Advances In The Linearization Of Microwave And Millimeter-wave Power Amplifiers

by Al Katz
The College of New Jersey
Linearizer Technology Inc
Linear Photonics LLC
Linear Space Technology LLC
OUTLINE (FOCUS ON ANALOG LINEARIZERS)

- WHY LINEARIZE
- TYPES OF LINEARIZERS
- THEORY/IDEAL AMPLIFIER
- PREDISTORTION LINEARIZERS
- TRADES DIGITAL VS. ANALOG
- 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 DUE AM/AM & AM/PM

\[ d^n(gain)/d(Pin)^n \& d^n(\varnothing)/d(Pin)^n \]
Ac \cos(\omega ct + M \cos[\omega mt]) = Ac \sum_{n=\infty}^{\infty} J_n(M) \cos(\omega c + n\omega m)t
\begin{align*}
n &= \infty \\
n &= -\infty
\end{align*}
FOR A DIGITALLY MODULATED CARRIER DISTORTION PRODUCES SPECTRAL REGROWTH
IDEAL HPA CHARACTERISTIC

WANT CONSTANT GAIN AND PHASE

SETS A LIMIT ON WHAT CAN ACHIEVE
WHY **PAPR** IS IMPORTANT

ONCE ABOVE **SAT**, NOT A LOT YOU CAN DO

WANT CONSTANT GAIN AND PHASE

SETS A LIMIT ON WHAT CAN ACHIEVE
PAPR LIMITS IDEAL PERFORMANCE

![Graph showing PAPR limits for ideal performance with lines labeled 2-TONE and MANY-TONE (NPR).]
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
WHY LINEARIZE

• TODAY'S HIGH INFORMATION RATE BANDWIDTH EFFICIENT SIGNALS REQUIRE LINEAR POWER AMPLIFIERS

• EFFICIENT LINEAR POWER AMPLIFIERS REQUIRE SOME FORM OF LINEARIZATION

MUST OPERATE AMPLIFIER AT REDUCED POWER LEVEL (BACKEDOFF)
WHY LINEARIZE

PRIMARILY ECONOMIC
THE MORE NONLINEAR A DEVICE IS, THE GREATER THE ADVANTAGE OF LINEARIZATION
THE MORE LINEARITY REQUIRED, THE GREATER THE ADVANTAGE OF LINEARIZATION

- FOR MANY APPLICATIONS C/I ~ 30 dB ENOUGH
FOR MANY HPAs [GaN] CAN ACHIEVE
  - 3 TO 6 dB MORE POWER
  - MORE THAN DOUBLING OF EFFICIENCY
  - REDUCED SIZE AND WEIGHT

BY LINEARIZATION

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WHY LINEARIZE – IMPROVED EFFICIENCY

- FOR DC POWER SENSITIVE APPLICATIONS EFFICIENCY IS OFTEN THE DECIDING FACTOR IN JUSTIFYING LINEARIZATION – AT 30 dB ~ X 2.5 IMPROV.

TYPICAL LINEARIZER EFFICIENCY IMPROVEMENT
WHY LINEARIZE

LINEARIZERS ALSO OFFER HPAs REDUCED THERMAL LOAD

SINCE LIN COST IS ~ FIXED, THE BIGGER THE HPA, THE MORE ECONOMICAL IT BECOMES

- LINEARIZING A 10 kW PA IS MUCH MORE COST EFFECTIVE THAN A 1 W PA

LINEARIZATION IS ALSO EASIER TO JUSTIFY AT HIGHER FREQ WHERE POWER IS MORE $$
CHOICE OF LINEARIZATION METHOD

• LEVEL OF LINEARITY (DISTORTION REDUCTION) NEEDED.

• BANDWIDTH REQUIRED (SIGNAL AND OPERATIONAL).

• COST/COMPLEXITY CONSTRAINTS.

• DIGITAL (DSP) vs. ANALOG
LINEARIZERS HAVE BEEN USED WITH

• TWTAs and KLYSTRONS
• BIPOLAR SSPAs (CLASS A, AB, B)
• FET SSPAs (GaN, GaAs, MOS, LDMOS)
• PHOTONIC (DIRECT, EO-MZM, EA)
LINEARIZERS ALLOW HPAs TO OPERATE CLOSER TO SAT

Greater Output Power

- AMP
- LAMP
- AMP

“SAME” Distortion

Greater Efficiency

- AMP
- LAMP
- AMP

Efficiency

- AMP
- LAMP
- AMP
FIRST RULE:

You Can’t Linearize An Amplifier That Is Already Linear!

WANT TO OPTIMIZE EFFICIENCY AND SATURATED POWER, NOT LINEARITY
SATCHELITE --

- 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/PC --

- 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.
RELATIVELY COMPLEX & **LIMITED EFFICIENCY**

- NOT EFFECTIVE FOR OPBOS \(< \sim 6 \text{ dB}\)
- MOST USEFUL BY VERY HIGH LINEARITY APPS
MINIMUM FEEDFORWARD OPBO FOR IMD CANCELLATION (20 dB)

DEPENDING ON: 1) AUX AMP SIZE,
               2) OUTPUT COUPLER COEF.
FEEDBACK LINEARIZATION

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

*INDIRECT FEEDBACK

- OPERATES ON ENVELOPE
- VERY LIMITED BW < 1/(4Δt_s)
- CAN BE POLAR OR CARTESIAN
FEEDBACK LINEARIZATION

< ~ 10 MHz MAX
(1 MHz)

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

*INDIRECT FEEDBACK

- OPERATES ON ENVELOPE
- VERY LIMITED BW < 1/(4Δt_s)
- CAN BE POLAR OR CARTESIAN
CARTESIAN FEEDBACK ELIMINATES THE NEED FOR PHASE CORRECTION CIRCUITRY
PREDISTORTION LINEARIZER — GENERATES FUNCTION WITH INVERSE MAG AND PHASE TO TRANSFER FUNCTION OF PA

\[ P_{outL} \] \[ P_{outA} \] \[ P_{out} \]

\[ P_{inL} \] \[ P_{inA} \] \[ P_{in} \]

FOR PERFORMANCE OVER FREQUENCY:

- MUST EQUALIZE LINEAR GAIN AND PHASE (DELAY)
- MUST MATCH NON-LINEAR CHARACTERISTICS OVER FREQ
PREDISTORTION (PDL)

MOST WIDELY USED

THE NATURAL CHOICE FOR LINEARIZATION

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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.

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

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

\[
GL(P_{inL}) = GL_{ss} + GA_{ss} - GA(P_{inL} + GL(P_{inL}))
\]

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

\( \Phi L \) depends on GL & cannot be set independently
AN IDEAL LINEARIZER MUST PROVIDE A GAIN EXPANSION THAT APPROACHES INFINITY NEAR SATURATION

\[ \frac{dG}{dP} \rightarrow \infty \text{ as } Pin \rightarrow \text{ Sat} \]
FOR WIDEBAND PDL

THE LINEARIZER MUST GENERATE A SURFACE FOR BOTH GAIN AND PHASE WITH FREQUENCY AS THE PARAMETER
5G - Superimpose **MULTIPLE SIGNALS** to produce **MULTIPLE BEAMS**

- When PA nonlinear get not just IMDs in **FREQUENCY**, but also IMDs in **SPACE** [unwanted beams].

Spatial IMDs corrected by **LINEARIZERS**
FORMS OF ANALOG PDL

1. TRANSMISSION

2. REFLECTIVE

3. IN LINE

Vout (HIGH)

Vout (LOW)

Vin

Vnl
Every input level has a corresponding output level
Correction (mag & phase) in look up tables (LUT) depends on input level
LUT is almost always adaptively updated over time
DIGITAL PDL DOMINANT

- DEVICE NONLINEARITY USUALLY NOT IMPORTANT:
  - GET NEAR IDEAL LINEARIZATION INDEPENDENT OF CHARACTERISTICS
- IF HPA INTEGRATED WITH DIGITAL MODULATOR
  - GET LINEARIZATION ESSENTIALLY AT NO $$$

- MODULATOR MUST HAVE SUFFICIENT BW
  BW(PROC) ≥ 3~7 BW (SIGNAL)
  (CAN’T COMBINE SIGNALS)

~ ALL USE ADAPTIVE APP.
DIGITAL PREDISTORTION

NEED TO CONVERT RF SIGNAL TO BASEBAND (BB) FOR PROC, THEN CONVERT BACK TO RF (DDC SHOWN ABOVE).

- CAN USE EITHER G AND $\Phi$ OR I AND Q
- MUST SAMPLE AT $> 2 \times$ CORRECTION BW FOR G AND $\Phi$
- BUT ONLY $> \text{CORRECTION BW FOR I AND Q}$
DIGITAL VS. ANALOG PDL

**DIGITAL PDL**
- IF DIGITAL MODULATOR AVAILABLE AND SUFFICIENTLY NARROW BAND – *NO BRAINER!*

**ANALOG PDL**
- AS BW INCREASES ANALOG GAINS THE ADVANTAGE AS DIGITAL’S COST AND POWER OVERHEAD INCREASE
- HAS ADVANTAGE FOR SIGNAL BW > ~ 50 MHz
- SELECTION DEPENDS ON BENEFIT PROVIDED
- FOR MANY APPS PERFORMANCE SIMILAR
- FOR MULTI GHz/MULTI OCTAVE OPERATION ANALOG IS THE ONLY PRACTICAL OPTION

*(DIGITAL CANNOT EASILY ADJ NL WITH FREQ)*
DIGITAL ADAPTIVE PREDISTORTION

Cubic, first-zone PA

Series reversion

Infinite bandwidth predistorter

\[ z(t) = k_1 y(t) + k_3 y^3(t) \]

\[ y'(t) = \sum_{n=0}^{\infty} K_{2n+1} z^{(2n+1)}(t) \]

\[ K_1 = k_1^{-1} \quad K_3 = -k_1^{-4} k_3 \quad K_5 = 3k_1^{-7} k_3^2 \quad K_7 = -12k_1^{-10} k_3^3 \]

CORRECTION BW MUST BE >> SIGNAL BW
DIGITAL ADAPTIVE PDL

CORRECTION BW MUST BE >> SIGNAL BW
DIGITAL ADAPTIVE PREDISTORTION

ADAPTIVE SYSTEMS CORRECT AT << ENVELOPE RATE
NEW ANALOG ADAPTIVE PDL (AAPDL)

➢ Real-time optimization for best linearity over entire operating band (Multi GHz).
➢ Improved WB performance – can compensate for ripple.
➢ Optimizes regardless of signal type/traffic (CW, QPSK, APSK, multi-carrier, or signal combination).

Ka-band AAPDL
➢ The AAPDL provides constant signal gain at all levels & temperatures; even corrects for aging.
AAPDL PERFORMANCE

KA-BAND AAPDL: IMPROVED WB PERFORMANCE

13.2 dB improvement  15 dB improvement  11.8 dB improvement  10.1 dB improvement
**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: \( SR = CBW = N \times BW \)
* Cost can be higher than analog
* Power consumption can be high
* Wide BW systems difficult to implement
WAYS TO IMPROVE EFF WITH NL PAs

- MANY WAYS TO ACCOMPLISH.
- CLASSICAL “KHAN METHOD” DEMODS ENVELOPE & LIMITS SIGNAL. THEN REMODULATES AT OUTPUT PA
- LINC SYSTEMS OBTAINS LINEAR AMPLIFICATION BY COMBINING TWO NON-LINEAR PAs.
- LOAD MODULATION AND OUTPHASING
  - DOHERTY MOST SUCCESSFUL EXAMPLE
EER – ENVELOPE ELIMINATION AND RESTORATION (POLAR & ENVEL TRACKING)

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 DIFFICULT.

• DATA USUALLY PRESENTED REL TO BACKOFF FROM SAT.

• SAT POINT SHOULD BE SINGLE CARRIER SAT. 2 CARRIER SAT ABOUT 0.5 ~ 1 dB LOWER, NOISE 1 ~ 1.5 dB.

• CANNOT 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

\[ C/I \text{ total} = C/ \sqrt{I_3^2 + I_5^2 + I_7^2 + \ldots} \]

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
SOME RESULTS FOR ANALOG PDL WITH TWTA: 3 TO 6 dB MORE POWER

WITH MULTIPLE CARRIERS THE IMPROVEMENT IS EVEN GREATER!
WITH GaAs SSPA: 1 TO 2 dB MORE POWER

PROVIDES > 1.5 dB POWER INCREASE FOR C/I OF 26 dB.
WITH GaN SSPA: 3 TO 5 dB MORE POWER

- FOR C/I = 30 dB, ALMOST 2.5 dB MORE POWER
- AND AN INCREASE IN EFFICIENCY > 60%

- FOR C/I = 30 dB, > 7 dB MORE POWER
- AND AN INCREASE IN EFFICIENCY > 200%
MORE RESULTS – GaN HPAs

RECENT KA-BAND GaN SSPA RESULTS

C/I = 30 dB, > 7.5 dB MORE POWER

Ka-Band GaN SSPA C/I

LSSPA

SSPA
MULTIPLE CARRIERS (N>2)

- EXERCISE OVER RANGE  \( P_{pk} = 2NP_{av} \)

- 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 TO BE MEASURED
USE OPBO, REFERENCE TO SINGLE CARRIER SAT DIGITAL VS. ANALOG
NPR PREDICTS AMPLIFIER PERFORMANCE WITH MANY CARRIERS

FOR NPR = 25 dB OBTAIN ALMOST 6 dB INCREASE IN POWER.
NPR GaN SSPA
PROVIDES SIGNIFICANT REDUCTION IN SPECTRUM (QPSK)
EVEN NEAR SAT

> 2 dB POWER INCREASE
REDUCTION IN SPECTRAL REGROWTH PROVIDED BY LINEARIZATION OF A TWTA

![Graph showing carrier to noise ratio vs. OPBO in dB for LTWTA and TWTA, with a 15 dB reduction indicated.](image)
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.
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.
• IMD is the major problem. It limits the bit error rate (BER) of digital signal.

• Coding used to increase BER for a small sacrifice 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

BER of uncoded 16QAM (in multicarrier environment through TWTA) vs Output backoff

Output Backoff of TWTA (dB)

LINEARIZER PROVIDES A HUGH ADVANTAGE
BER OF 3/4 CONVOLUTIONAL FEC DATA
QEF STILL CANNOT BE ACHIEVED

BER of FEC coded 16QAM (in multicarrier environment through TWTA) vs Output backoff

LINEARIZER PROVIDES ~ 3 dB ADVANTAGE
BER OF FEC/REED-SOLOMON CODED DATA

BER of FEC & Reed-Solomon coded 16QAM (in multicarrier environment through TWTA) vs Output backoff

LINEARIZER PROVIDES > 2 dB ADVANTAGE AT QEF
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°
WIDEBAND LINEARIZER AT MMW

• BELOW IS SHOWN AN EXPERIMENTAL Ka-BAND WB LINEARIZER
• FOR HPA ($\Delta G > 4$ dB & $\Delta$PHASE 50°) APPLICATION
• WITH BANDWIDTH > 10 GHz (26 TO 36 GHz)
WB LIMITATIONS FROM RIPPLE

• GAIN AND PHASE (TD) MUST BE MAINTAINED OVER FREQUENCY – CAN CORRECT WITH EQUALIZER

• GAIN RIPPLE A MAJOR PROBLEM – LIMITS CORRECTION

GAIN RIPPLE AFFECT ON C/I

2 dB RIP at 30 dB C/I Lose ~ 3 dB
MULTI-OCTAVE PROBLEM

FOR WB OPERATION (> OCTAVE BW) - EVEN & ODD ORDER DISTORTION MUST BE CONSIDERED

- IM AND HARMONIC DISTORTION A PROBLEM
- 2F1, F2-F1, 2F2-F1 AND 2F1-F2 PRODUCTS OF MOST CONCERN
- MOST PREDISTORTERS CORRECT ONLY ODD ORDER DISTORTION
MULTI-OCTAVE LINEARIZATION

Utilize Push-Pull PA/Linearizer design to minimize even order distortion

- Use pre-distortion linearizer to minimize odd order intermodulation distortion
- Use push-pull to minimize 2nd harmonic & F2-F1 products
- Push-pull provides > 25 dB of suppression
MULTI-OCTAVE LINEARIZERS

PREDISTORTORS CAN GENERATE 2\textsuperscript{ND} IN ADDITION TO 3\textsuperscript{RD} ORDER NONLINEARITIES

2\textsuperscript{ND} ORDER TERMS MAY WORSEN PERFORMANCE FOR > OCTAVE BW

EVEN TERMS NOT IN THE PROPER PHASE TO CANCEL

DEVELOPED PREDISTORTORS TO GENERATE ONLY 3\textsuperscript{RD}-ORDER TERMS AND OPERATE OVER MULTI-OCTAVE BANDWIDTH
A MULTI-OCTAVE BROADBAND WITH EVEN ORDER CANCELATION
- OPERATING FROM 1 TO 20 GHZ
- WITH SINGLE LINEARIZER PROVIDING BOTH IM AND HARMONIC DISTORTION CORRECTION USING PUSH-PULL NLG
WB GaN LINEARIZER

- LINEARIZER DESIGNED FOR 4 TO 18 GHz GaN FOR MMIC SSPA
- USES 2 ACTIVE FET NON-LINEAR GENERATORS, COMBINED USING 180° HYBRID MAGIC TEE BALUNS
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
REDUCTION IN SPECTRAL REGROWTH PROVIDED BY LINEARIZATION OF A TWTA

2-TONE CARRIER TO INTERMOD (C/I) IS A COMMON MEASURE OF DISTORTION REDUCTION

At 6, 10, & 16 GHz: C/I INCREASE OF 5-11 dB FOR OPBOs OF 5–8 dB
EXTENDING FREQUENCY LIMITS TO V-BAND

Operating Freq: 47.2 to 51.4 GHz
GAIN: >22 dB
Pout: +15 dBm
35 dB Input Attenuator
15 dB Output Attenuator
MUTE Mode (>60 dB)
Pdc ~ 4W

ΔG = 5 dB
Delta GAIN vs. Input Drive Power

ΔØ = 50°
Delta PHASE vs. Input Drive Power

GAIN
Large Signal
Small Signal

PHASE
Large Signal
Small Signal

47 – 52 GHz
V-BAND LINEARIZED TWTA RESULTS

2 Tone C/I Measurements

L-TWT

~5 dB Operating Point Improvement

<table>
<thead>
<tr>
<th>LINEARITY STIMULUS</th>
<th>OPBO=3dB</th>
<th>OPBO=4dB</th>
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<tbody>
<tr>
<td></td>
<td>HPA</td>
<td>LINEARIZED HPA</td>
</tr>
<tr>
<td>2- Tone C/I</td>
<td>16  dB</td>
<td>&gt;25 dB</td>
</tr>
<tr>
<td>NPR</td>
<td>12  dB</td>
<td>&gt;16 dB</td>
</tr>
<tr>
<td>ACPR (1 symbol spacing)</td>
<td>25  dB</td>
<td>&gt;30 dB</td>
</tr>
</tbody>
</table>
EXTENDING FREQUENCY LIMITS TO E-BAND

Today pushing frequency to > 100 GHz

W-band demonstration linearizer

Huge C/I increase at 81-86 GHz
EXTENDING FREQUENCY LIMITS TO > 100 GHz

W BAND DEVELOPMENT / TEST RESULTS

Note: Test frequency up/down converted to W-Band (94 GHz)

W-Band Linearizer
91-96 GHz
40 dB Gain
O/P Attenuator
WR-10 Interface
• 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
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
Big improvement in C/I at all levels except near SAT
> 10 dB over much of the range with a peak of > 30 dB
<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>IMD Improvement (dB)</th>
<th>IIP3 Improvement (dBm)</th>
<th>SFDR3 Improvement (dB·Hz$^{2/3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>13.3</td>
<td>6.65</td>
<td>4.43</td>
</tr>
<tr>
<td>6</td>
<td>20.0</td>
<td>10.0</td>
<td>6.67</td>
</tr>
<tr>
<td>8</td>
<td>23.6</td>
<td>11.8</td>
<td>7.87</td>
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<tr>
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<td>17.9</td>
<td>8.95</td>
<td>5.97</td>
</tr>
<tr>
<td>12</td>
<td>12.3</td>
<td>6.15</td>
<td>4.10</td>
</tr>
</tbody>
</table>

Significant improvement in linearity provided over 1.5 octave frequency range
SFDR increased by > 4 dB over this range
MEMORY EFFECTS (ME)

ME ARE CHANGES IN A HPA’S NONLINEARITY DUE TO PAST HISTORY OF THE INPUT SIGNAL

\[ V_o = f(V_{in}, \text{time}) \]

SOURCES OF ME

- Frequency ME
- Drain/collector ME
- Gate/base ME
- Device related ME
- Thermal ME
GAIN 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 with the spacing of tones increased
THE LINEARITY OF AMPLIFIERS DEGRADE WITH INCREASING CARRIER SPACING
MAJOR CAUSE OF DEGRADATION --

INABILITY OF AMPLIFIERS TO FOLLOW RAPIDLY CHANGING ENVELOPE

ENVELOPE FREQUENCY $F_e = \frac{F_\Delta}{2}$

TRANSFER CHARACTERISTICS CHANGE WITH $F_e$
RF ENVELOPE (GREEN) IS ~ 140° OUT OF PHASE WITH DRAIN RIPPLE (YELLOW)

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

OUTPUT BACKOFF IN dB

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SUMMARY

• LINEARIZERS ESSENTIAL FOR BW-EFFICIENT, HIGH DATA RATE COMMUNICATIONS
• INCREASE HPA’s EFF POWER AND EFFICIENCY
• DIGITAL PDL DOMINANT WHEN HPA IS USED WITH A DIGITAL MODULATOR AND SIGNAL BW NARROW ENOUGH
• ANALOG PDL GAINS THE ADVANTAGE FOR WIDEBAND APPLICATIONS
• UNDERSTANDING LIMITATIONS ENABLES BETTER HPA DESIGNS
• LINEARIZERS FOR MULTI GHz/OCTAVE AND TO > 100 GHz AVAILABLE


