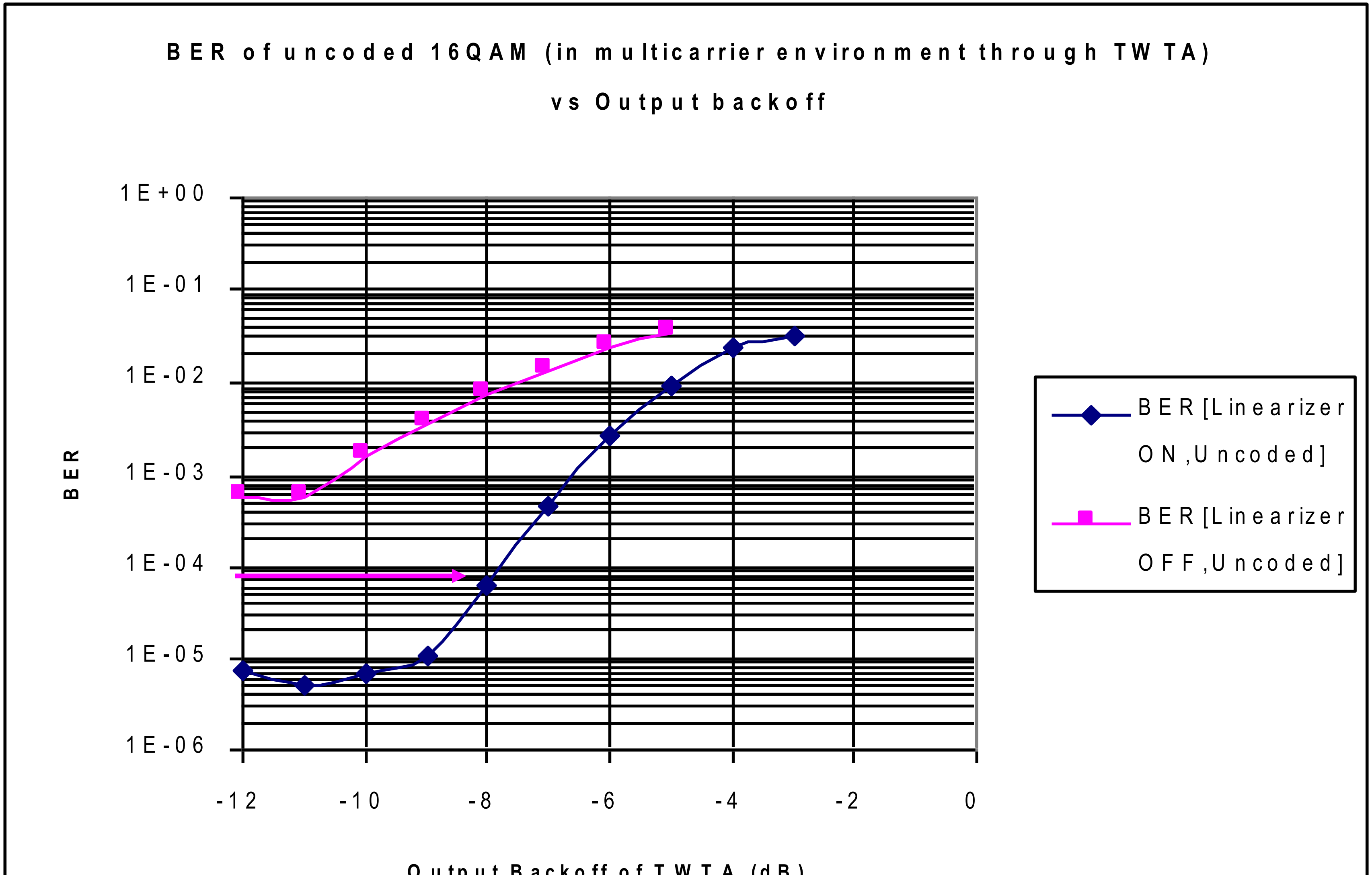
- CODING USED TO INCREASE BER FOR A SMALL SACRIFIC IN BW EFFICIENCY.

- NO DATA AVAILABLE ON THE AFFECT OF DISTORTION ON MULTI-CARRIER QAM WITH OR WITHOUT CODING.

- A HARDWARE TEST PLATFORM WAS SET UP TO INVESTIGATE THE PERFORMANCE OF CODED FDM QAM THROUGH A LINEARIZED TWTA.

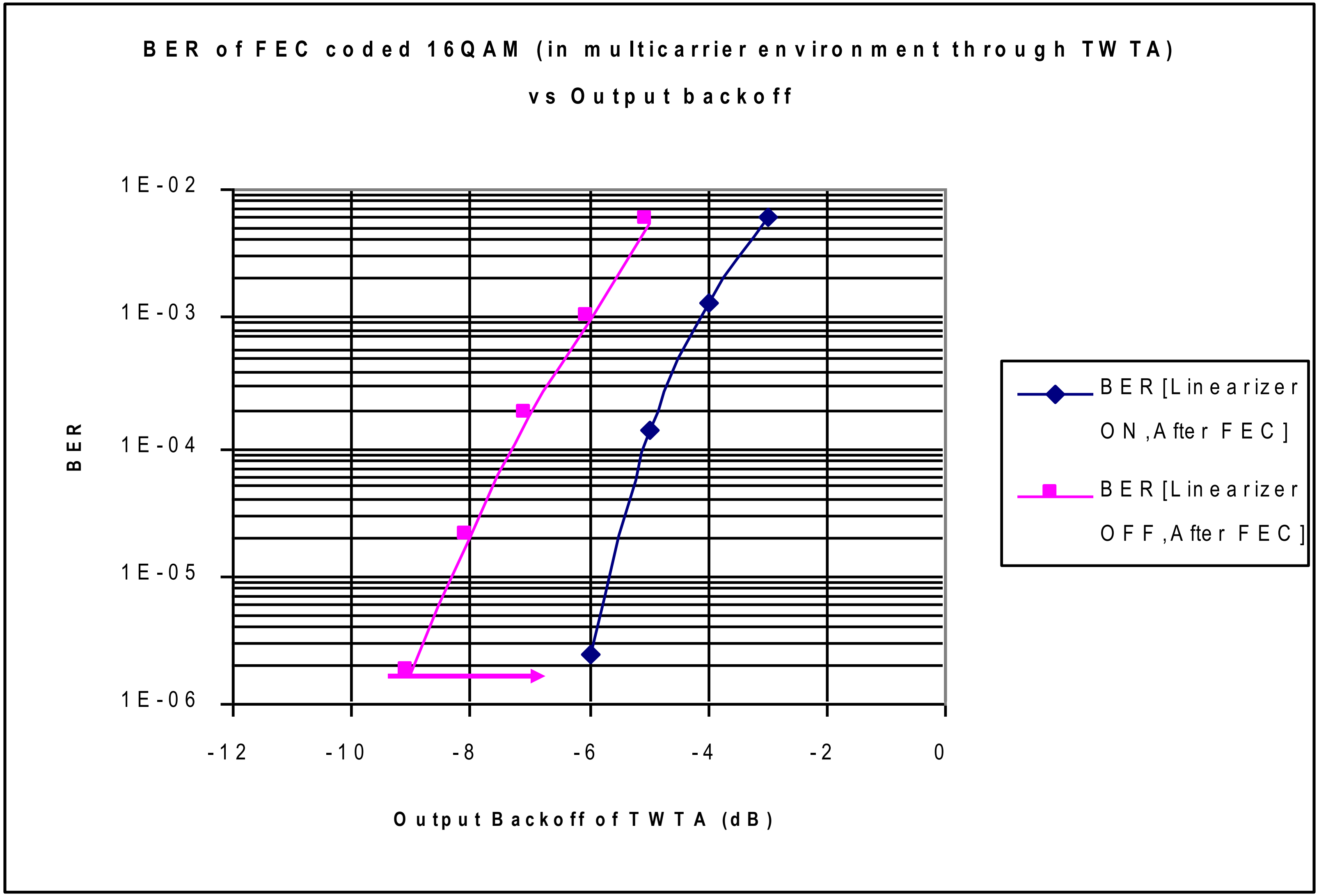
BER OF UNCODED DATA

QEF CAN NOT BE ACHIEVED



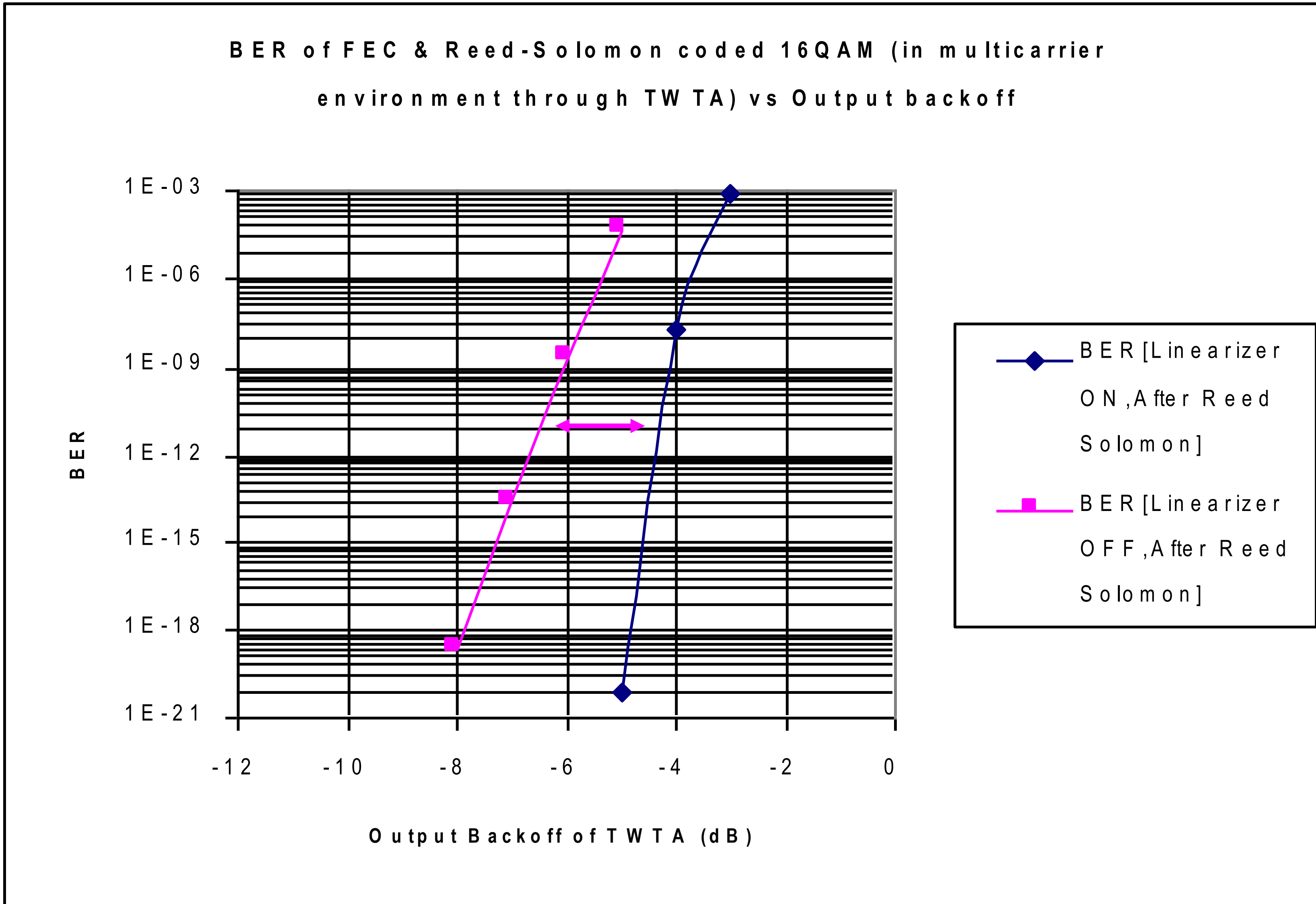
LINEARIZER PROVIDES A HUGH ADVANTAGE

BER OF 3/4 CONVOLUTIONAL FEC DATA
QEF STILL CAN NOT BE ACHIEVED



LINEARIZER PROVIDES ~ 3 dB ADVANTAGE

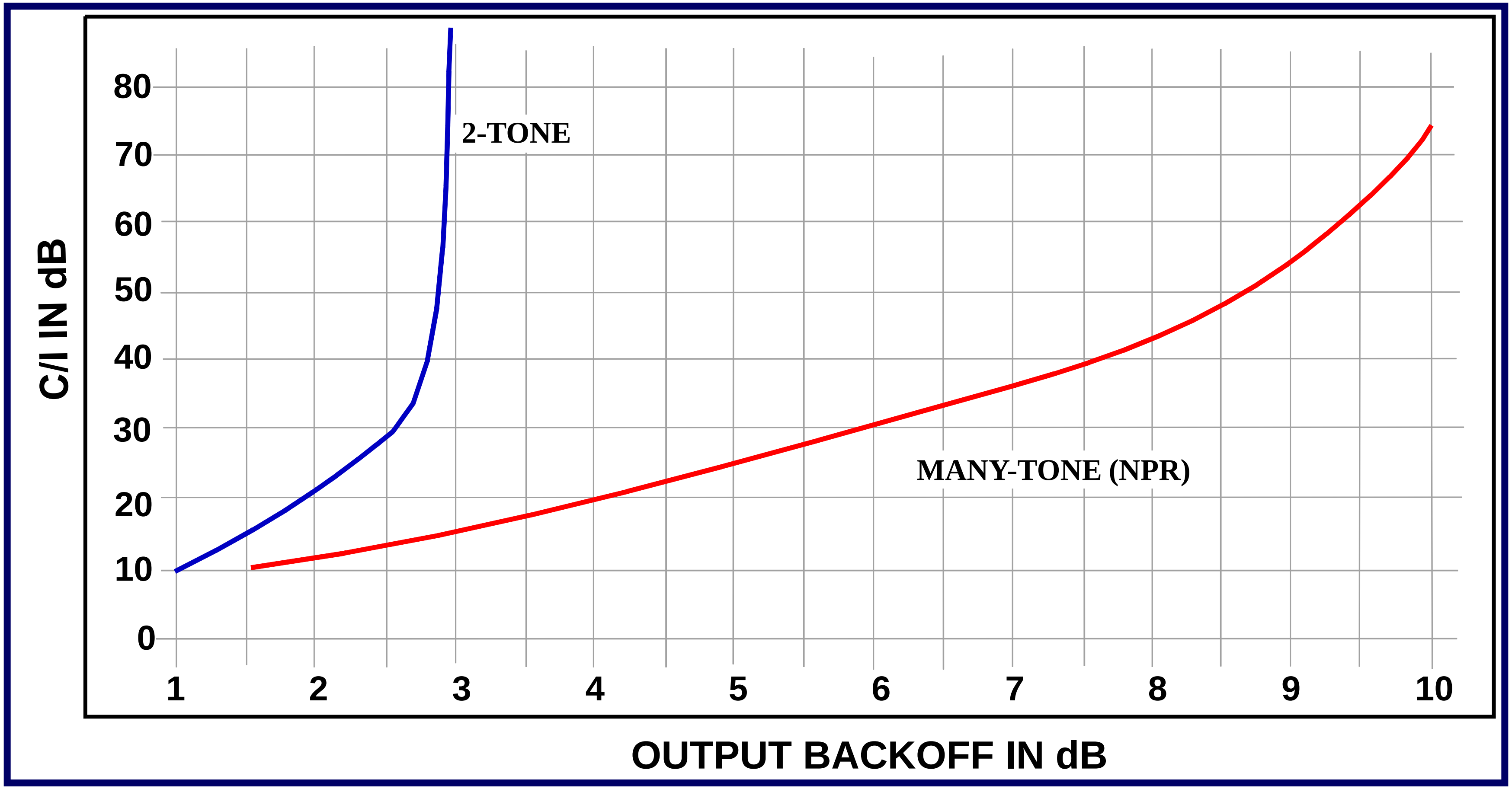
BER OF FEC/REED-SOLOMON CODED DATA



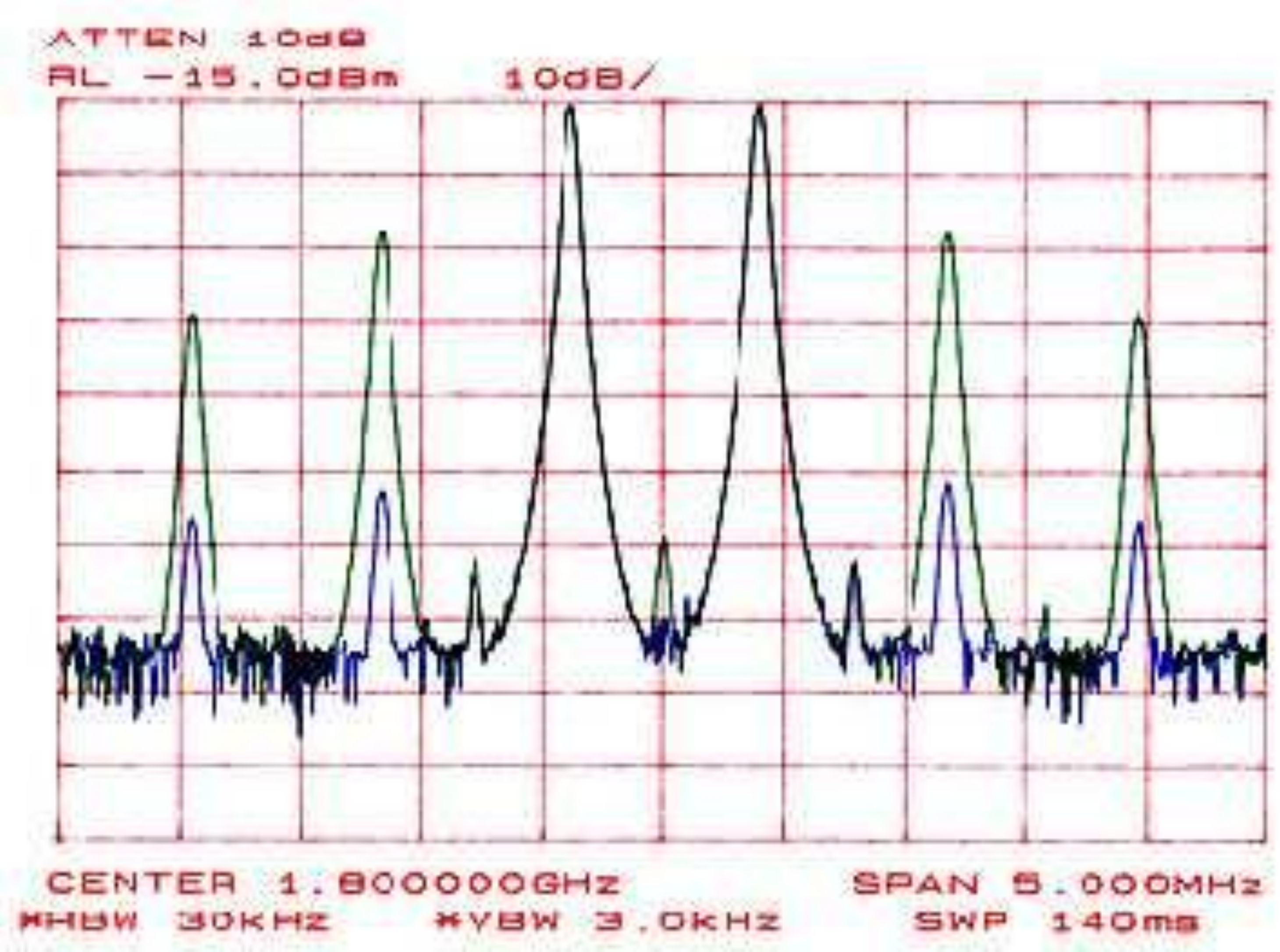
LINEARIZER PROVIDES > 2 dB ADVANTAGE AT QEF

IDEAL LINEARIZER PERFORMANCE IS LIMITED BY SIGNAL PEAK-TO-AVERAGE CHARACTERISTICS (PAC)

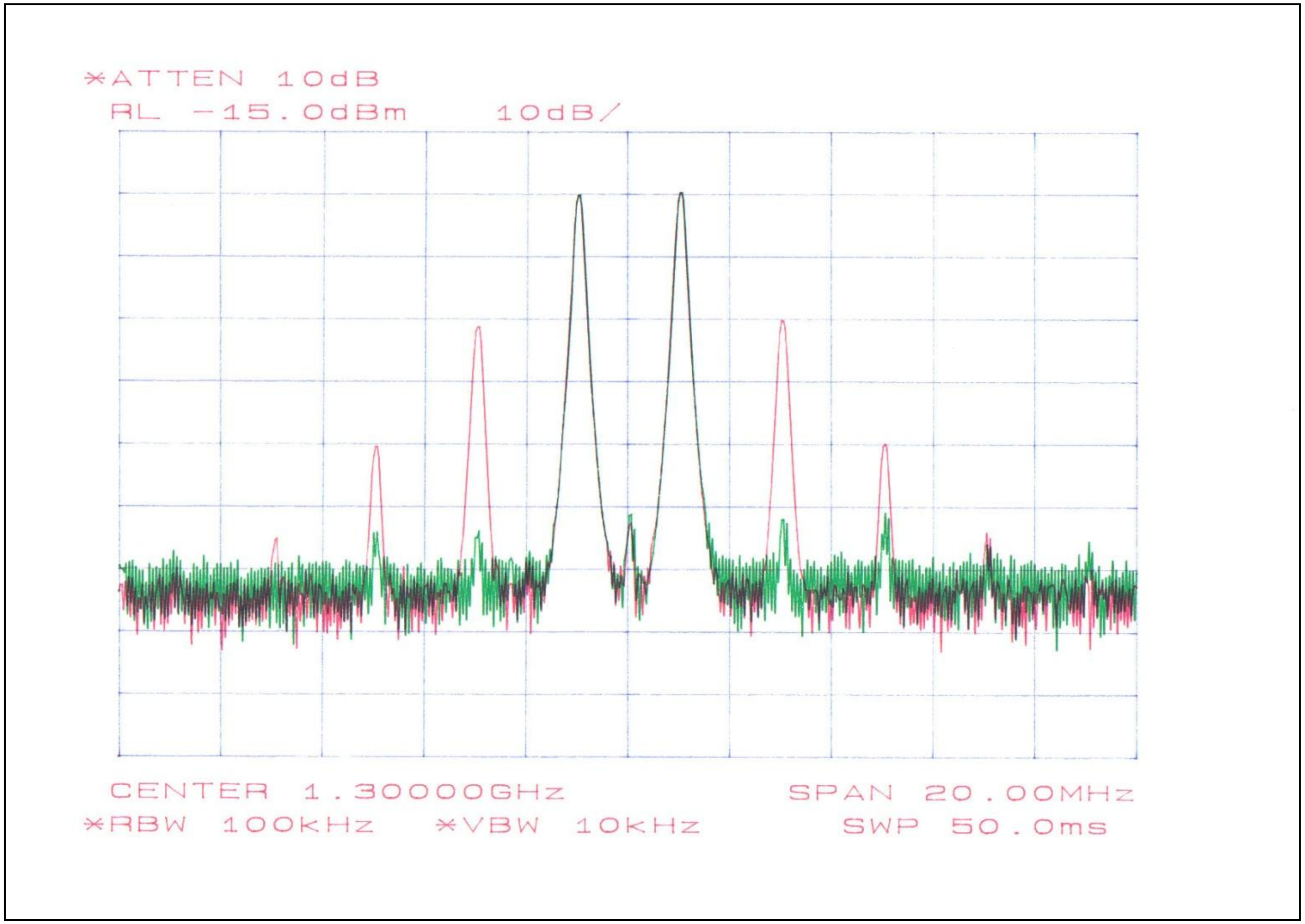
PAC SETS MINIMUM BACKOFF OF PA!
CANNOT IMPROVE BY LINEARIZATION.
MUST USE PA WITH HIGHER POWER/EFFICIENCY



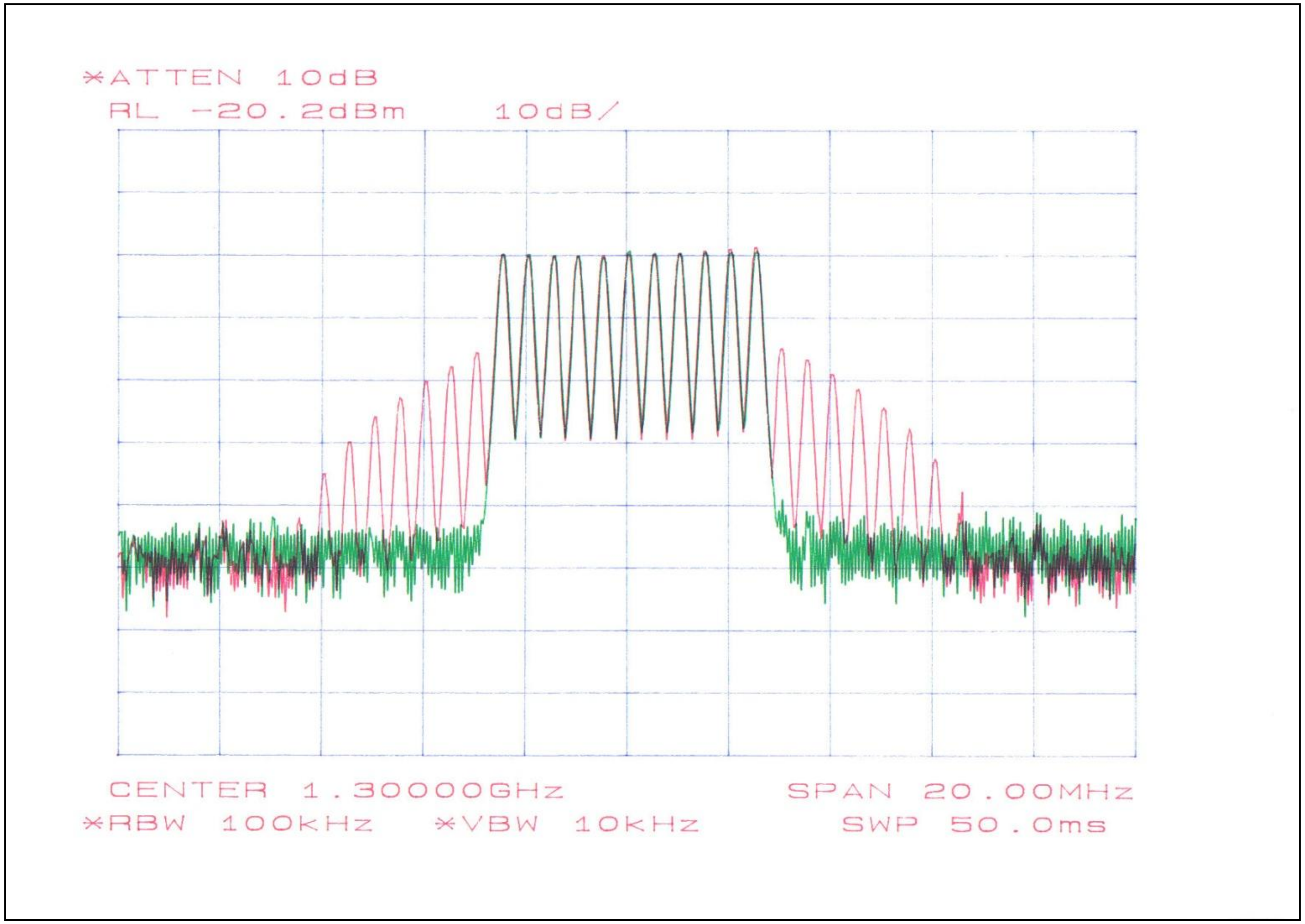
DSP L/TWTA AT 3 dB OPBO – C/I > 50 dB



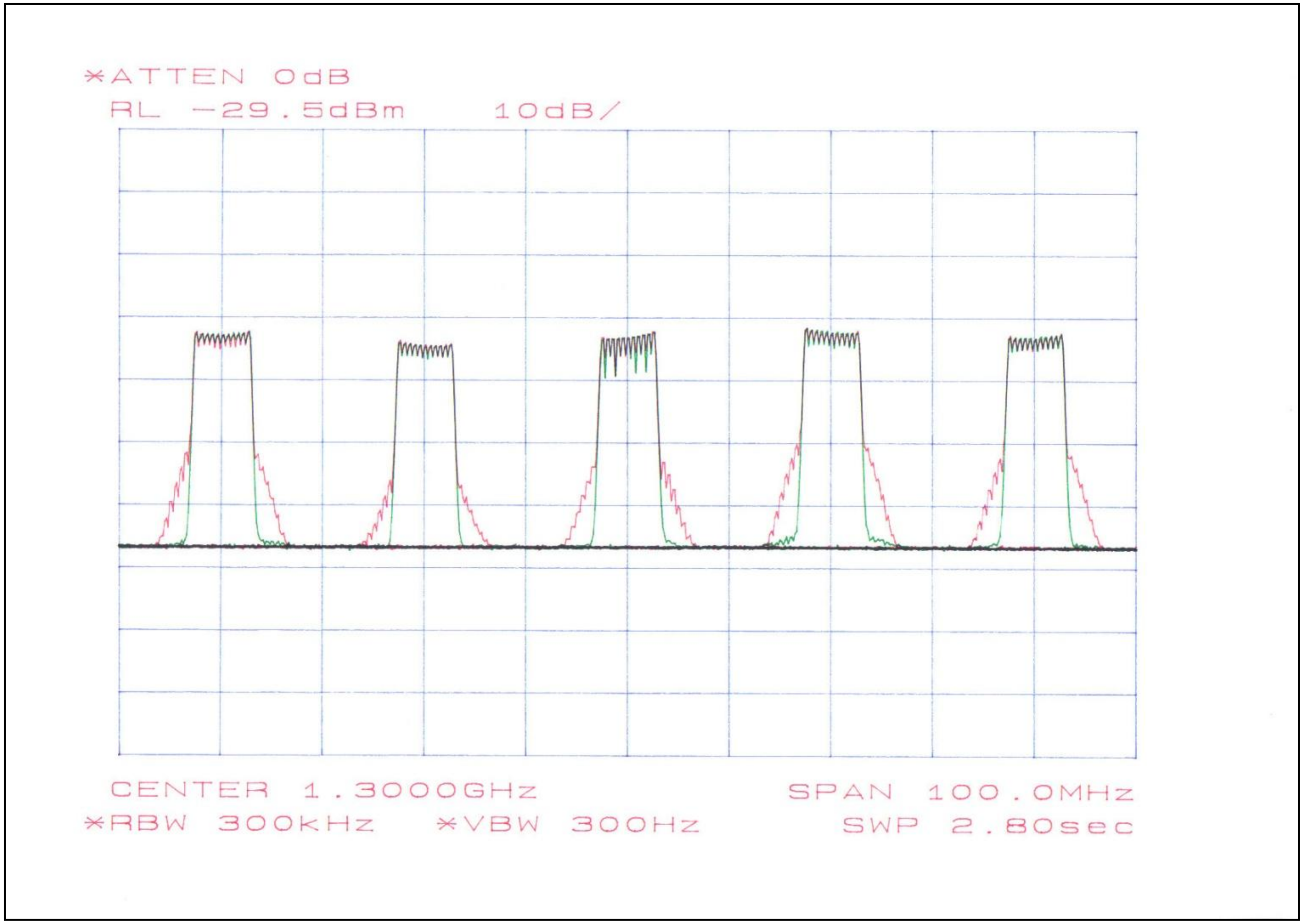
IMD CANCELLATION> 30 dB



MULTI-TONE

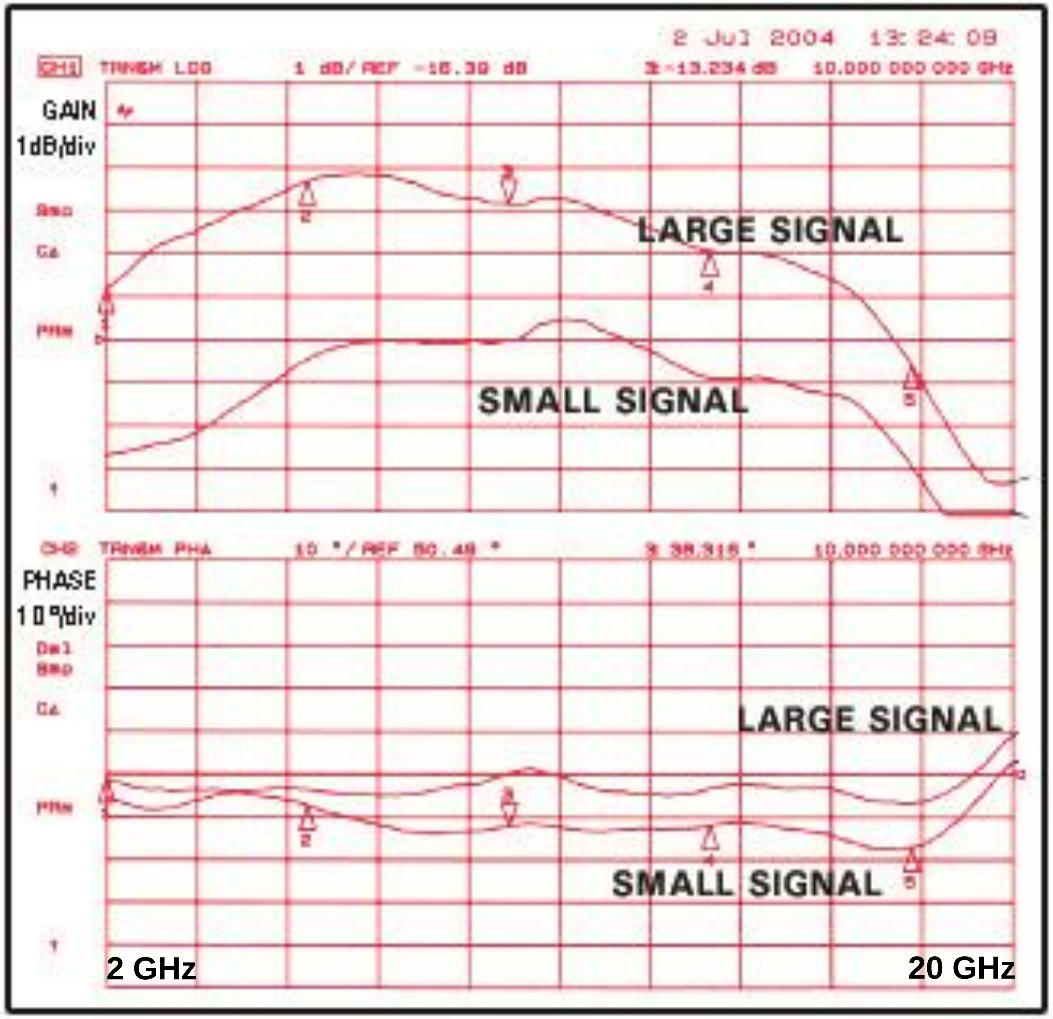

*ATTEN 10dB
RL -20.2dBm 10dB/
CENTER 1.30000GHz SPAN 20.00MHz
*RBW 100kHz *VBW 10kHz SWP 50.0ms

WIDE BAND (100 MHz)



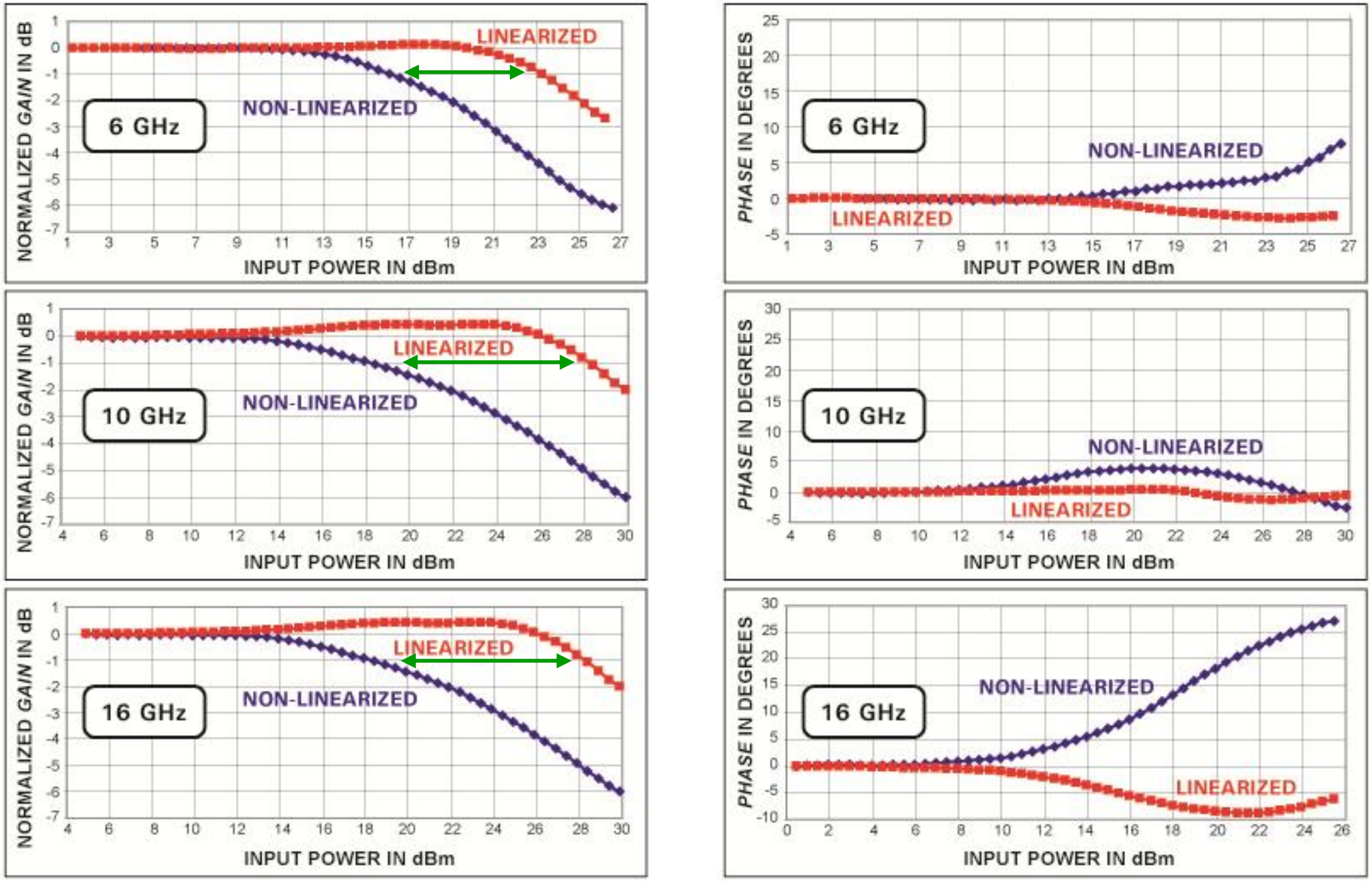
Digital linearization across 100 MHz using filters to correct for frequency memory effects

ANALOG PREDISTORTION CAN PROVIDE A VERY BROAD FREQUENCY RESPONSE



- USEFULL LINEARIZER CHARACTERISTICS < 2 GHz TO > 20 GHz.
- ~3 dB GAIN INCREASE FROM 6 TO 16 GHz.
- DECREASING PHASE CHANGE OF 5° TO 10°

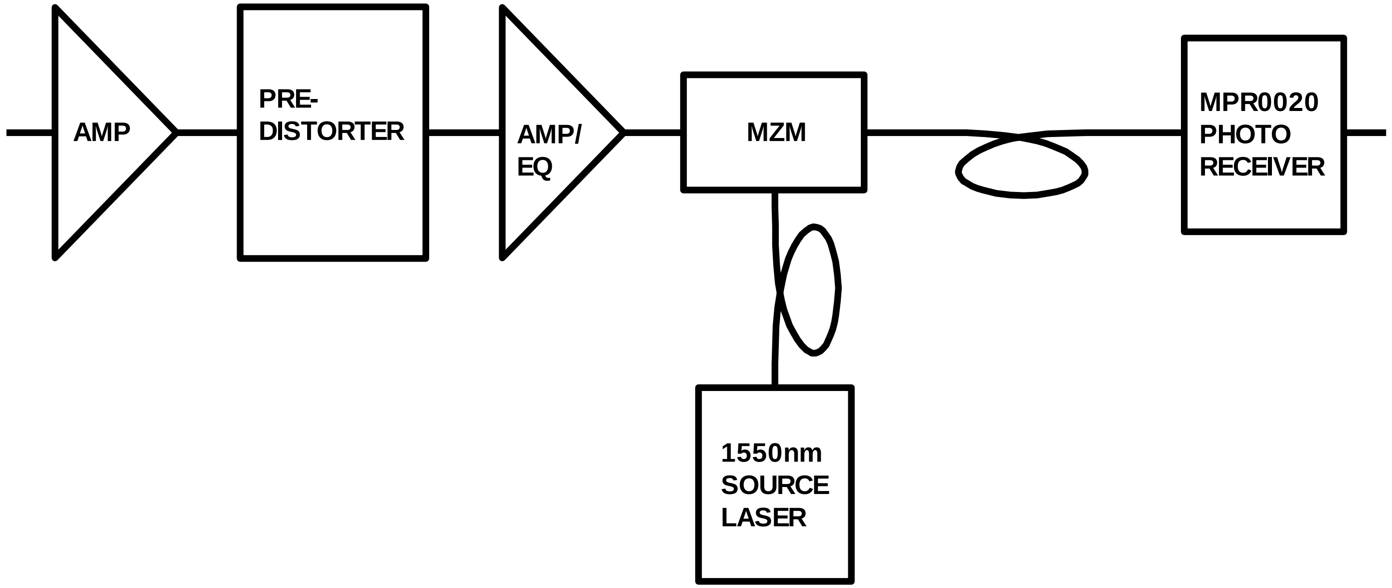
LINEARIZER'S PERFORMANCE WITH GaN PA



1 dB CP IS MOVED > 6 dB CLOSER TO SAT FROM 6 TO 16 GHz

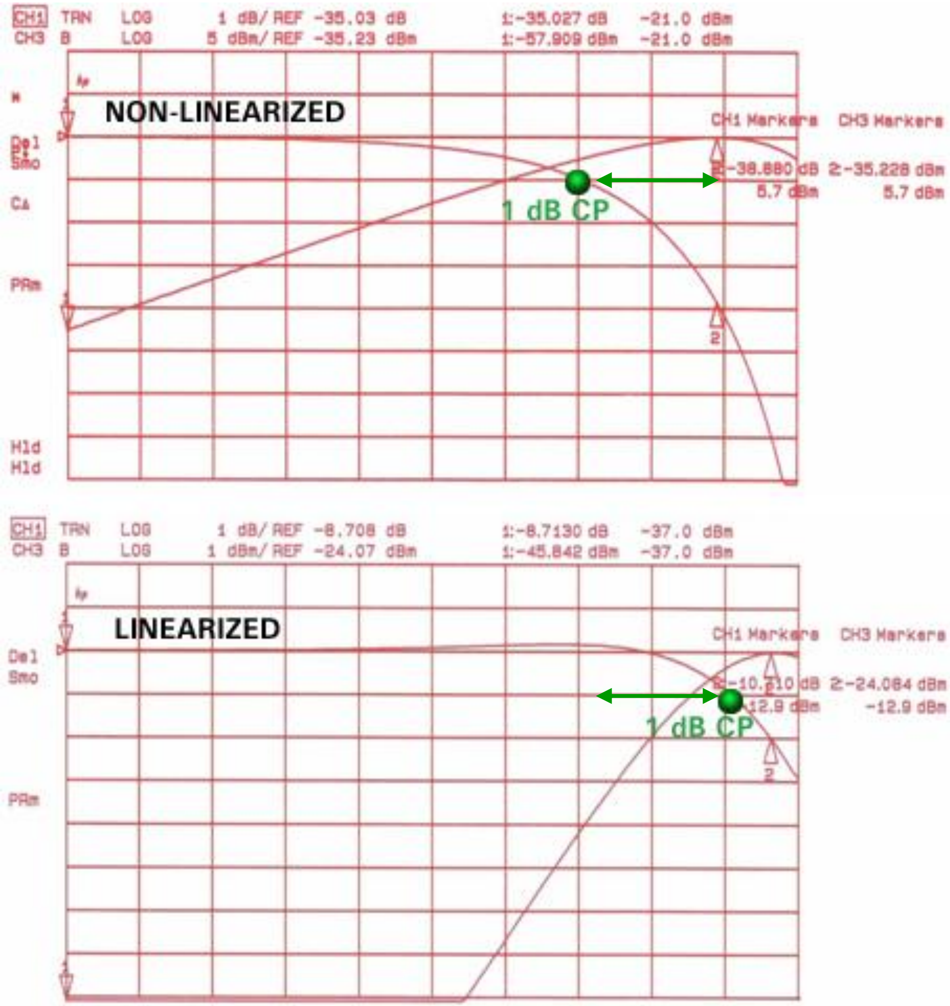
PHASE SHIFT IS REDUCED FROM > 30° TO < 10 ° OVER THIS BAND

LINEARIZER PERFORMANCE WITH PHOTONIC LINK



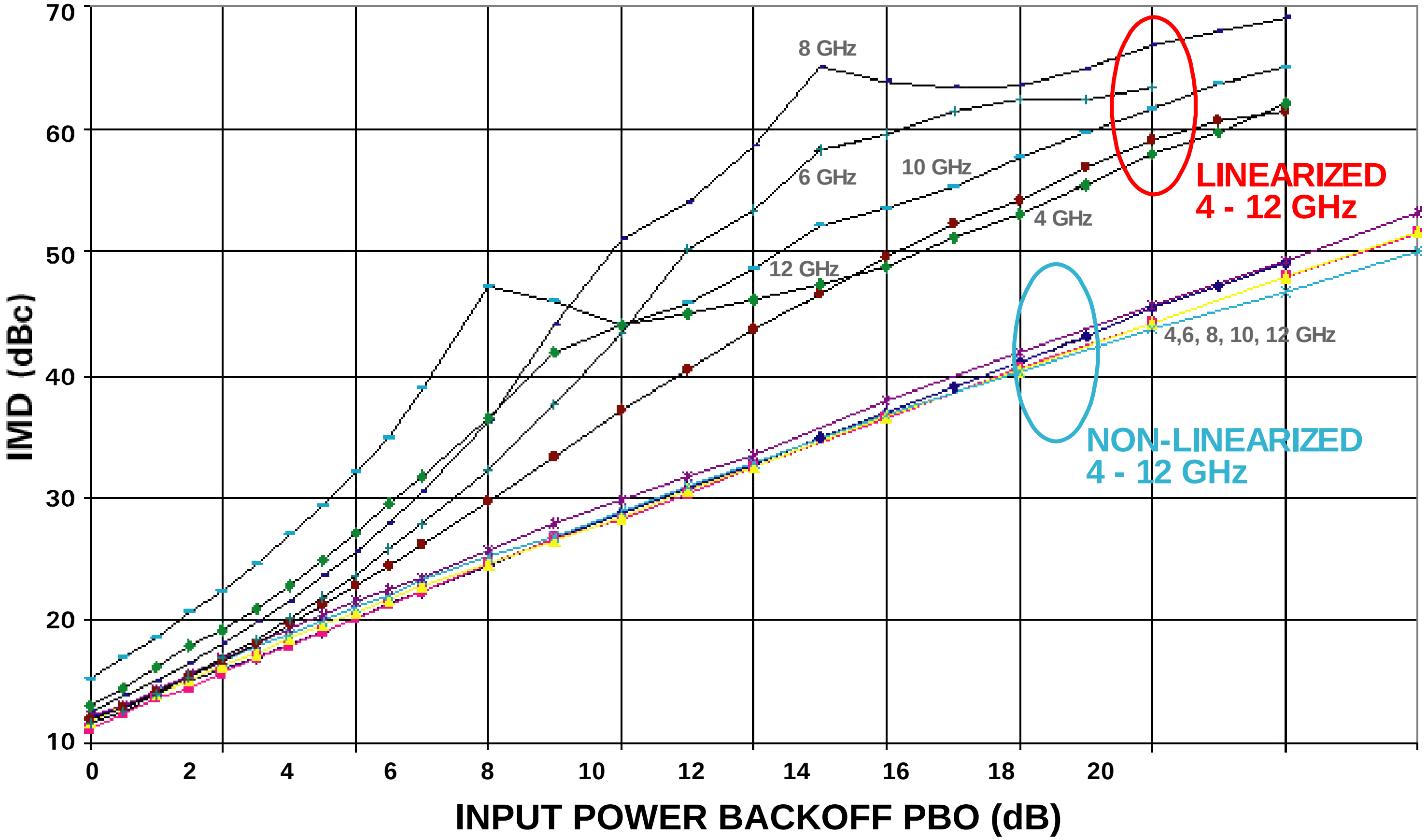
- NON-LINEAR CHARACTERISTICS OF THE MODULATORS USED FOR THE TRANSMISSION OF SIGNALS OVER FIBER OPTIC LINKS ARE SIMILAR TO CHARACTERISTICS OF PAs
- WIDEBAND GaN LINEARIZER WAS TESTED WITH A MACH ZEHNDER MODULATOR (MZM) FIBER OPTIC LINK OVER 4 TO 12 GHz BAND
- FOR MZM LINKS, LITTLE OR NO NONLINEAR PHASE CHANGE IS PRODUCED AND THE LINEARIZER WAS THUS BIASED FOR MINIMUM PHASE CORRECTION

GAIN TRANSFER RESPONSE OF MZM LINK AT 8 GHz WITH AND WITHOUT LINEARIZATION



- MZM HAS FREQUENCY INDEPENDENT NON-LINEAR CHARACTERISTICS
- THE LINEARIZER MOVES THE 1 dB CP 5 dB CLOSER TO SATURATION
- SIMILAR RESULTS WERE ACHIEVED FROM 4 TO 12 GHz
- WITH NO SIGNIFICANT DEGRADATION OF THE LINK’S NEAR ZERO PHASE SHIFT

2-TONE C/I OF NONLINEARIZED AND LINEARIZED LINK



BIG IMPROVEMENT IN C/I AT ALL LEVELS EXCEPT NEAR SAT

> 10 dB OVER MUCH OF THE RANGE WITH A PEAK OF > 30 dB

IMD, IIP3 AND SFDR IMPROVEMENTS OF LINEARIZED LINK

Frequency (GHz)	IMD Improvement (dB)	IIP3 Improvement (dBm)	SFDR3 Improvement ($dB \cdot Hz^{2/3}$)
4	13.3	6.65	4.43
6	20.0	10.0	6.67
8	23.6	11.8	7.87
10	17.9	8.95	5.97
12	12.3	6.15	4.10

SIGNIFICANT IMPROVEMENT IN LINEARITY PROVIDED OVER 1.5 OCTAVE FREQUENCY RANGE

SFDR INCREASED BY > 4 dB OVER THIS RANGE

MEMORY EFFECTS (ME)

- SOURCES OF ME

  - Frequency ME
  - Drain/collector ME
  - Gate/base ME
  - Device related ME
  - Thermal ME

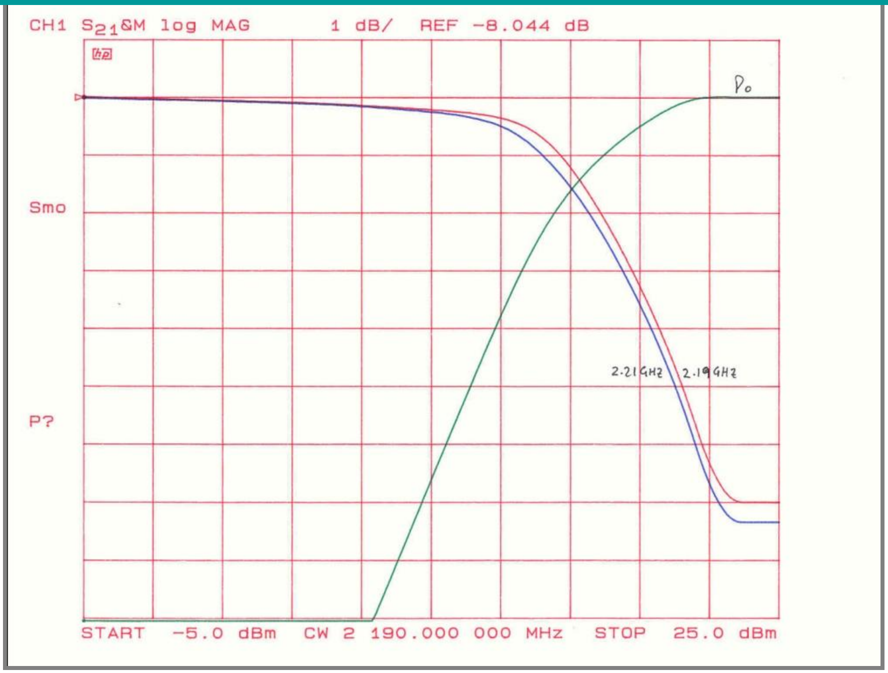
MEMORY EFFECTS

- Memory Effects are changes in a Power Amplifier's (PA) non-linear characteristics resulting from the past history of the input signal.

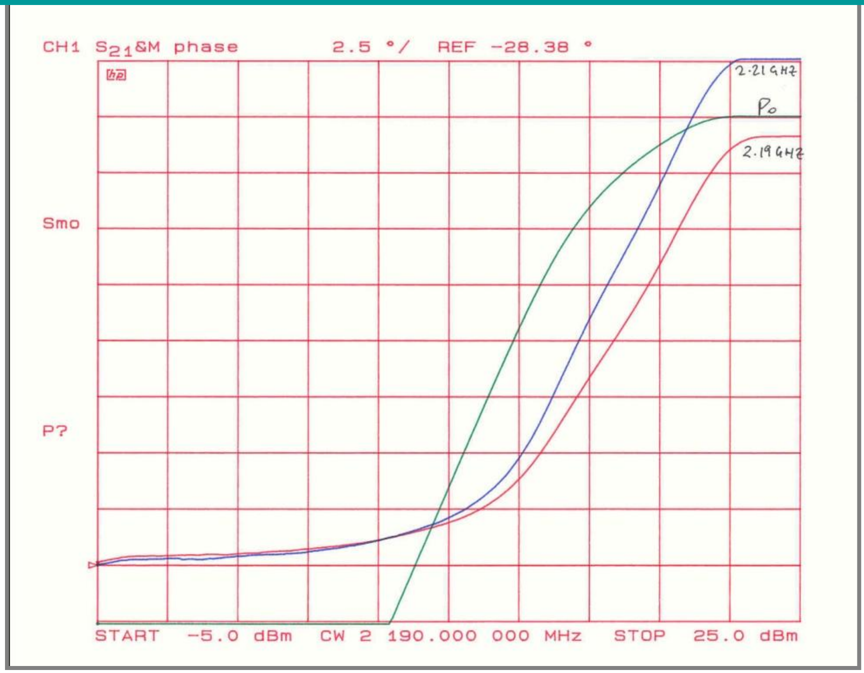
Vo = f(Vin, time)

- Primary cause drain/collector and gate/base bias change.
- Thermal, device and frequency are also factors.
- Standard predistortion linearizers depend on a stable non-linear response, and can be particularly degraded by memory effects.

FREQUENCY MEMORY EFFECTS



GAIN VS. INPUT POWER IS AFFECTED BY FREQUENCY



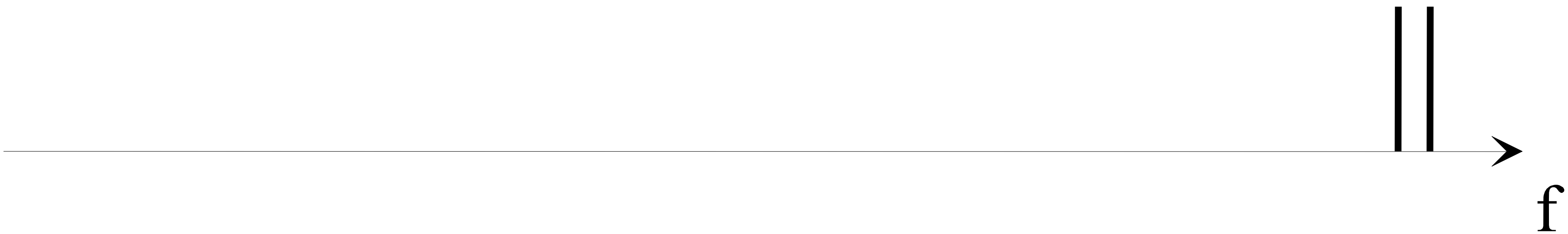
PHASE VS. INPUT POWER IS AFFECTED BY FREQUENCY

- Standard predistorter look-up tables have the same correction for every frequency
- Real PA non-linearities do change with frequency

TWO KINDS OF BANDWIDTH

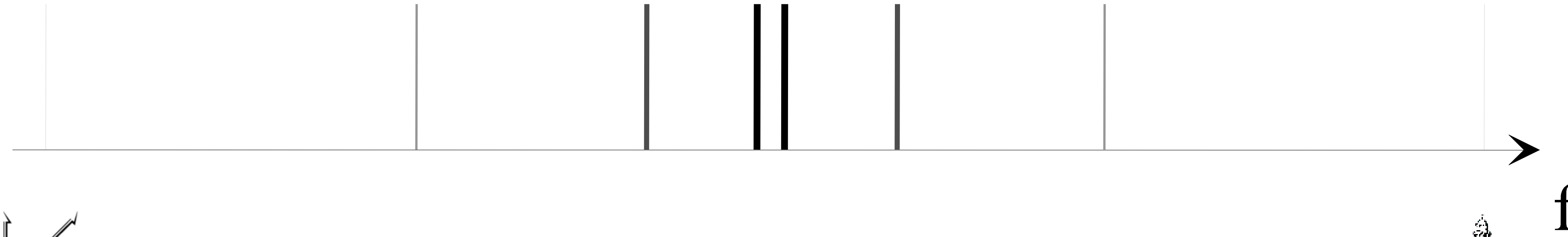
1) STATIC BANDWIDTH - ABILITY OF LIN MAG/PHASE TRANSFER RESP TO EQUALIZE AMP AT ALL FREQ OF INTEREST

- MEAS WITH 2 CLOSE SPACED TONES AT ALL FREQ OF INTEREST



2) DYNAMIC BANDWIDTH - ABILITY OF LIN MAG/PHASE TRANSFER RESP TO FOLLOW ENVELOPE OF SIGNALS

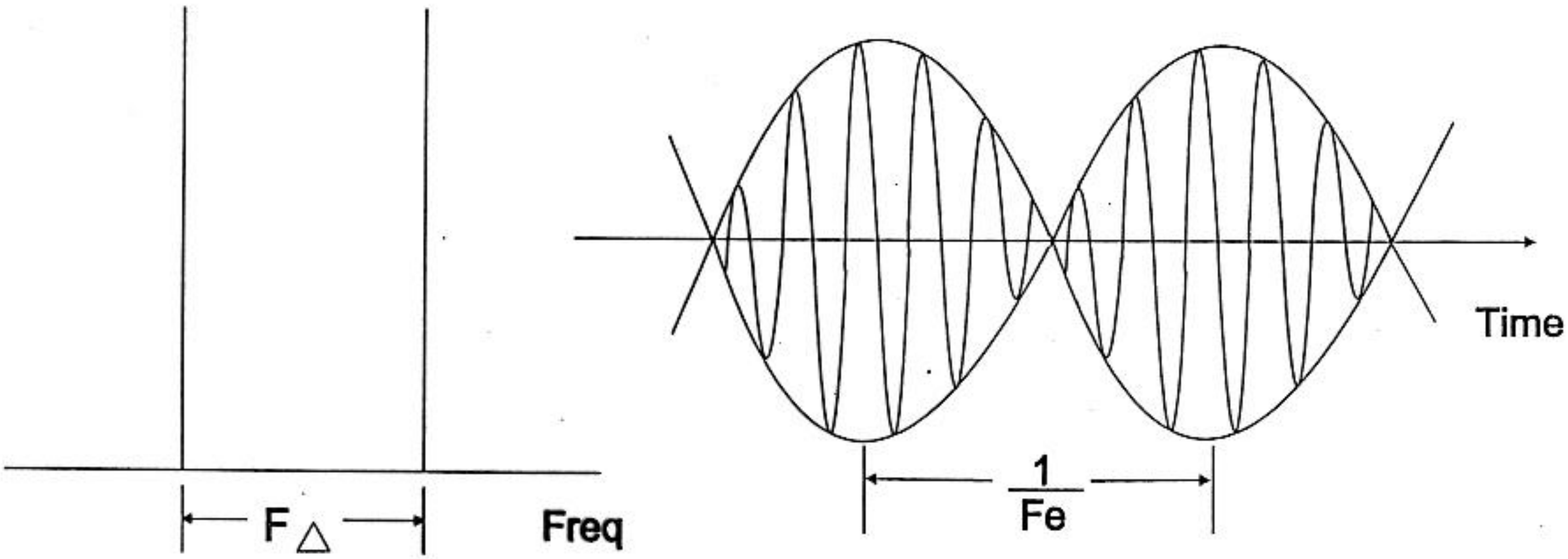
- MEAS WITH 2-TONE SIGNAL IN WHICH THE SPACING OF THE TONES IS INCREASED



THE LINEARITY OF AMPLIFIERS DEGRADE WITH INCREASING CARRIER SPACING

MAJOR CAUSE OF DEGRADATION --

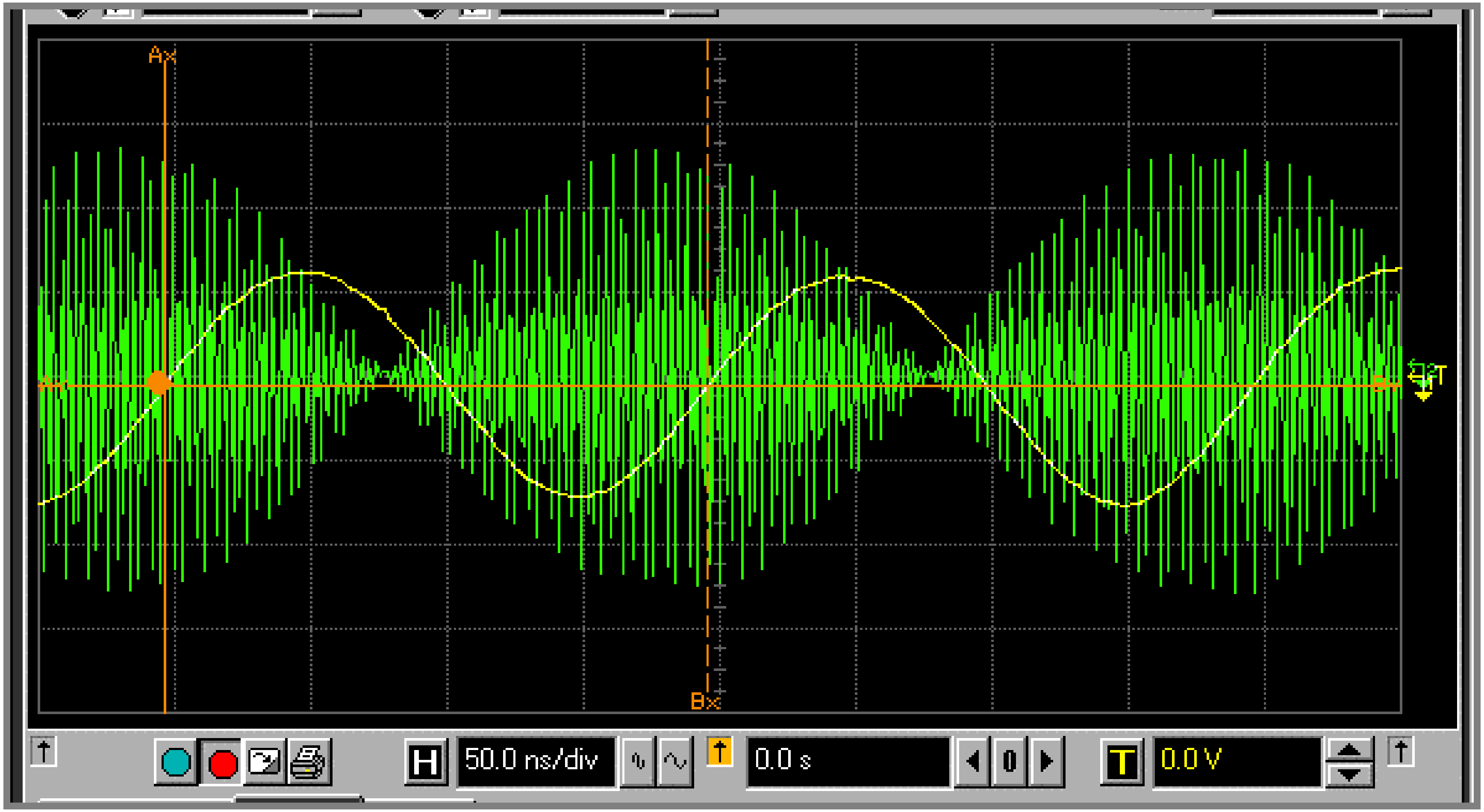
INABILITY OF AMPLIFIERS TO FOLLOW RAPIDLY CHANGING ENVELOPE



ENVELOPE FREQUENCY $F_e = F_\Delta/2$

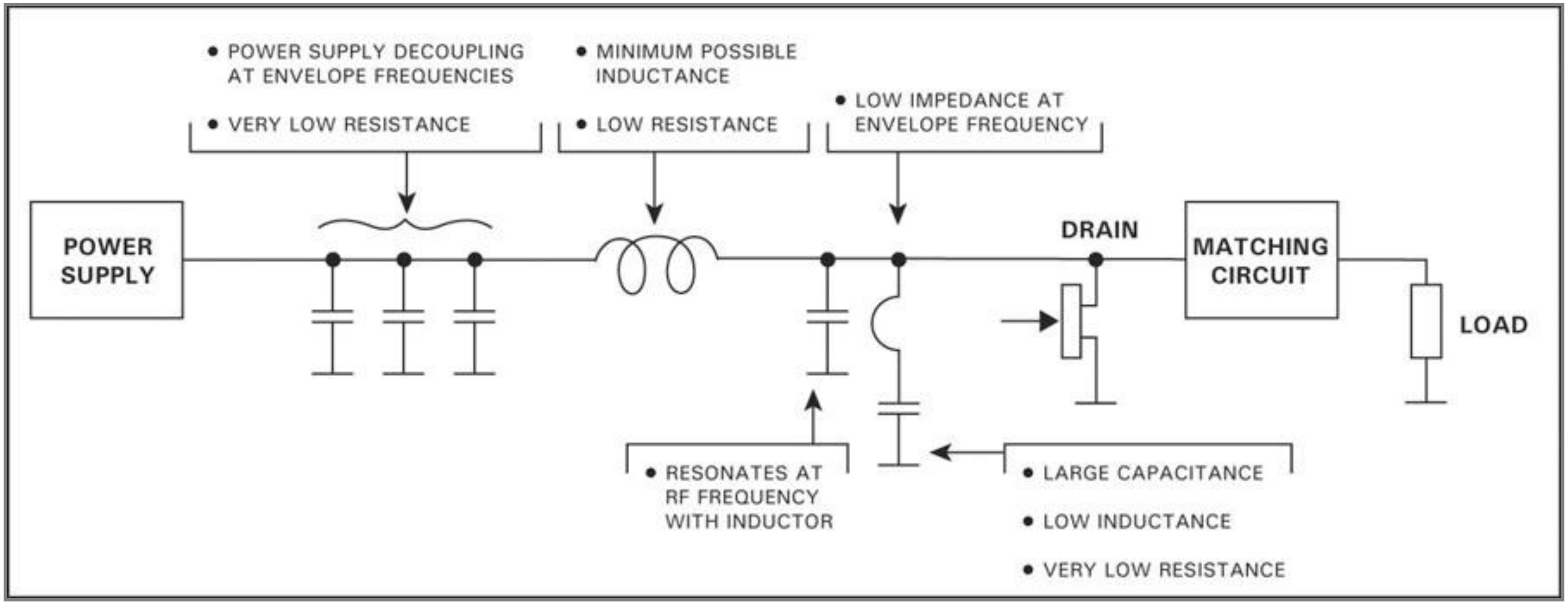
TRANSFER CHARACTERISTICS CHANGE WITH F_e

RF ENVELOPE (GREEN) IS ~ 140º OUT OF PHASE WITH DRAIN RIPPLE (YELLOW)



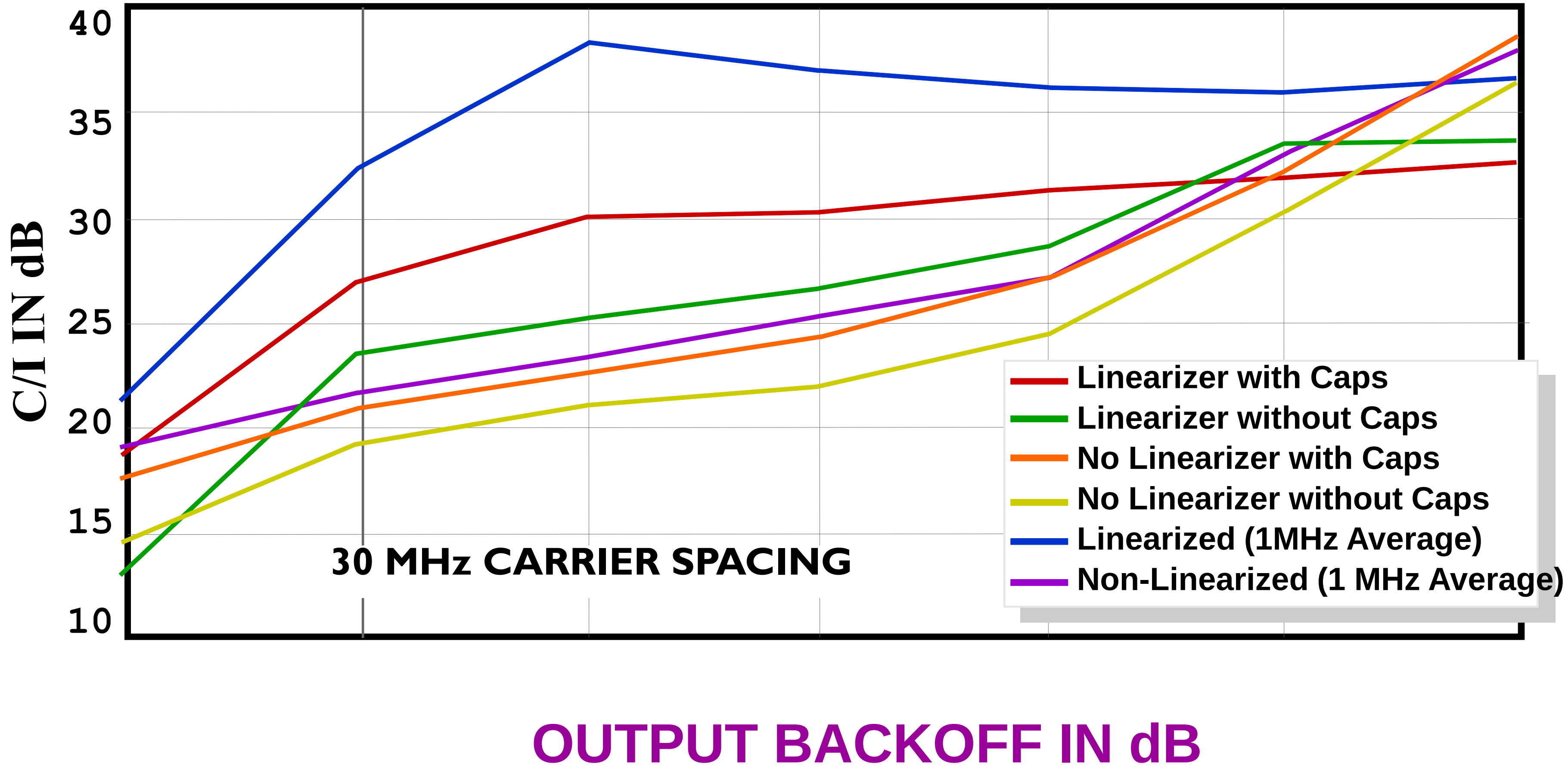
IMDs caused by the PA non-linearity subtract from the ripple induced IMDs

BIAS (DRAIN) INDUCED ME



A low impedance network at envelope frequencies across the drain and effective power supply decoupling can minimize memory effects

IMPROVEMENT IN C/I RESULTING FROM ADDED LOW INDUCTANCE DRAIN CAPACITORS (RESONATE AT 12 MHz)



SUMMARY

LINEARIZERS INCREASE HPA POWER CAPACITY AND EFFICIENCY FOR MULTI-CARRIER AND COMPLEX DIGITAL SIGNALS

NEW LINEARIZER DESIGNS HAVE GREATLY ENHANCED PERFORMANCE

SSPAs - BENEFIT GREATEST FOR CLASS B AND AB
2 X POWER INCREASE IN HIGH LIN APPLICATIONS

TWTAS - 4 X POWER INCREASE AND DOUBLE EFFICIENCY

SUMMARY

FEEDFORWARD:

LINEARIZATION IS MOST VALUABLE
WHEN VERY HIGH LIN REQUIRED.

INDIRECT FEEDBACK:

WORKS WELL, BUT LIMITED
IN BANDWIDTH.

PREDISTORTION:

ADVANTAGES SIMPLICITY, WIDEBAND,
VIABLE BOTH LOW AND HIGH LIN.
DSP CAN PROVIDE VERY HIGH LIN.

FOR MORE INFORMATION

1. A. Katz, "Linearization: Reducing Distortion in Power Amplifiers," IEEE Microwave Magazine, pp. 37-49, December 2001.
2. Vuolevi and Rahkonen, "Distortion in RF Power Amplifiers", Artech House, 2003.
3. S. Cripps, "Advanced Techniques in RF Power Amplifier Design", Artech House, 2002.
4. A. Katz and R. Gray, "The Linearized Microwave Power Module," MTT-S International Microwave Symposium Digest, June, 2003.
5. A. Katz, "Performance Of Multi-carrier 16QAM Over a Linearized TWTA Satellite Channel," AIAA 20th International Communications Satellite Systems Conference Proceedings, Montreal, May 2002.
6. P. Kenington, "Methods Linearize RF Transmitters and Power Amps, Part 1, "Microwaves & RF Magazine," pp. 103-116, December 1998, Part 2, pp. 79-89, January 1999.