MEMRISTORS AS NON-LINEAR BEHAVIORAL MODELS FOR PASSIVE INTER-MODULATION SIMULATION

Jacques Sombrin
Patrice Michel
TéSA Laboratory

Geoffroy Soubercaze-Pun
Isabelle Albert
CNES

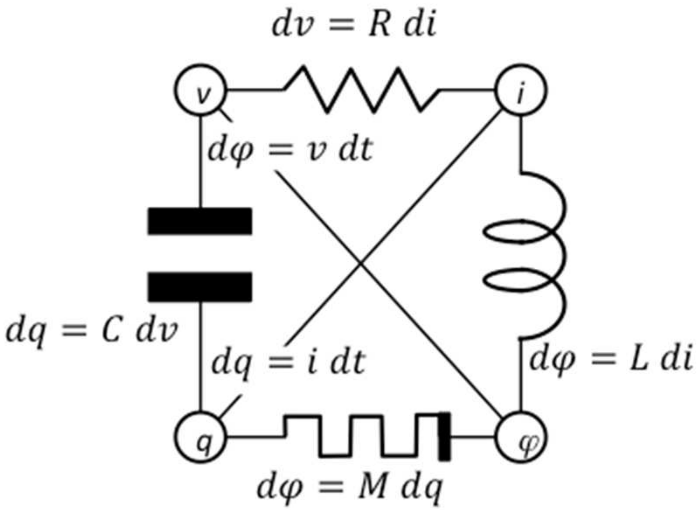
Journée Thématique
Télécommunications Spatiales Militaires

Outline of talk

- Introduction on Memristors
- Passive Inter-Modulation
    - Non-integer PIM power slopes
- Memristors as non-linear models
    - Effects of memory on a non-linearity
    - PIM generator behavioural model
    - Simulation results
    - Comparison with measurements
- Conclusion

Memristors

- Memristors invented in 1971 by Leon Chua
- Theoretical 4th ideal electrical element
- Complements R, L and C elements
- Links derivative of flux to derivative of charge



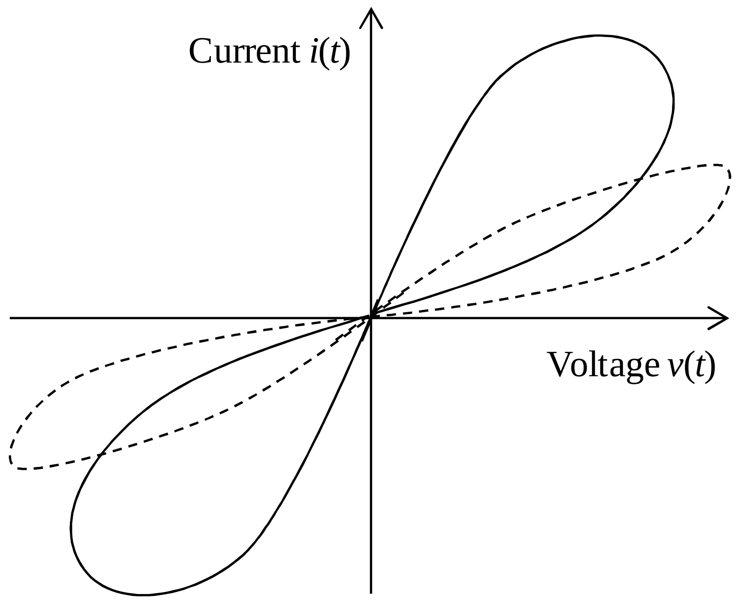
$$M(q) = \frac{d\varphi(t)}{dq(t)}$$

$$v(t) = M(q) \cdot i(t)$$

09/10/2014

Typical response to alternative current

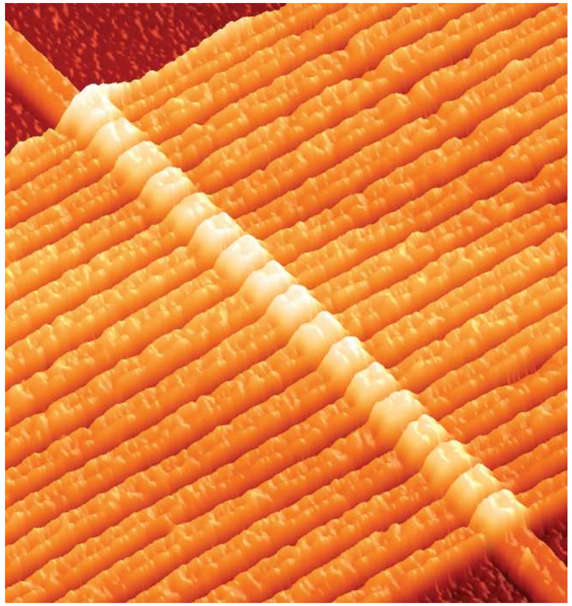
- Pinched hysteresis or “bow-tie” response to an alternative current or voltage
  - Proposed as characteristic of memristors but also found on other circuits



- Loop opening depends on frequency of input signal and phase delay between i(t) and M(q(t))
  - Perfect 90°phase delay gives a collapsed loop, reduced to a single curve

Practical passive memristors

- In 2008, HP engineers found that some contacts of Platinum wires through Titanium oxides they were investigating had the same pinched hysteresis response as memristors
- There is a lot of controversy on the memristor invention and patents
- Found also on some spots on Galena crystals and in gas discharge lamps



- Resistances vary with temperature, which can be a function of integrated input power

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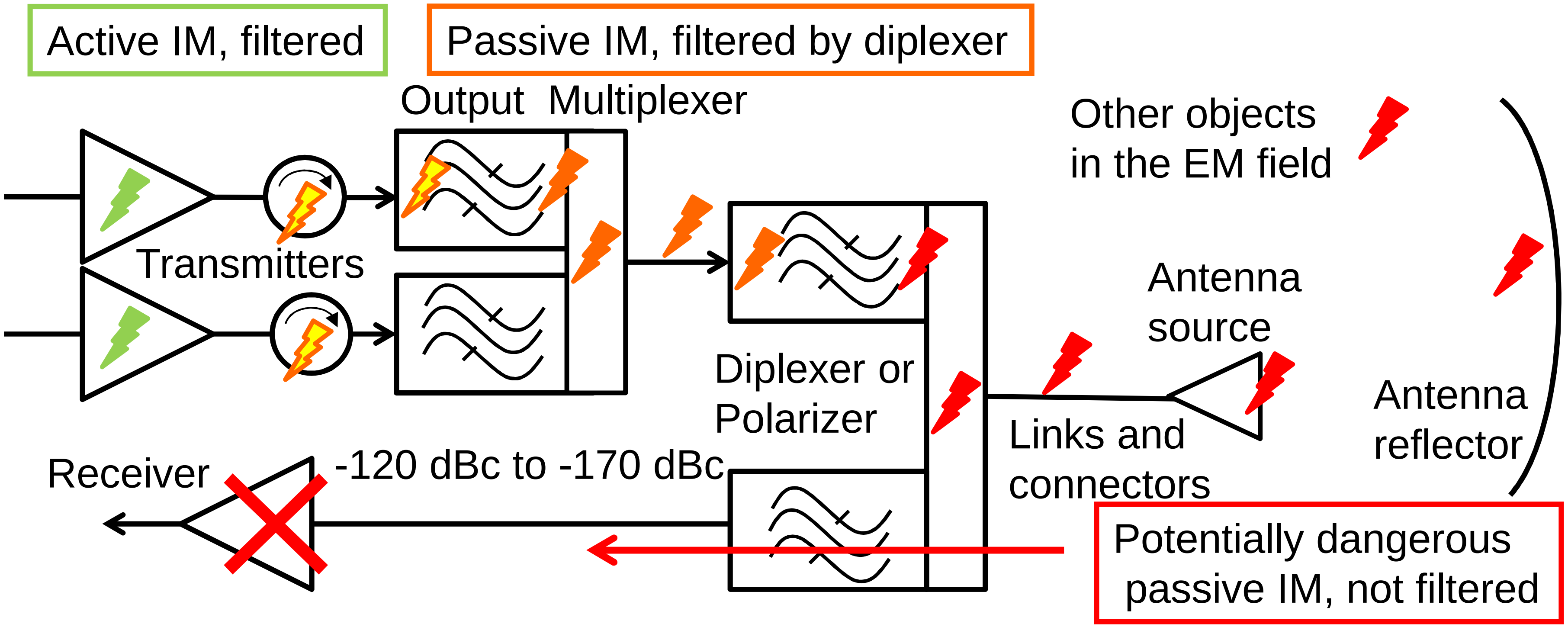
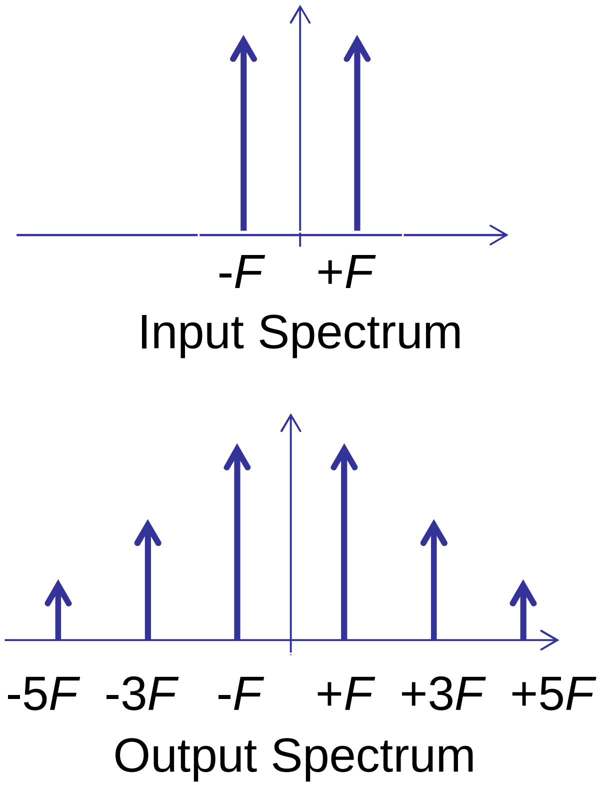
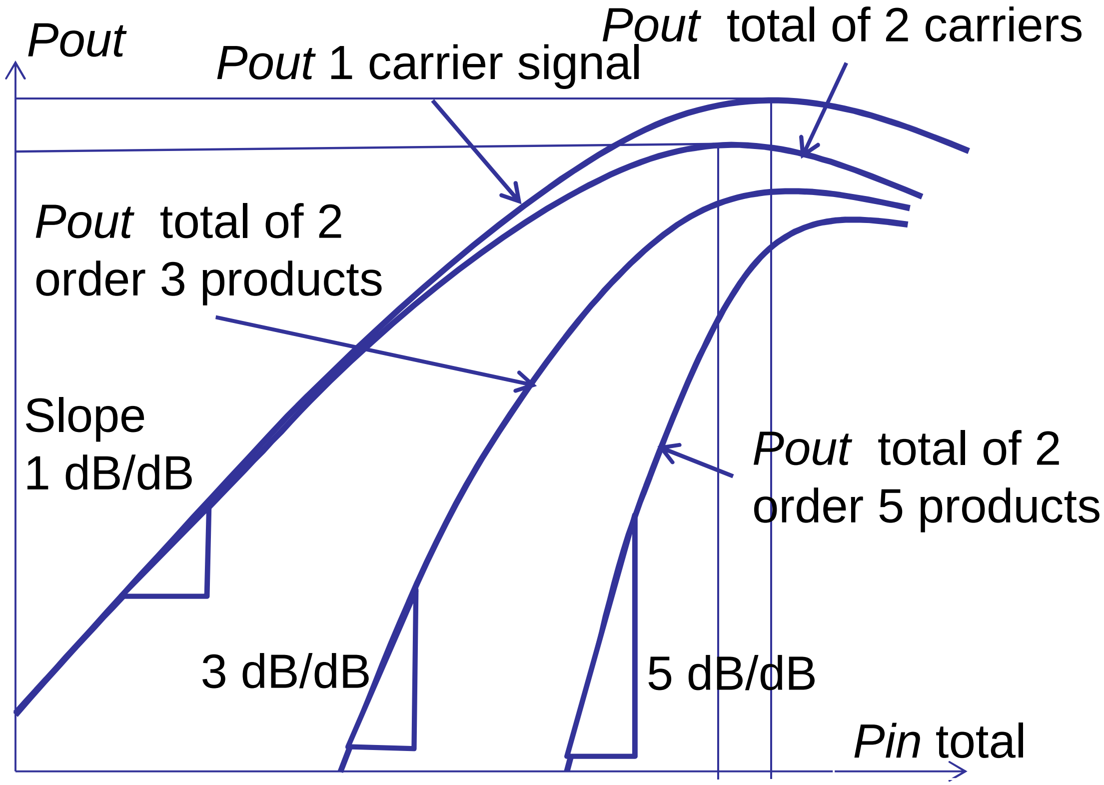
Passive intermodulation (PIM) generation

- Problem in space technology such as filters, diplexer, polarizer, connectors and common antennas for transmission and reception
- Also in Aeronautics and in telephony base stations



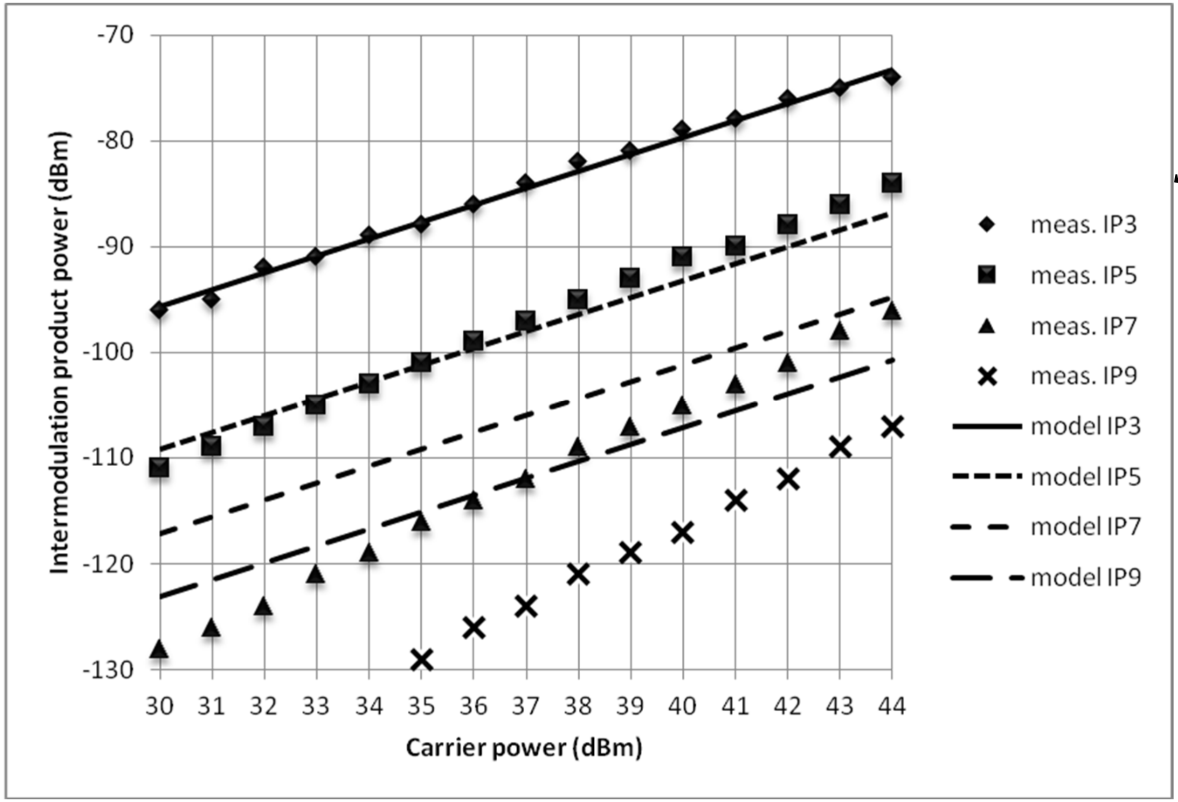
Classical 2-carrier C and IM curves





- "Well known result : IM power versus input power slope in dB/dB = order"
- True only for an <u>analytical</u> function (i.e. continuous and equal to its Taylor development) having a <u>non zero term of degree equal to the order</u>.

PIM published measurements and non-analytical memoryless model



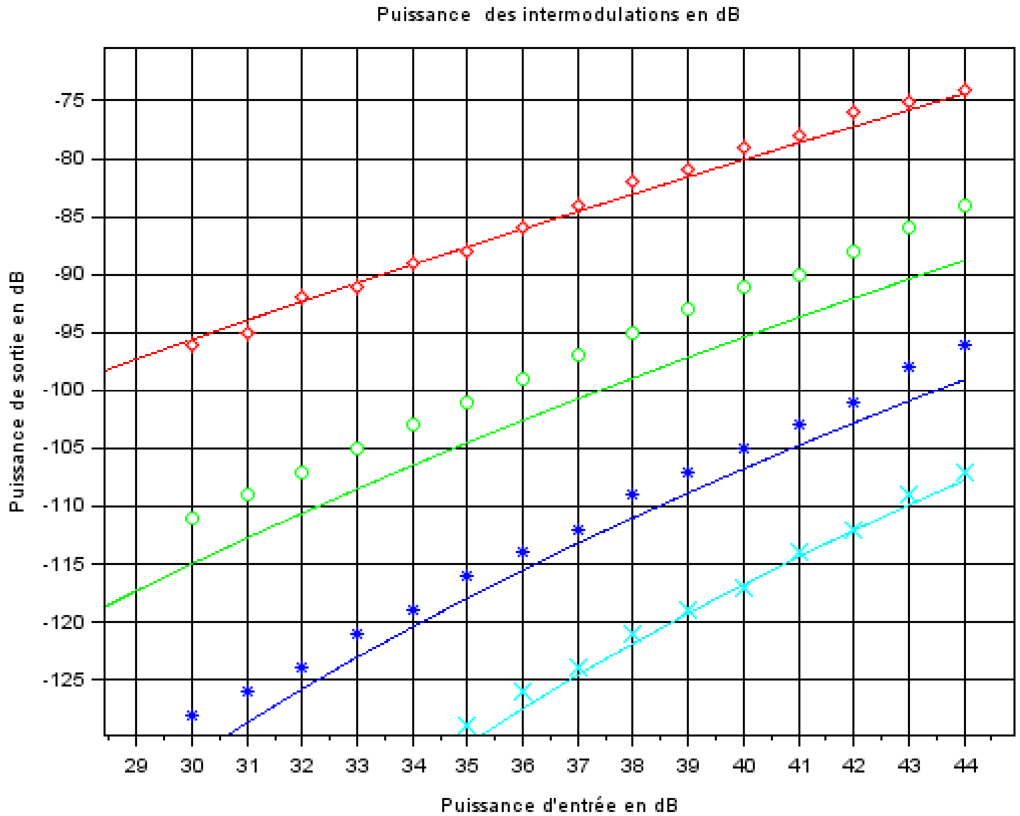
$$y = x \cdot \left(1 - \alpha |x|^{0.6}\right)$$

Measurements

Simulation with non-analytical model

- Coefficient α has been chosen for best fit with 3rd order IM
- 5th IM around 13 dB under the 3rd IM

Padé-like non-analytical model



$$y = x \cdot \left(1 - \frac{\alpha |x|^{1.2}}{1 + \beta |x|^{0.8}} \right)$$

Relaxation of 2-carrier specification for the same multicarrier C/I performance

Reference is the classical model: polynomial, slope = 3 dB/dB

Degree of NL = slope	2-carrier C/I_3 (dB) = specification	8-carrier C/I_3 (dB) type $2f_1 - f_2$ = required performance	8-carrier C/I_3 (dB) type $f_1 + f_2 - f_3$ = required performance	Δ (dB)
1.5	108.3	121.3	115	-12.7
2	112.5	121.3	115	-8.5
2.5	116.7	121.1	115	-4.3
3	121	121	115	Ref.
3.5	125.4	120.9	115	4.4

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Effects of memory in non-linearity

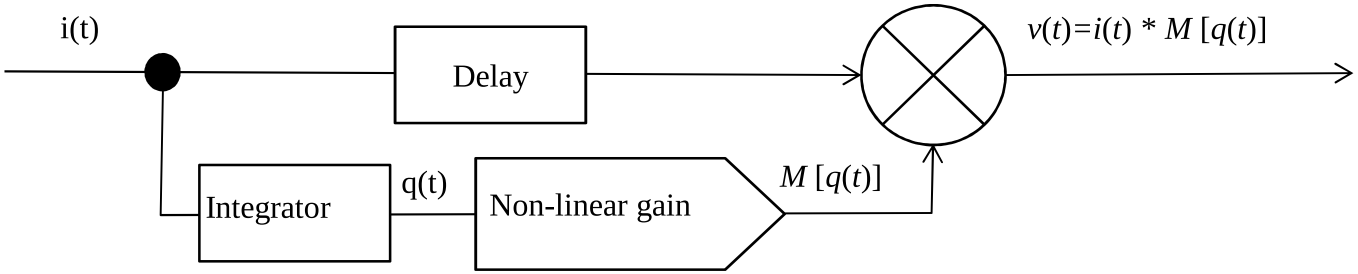
- Products are out-of-phase with input signal:
  - Equivalent to AM/PM conversion if the signal bandwidth is low
- Random effect of integration constant or time at beginning of integration
  - Generation of even order harmonics and products
  - Decrease of odd order harmonics and products
  - Averaging on many random or equally spread initial conditions is needed

Interest of memristors for PIM simulation

- Possible physical explanation
  - Passive contacts, gas discharges, thermal effects
- Memory changes the non-linear behaviour
- May explain variability of measurements
  - Initial conditions can never be reproduced exactly
- Easy to simulate behavioural model
  - Improves simulation time
  - Allows us to average outputs for different initial conditions in a distribution of non-linear generators

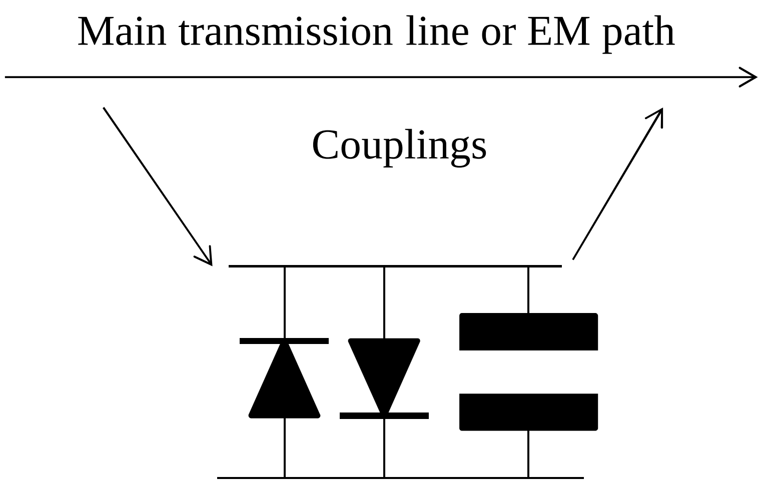
Easy to simulate behavioural model

- Value of $M(q)$ depends on charge:
  - Charge = integral of current having gone through the memristor since time origin: $t=0$
  - Time origin controlled by the delay in RF branch or phase of current at $t=0$
  - Must be positive or null for a passive element
  - Non-linear resistor: $v(t) = M(q) \cdot i(t)$

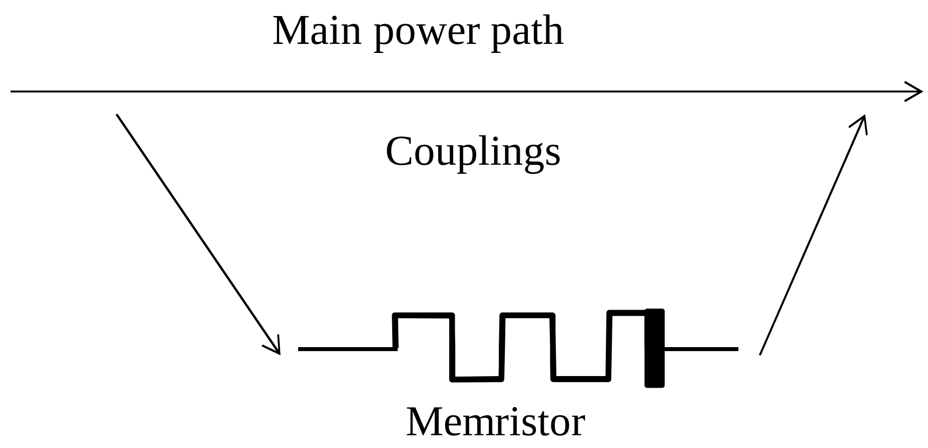


Replacement of circuits by memristors

- Physical circuit model of a microscopic PIM generator with memory
- Behavioural Memristor model of a microscopic PIM generator with memory



Classical non-linear circuit with memory



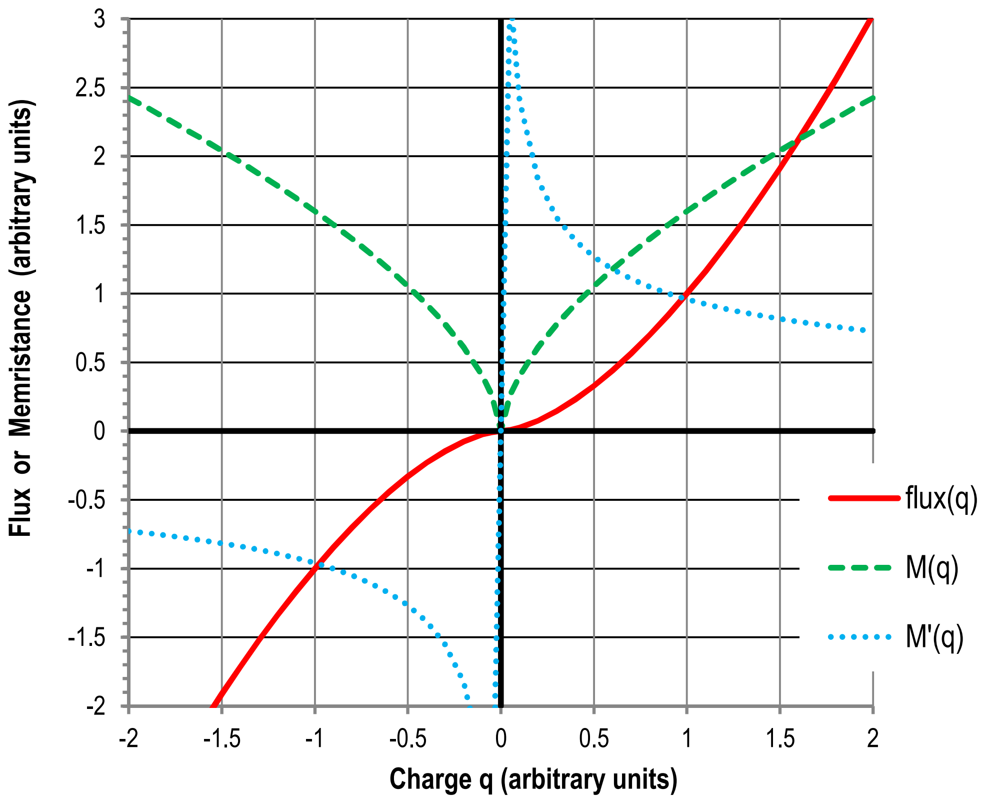
Model of memristor used for PIM simulation

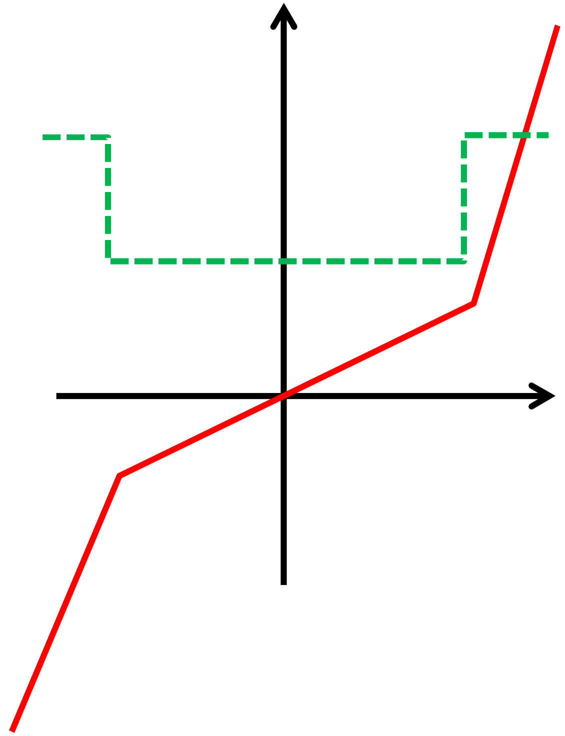
- We keep a non-analytical non-linearity that gives us non-integer dB/dB slopes, typically:

$$M(q) = 1 - \alpha |q|^{0,6}$$

- The discontinuity at origin appears on the i-v response for phases different from 0 and 90°
  - Memristances used by Chua are also non-analytical and symmetrical but are continuous near origin, piecewise polynomial or piecewise linear.
  - They do not give non-integer dB/dB slopes

Flux, memristance and its derivative





$$\text{Non-linear part:} \quad M(q) = \frac{d\varphi}{dq} = |q|^{0.6}$$

PIM small signal slope = 1.6 dB/dB

Example of flux curve and memristance used by Chua

Piecewise polynomial:

PIM small signal slope = 3 dB/dB

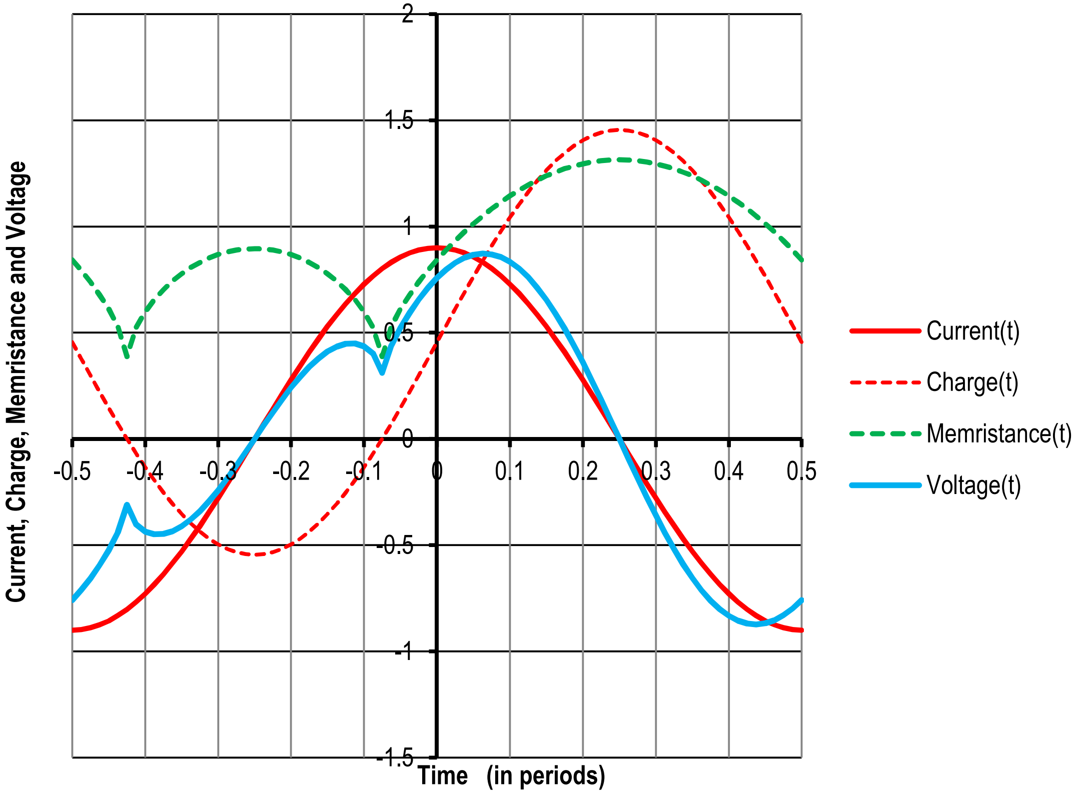
Simulation results

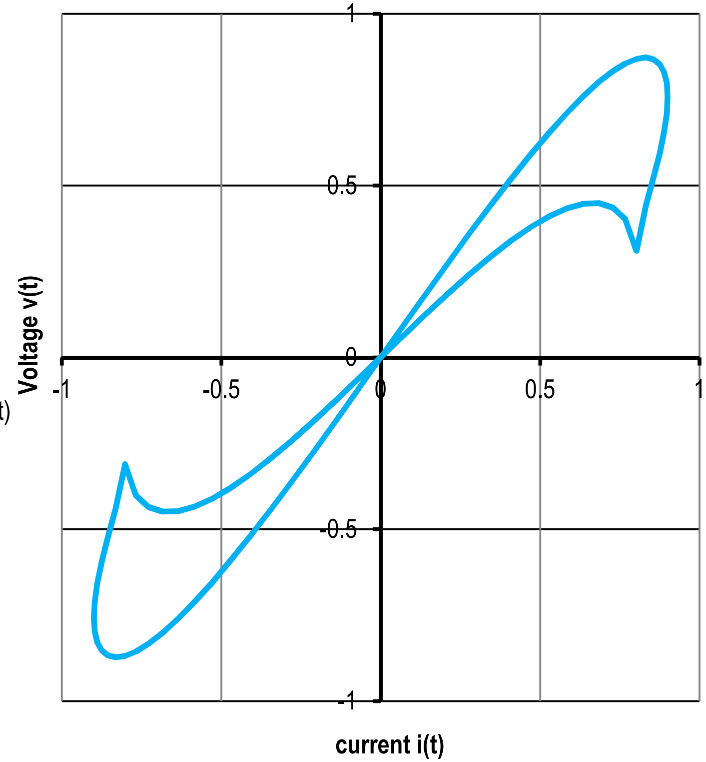
1. Simulation with one carrier
   - Current-voltage response
   - Harmonic response
2. Simulation with two carriers
   - Inter-modulation products response

- Variable initial conditions, 2 possibilities
   - Different phase delay between the two branches of the memristor behavioural model
   - Different integration constant or initial time

Time curves for i and v and i-v response

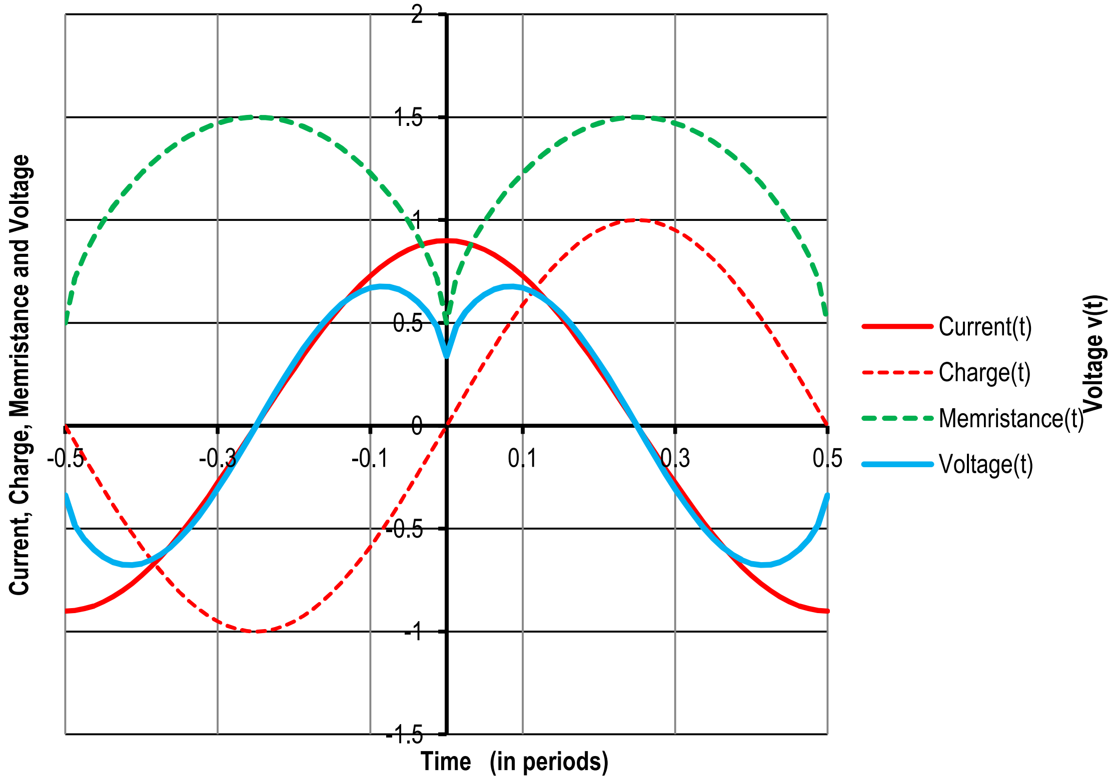
With non zero integration constant

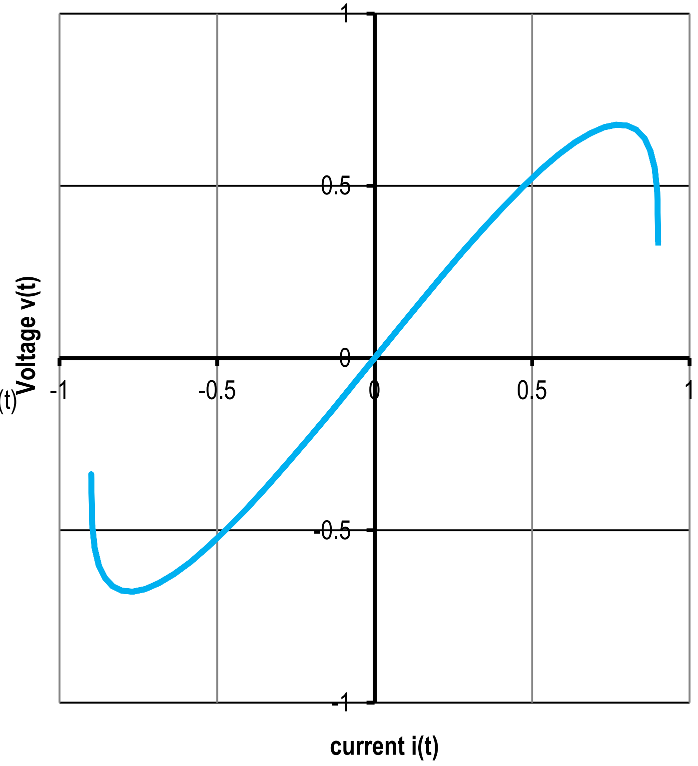




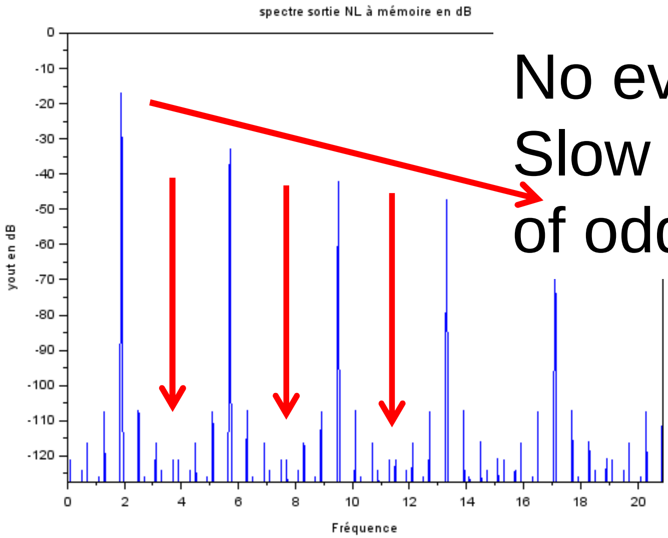
Time curves for i and v and i-v response

With zero integration constant





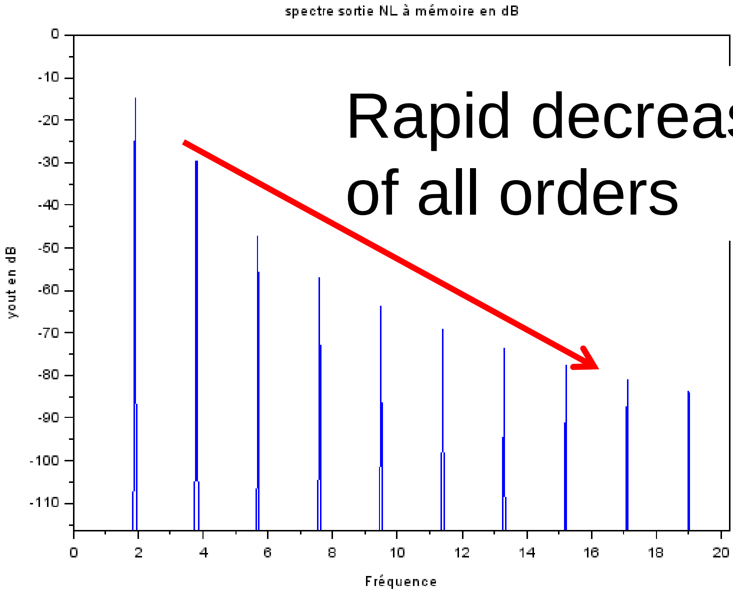
Spectra for signal phases 0, 45 & 90°



No even order
Slow decrease
of odd orders

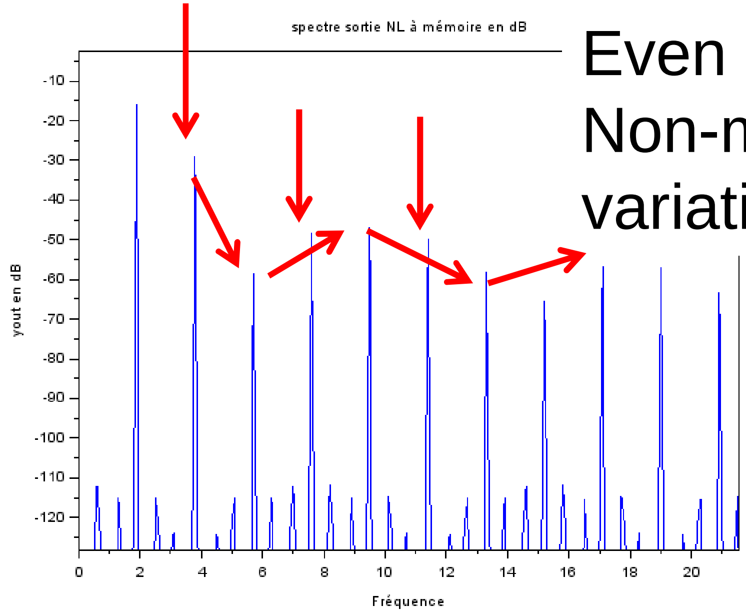
0°

90°



Rapid decrease
of all orders

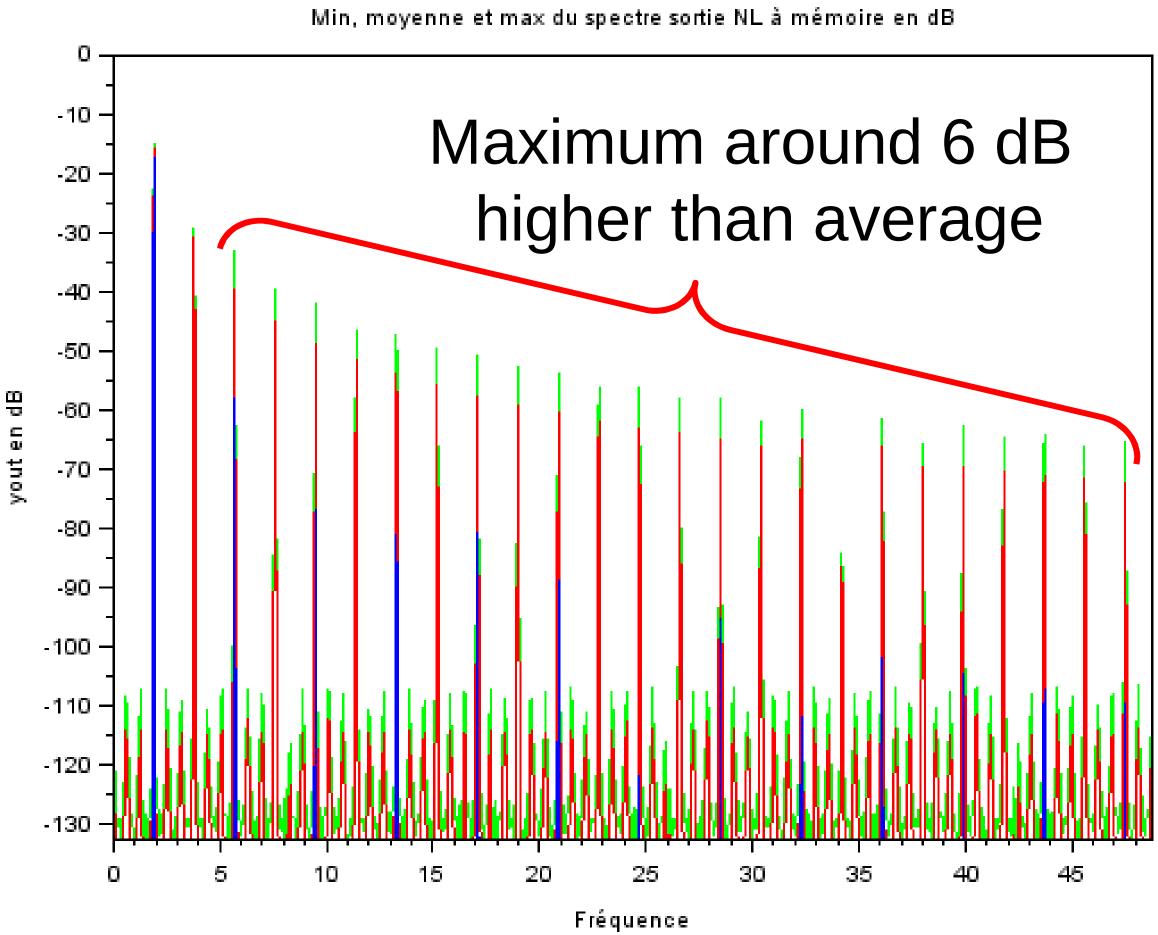
45°



Even & odd order products
Non-monotonic and slow
variation as a function of order

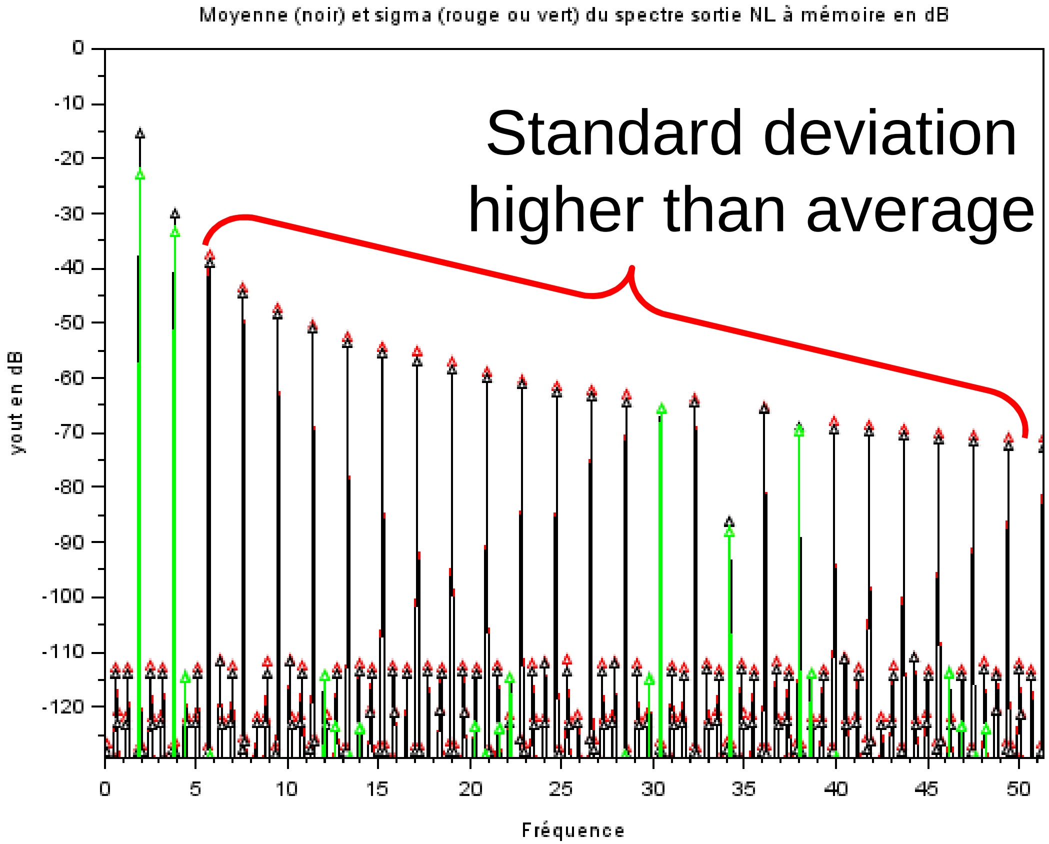
Minimum, maximum and average of harmonic spectrum for delay 0 to 360°

Minimum in blue, average in red, maximum in green



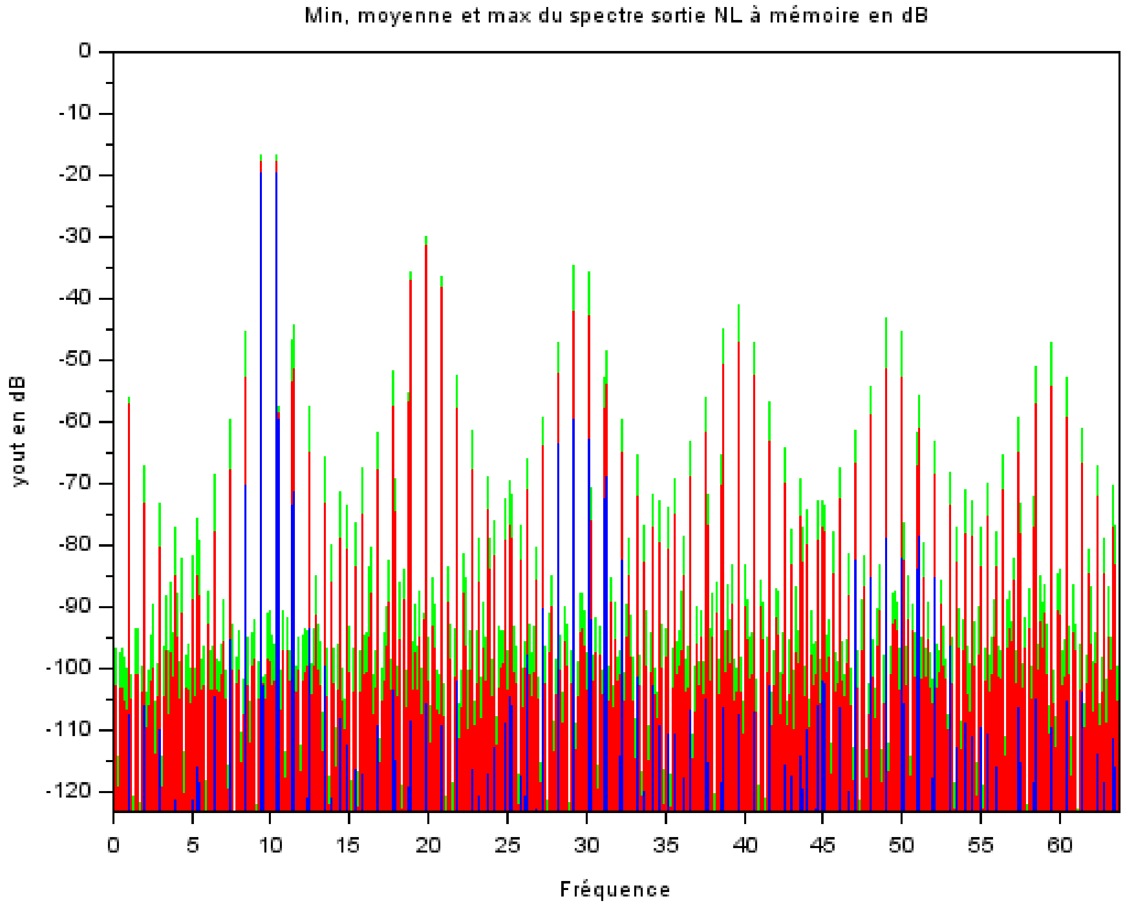
Average spectrum and standard deviation

Average in black, standard deviation in green if lower than average, in red if higher



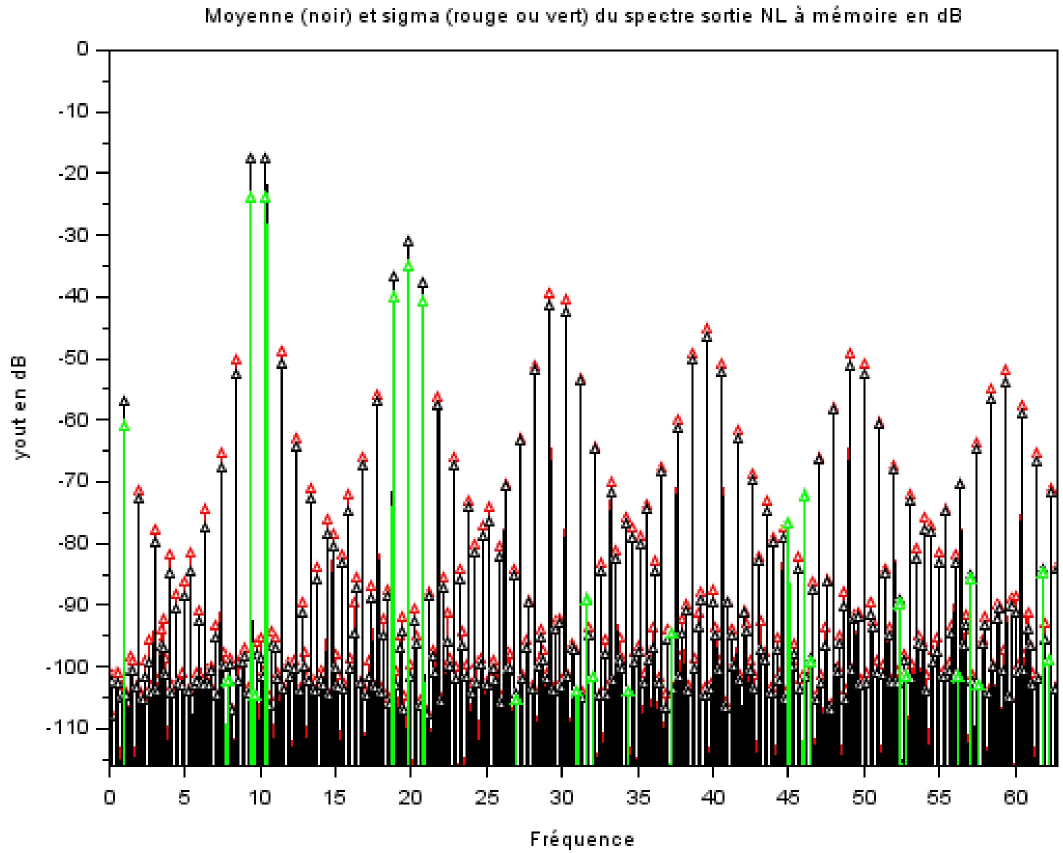
Minimum, maximum and average of 2-carrier spectrum for delay 0 to 360°

Minimum in blue, average in red, maximum in green

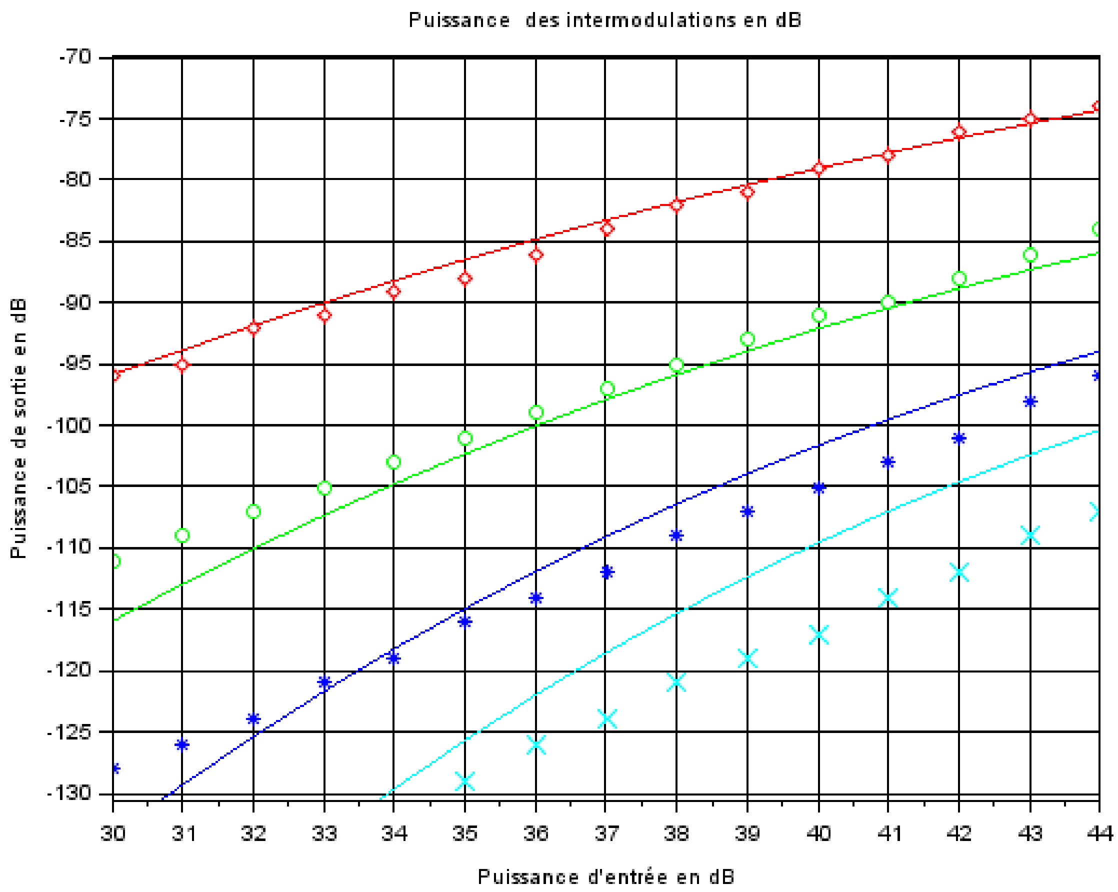


Average spectrum and standard deviation 2 carriers

Average in black, standard deviation in green if lower than average, in red if higher



Measured and averaged simulated results
Padé-like non-analytical model



3rd order IM

5th order IM

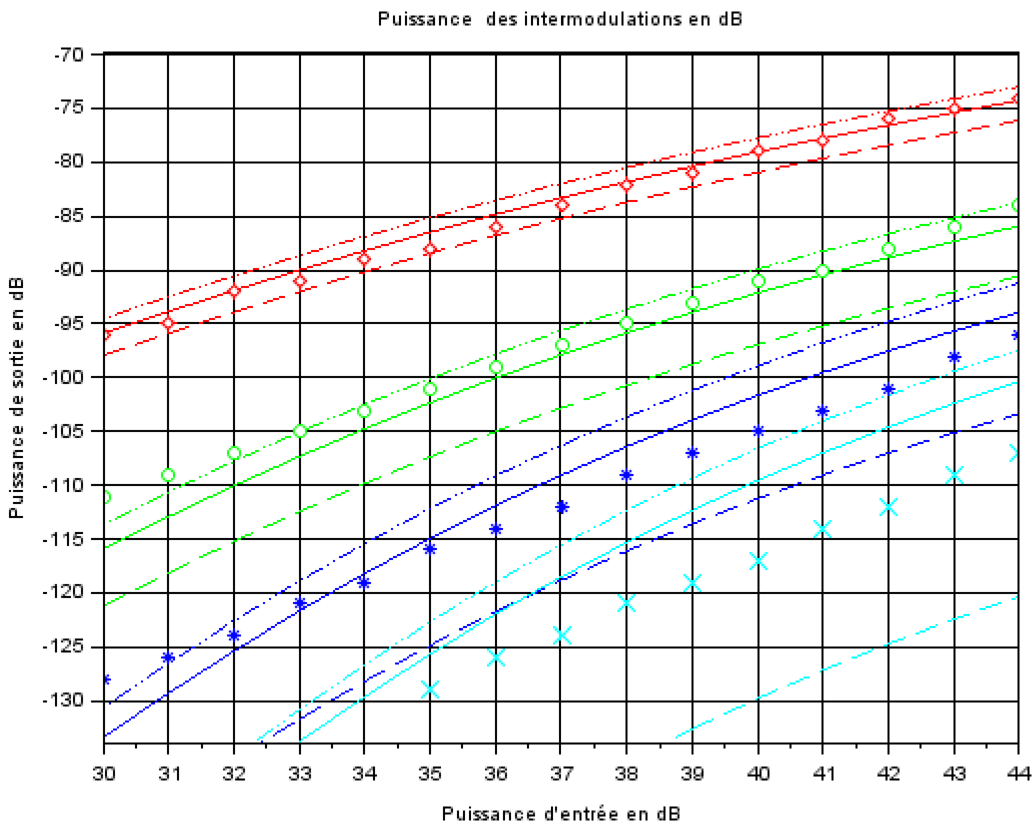
7th order IM

9th order IM

Dots: measured
Lines: simulation

Measured and averaged simulated results

Left and right products have different power even after averaging



3rd order IM

5th order IM

7th order IM

9th order IM

Dots: measured
Lines: simulation,
Left, average, right

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Conclusion

- Memristor have been used as behavioral models for passive inter-modulation generators
- Well chosen non-analytical non-linear flux vs. charge curves result in measured non-integer dB/dB slopes
- Memory may explain variability in measurements and non-monotonic variation of product power as a function of order. No control of all initial conditions.
- Memristor models are easy to simulate
  - compute average and standard deviation for a distribution of many generators and initial conditions (e.g. on an antenna reflector) in seconds on a desktop computer
- Memristors could be physical models of some PIM

Thank you for your attention

Contact information

jacques.sombrin@tesa.prd.fr

Phone: +33 5 61 24 73 79

Fax: +33 5 61 24 73 73

Mobile: +33 6 89 74 97 00

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References on Non-linearity (Bold: Passive Inter-Modulation)

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Controversy over memristor invention and patents

B. Mouttet, “The mithology of the memristor”, ISCAS 2010

Unexplained measurements (1974-1976)

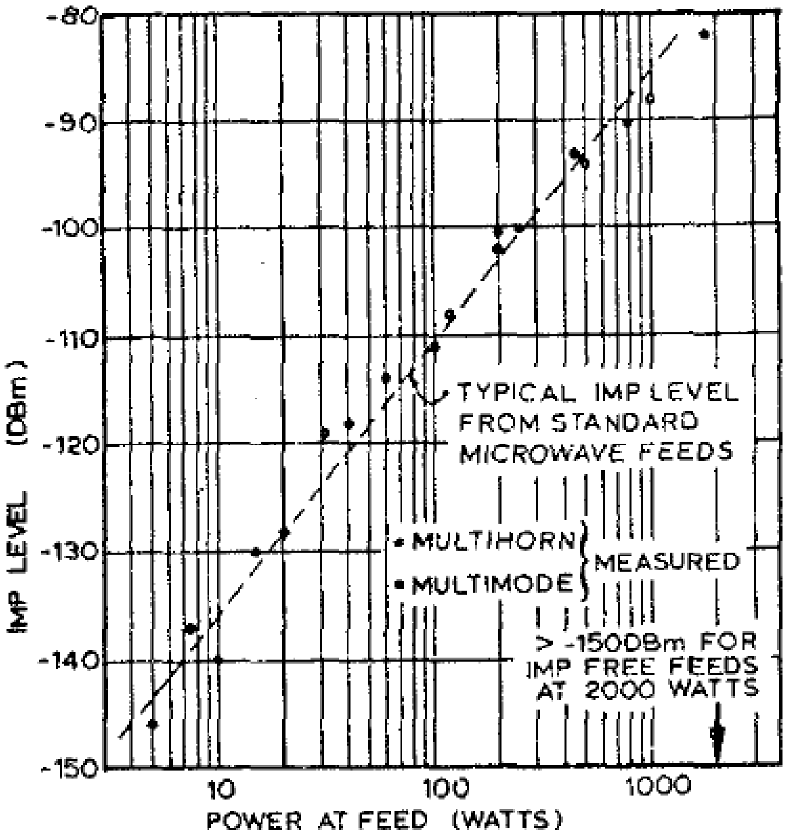


FIGURE 2 IMP LEVELS FROM TYPICAL STANDARD MICROWAVE FEEDS

First publication on 3rd order PIM
Slopes: 2.3 and 2.5 dB/dB

Chapman, Rootsev, Polidi and Davison

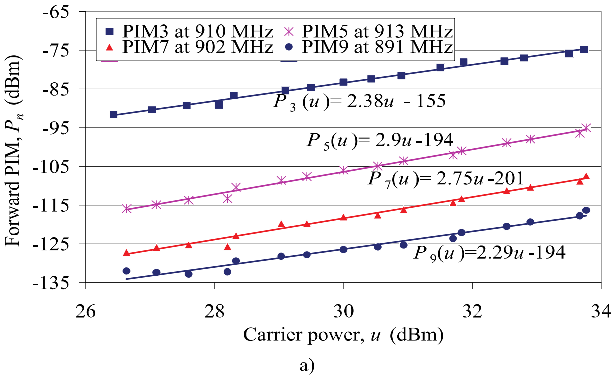
"Hidden threat multicarrier passive component IM generation",

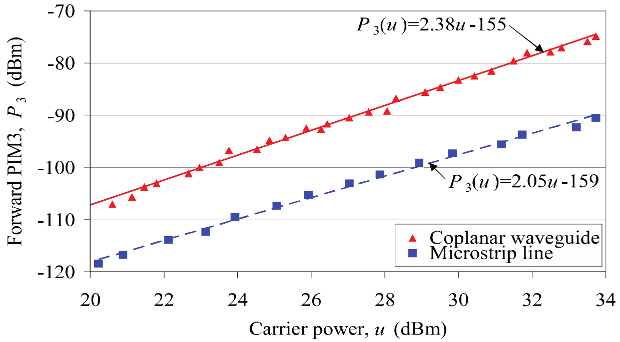
AIAA 6th Communications Satellite Systems Conference, April 1976, Montreal, Canada, pp. 296/ 1-9

Reports on unexplained measured PIM slopes in FLTSATCOM since 1974

Unexplained measurements (2009)

3rd, 5th, 7th and 9th order IM   Slopes 1.6 to 2.9 dB/dB





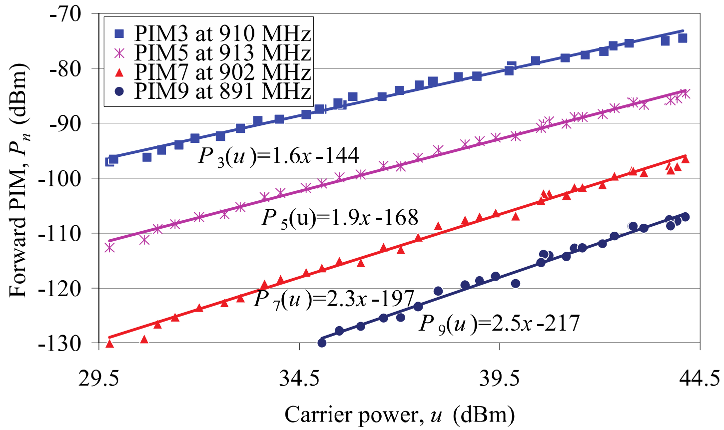
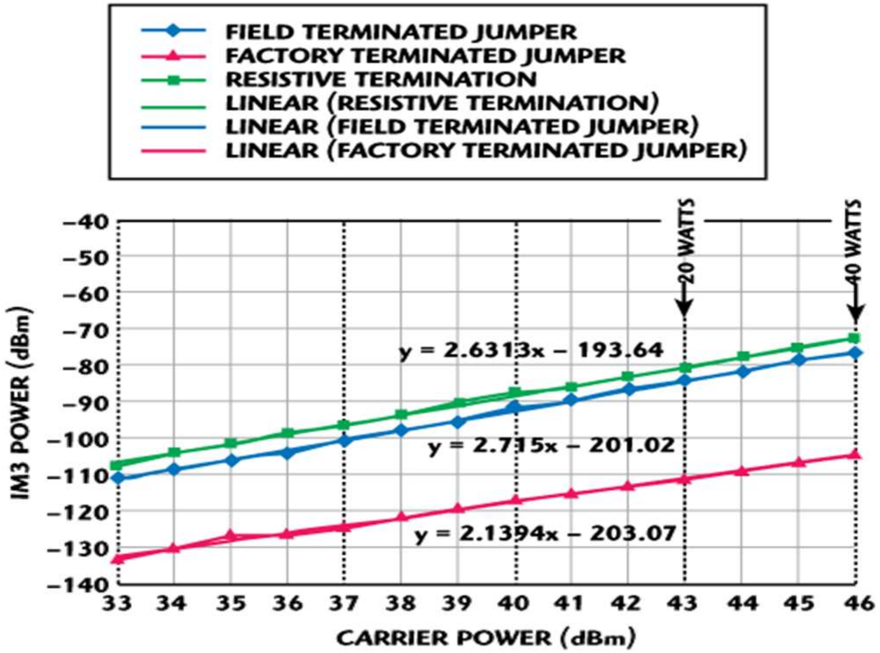


Fig. 4 Measured forward PIM3, PIM5, PIM7 and PIM9 products vs. carrier power on the microstrip line with central section of width Wc=7.44 mm with the tapered matching transformers.

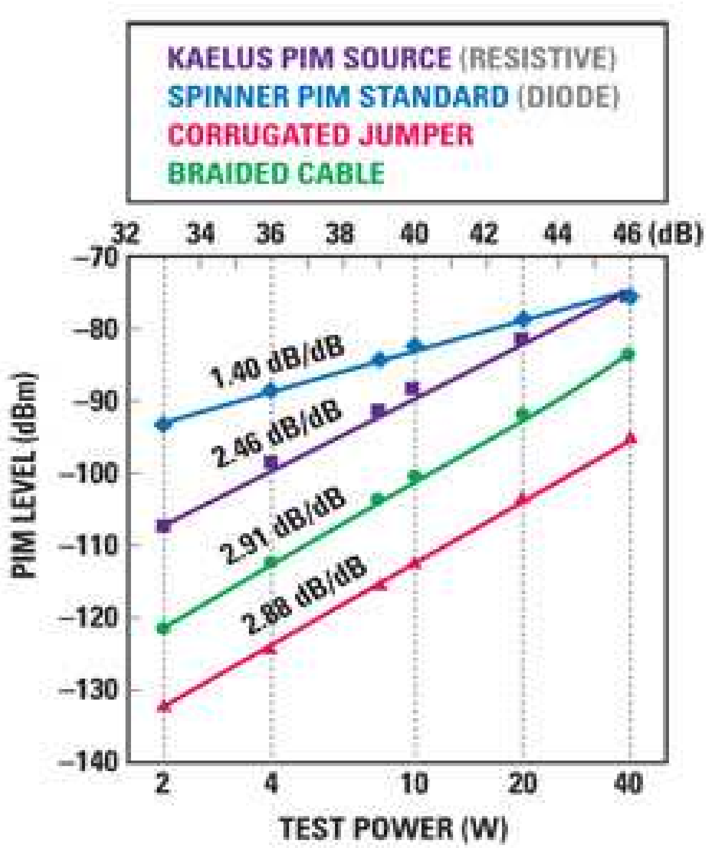
Data used for validation

A. Shitvov, D. Zelenchuk, A. Schuchinsky, "Carrier-Power Dependence of Passive Intermodulation Products in Printed Lines", 2009 Loughborough Antennas & Propagation Conference, 16-17 November 2009, pp. 177-180

Unexplained measurements (2011-2013)



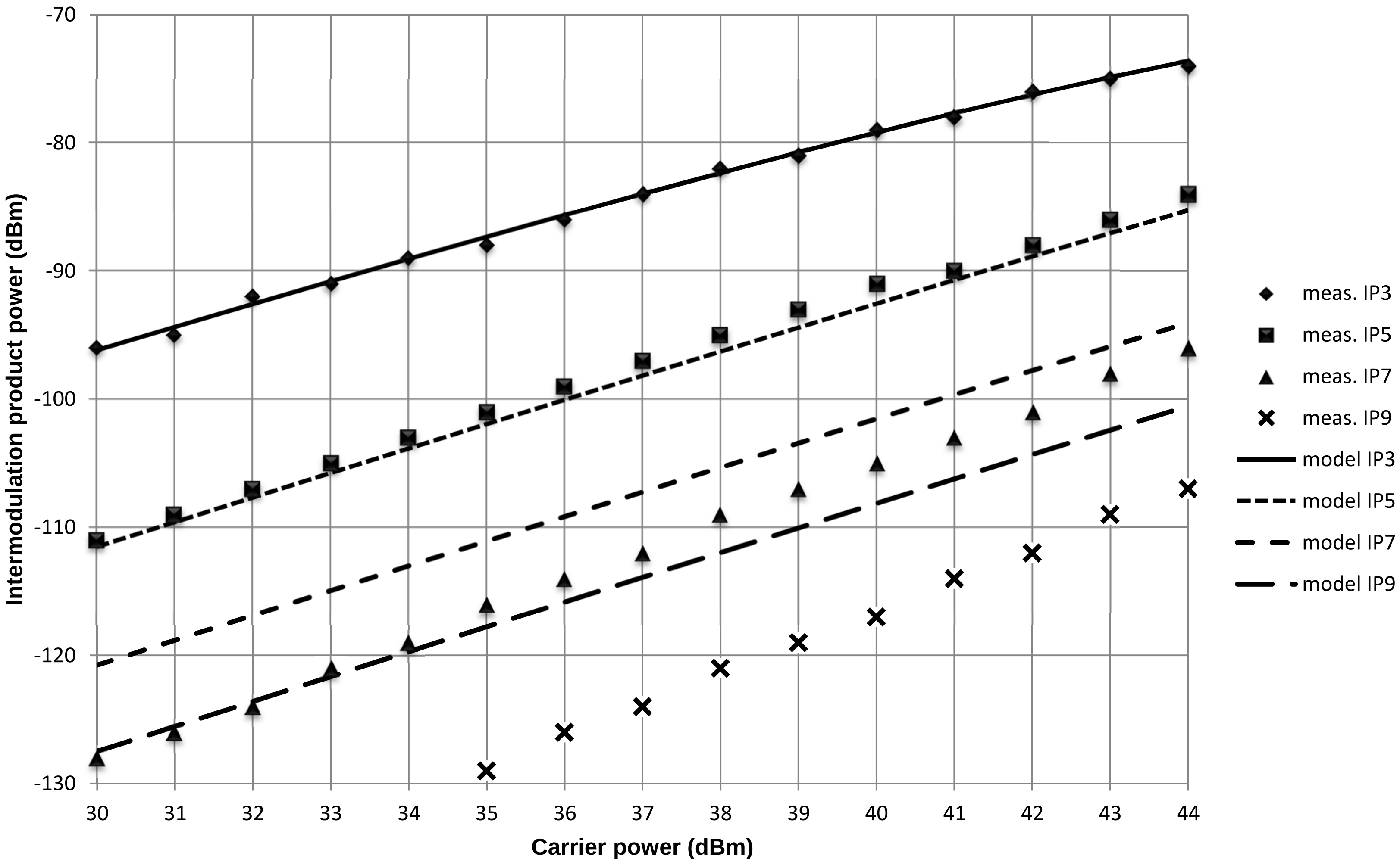
Hartman (2011)



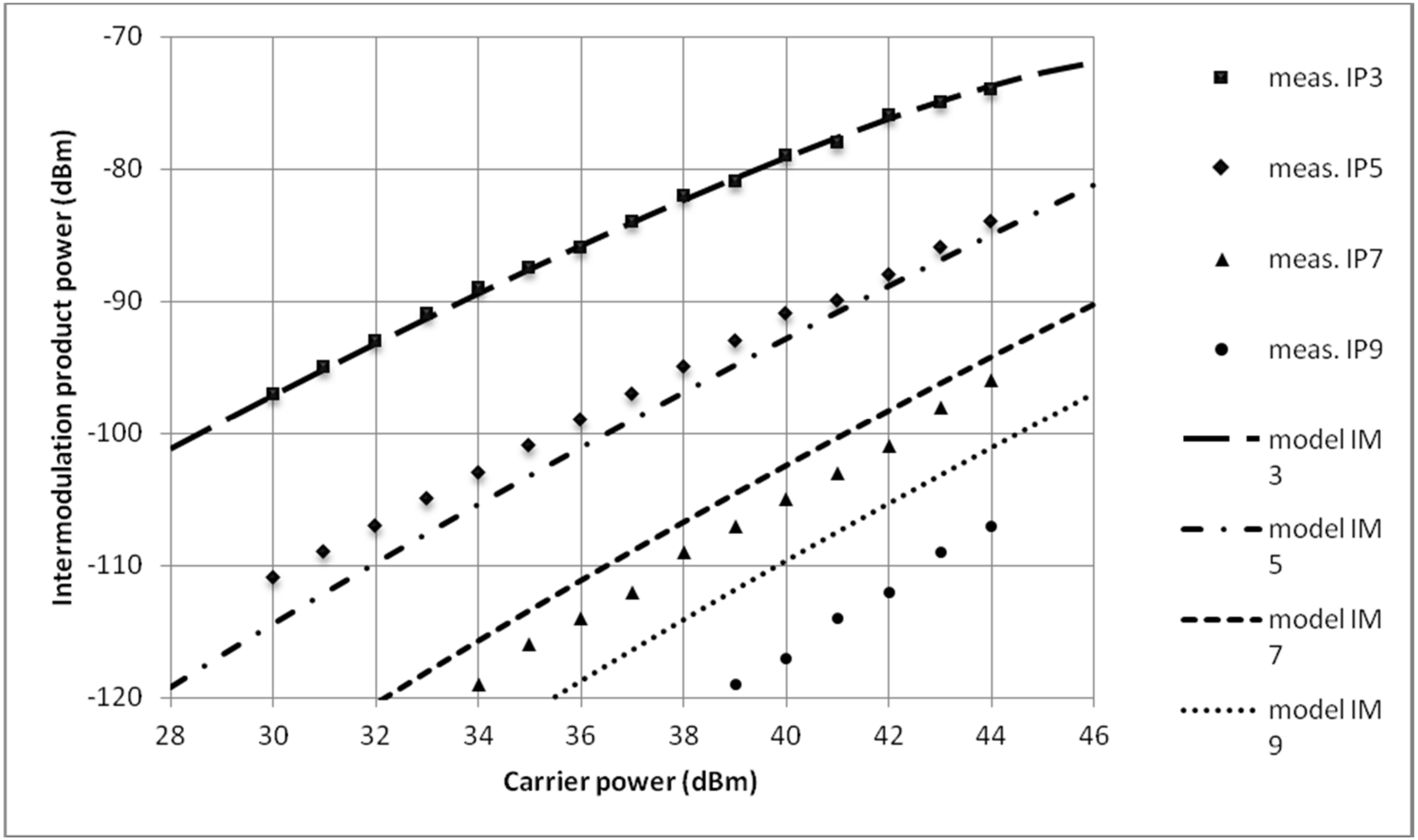
Hartman and Bell (2013

R. Hartman “Passive Intermodulation (PIM) Testing Moves to the Base Station” Microwave Journal , May 11, 2011
R. Hartman and T. Bell “PIM Test Power Levels For Mobile Communication Systems” Microwave Journal , March 15, 2013

Non-analytical model
2 non-linear terms degrees: 2 and 2,5

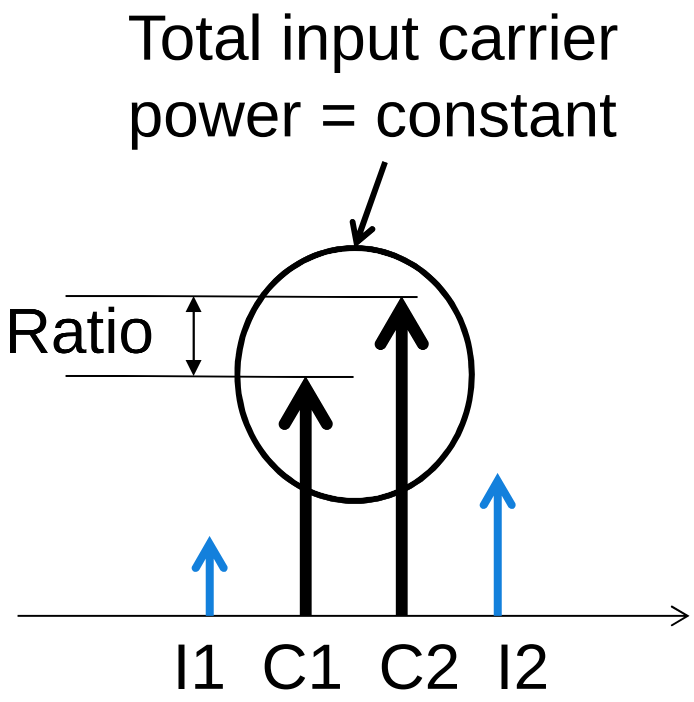


Non-analytical model
3 non-linear terms degrees: 1.5, 2 and 2.5

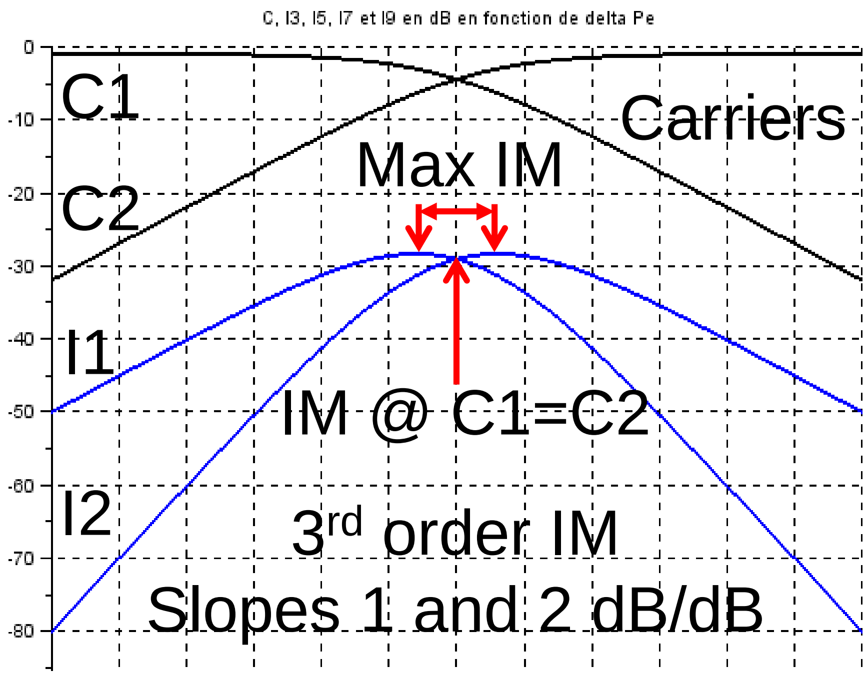


Well known classical measurement of 3rd order IM power with non-equal carriers

Simulation with a 3rd degree polynomial

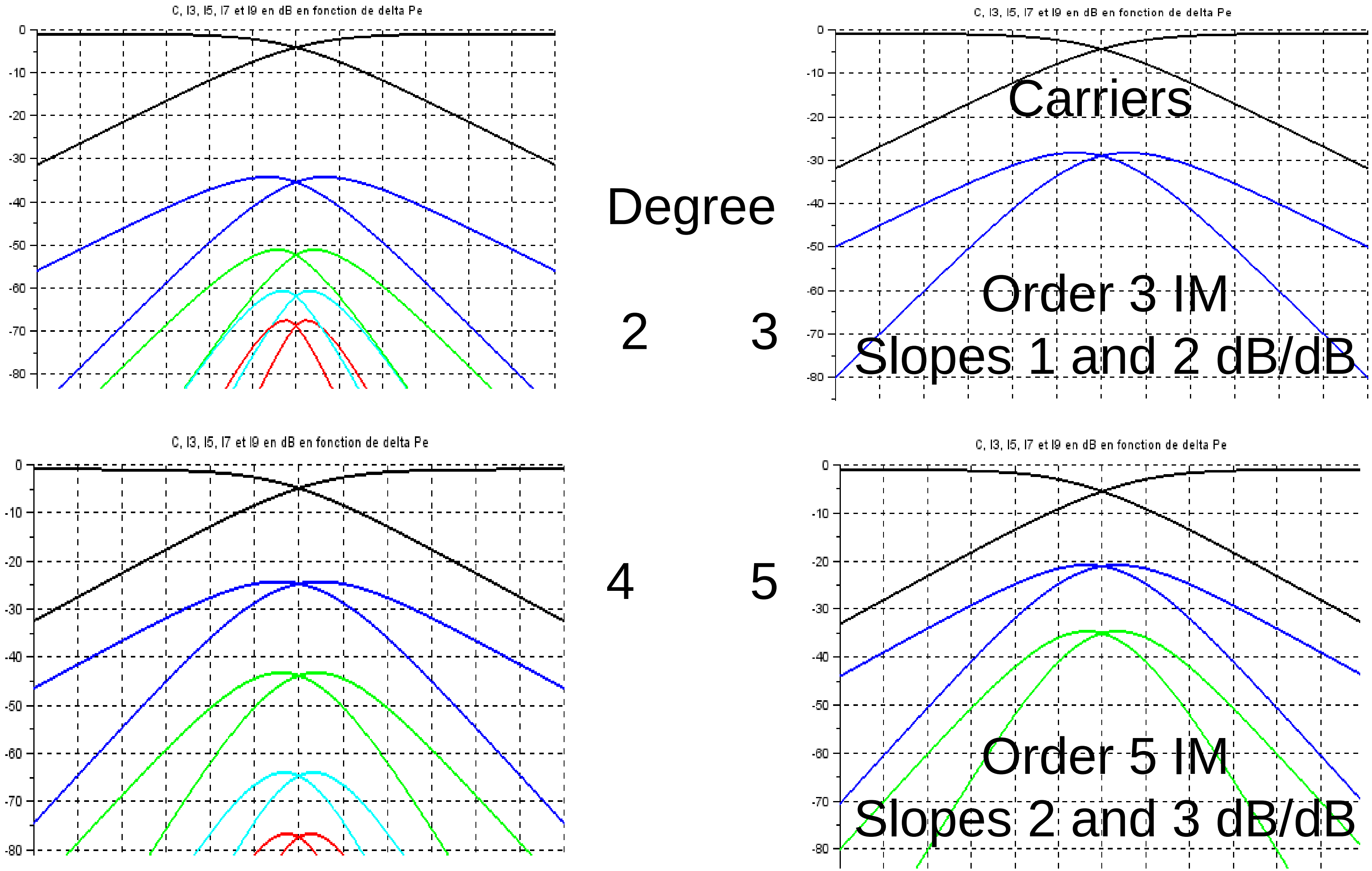


Spectrum

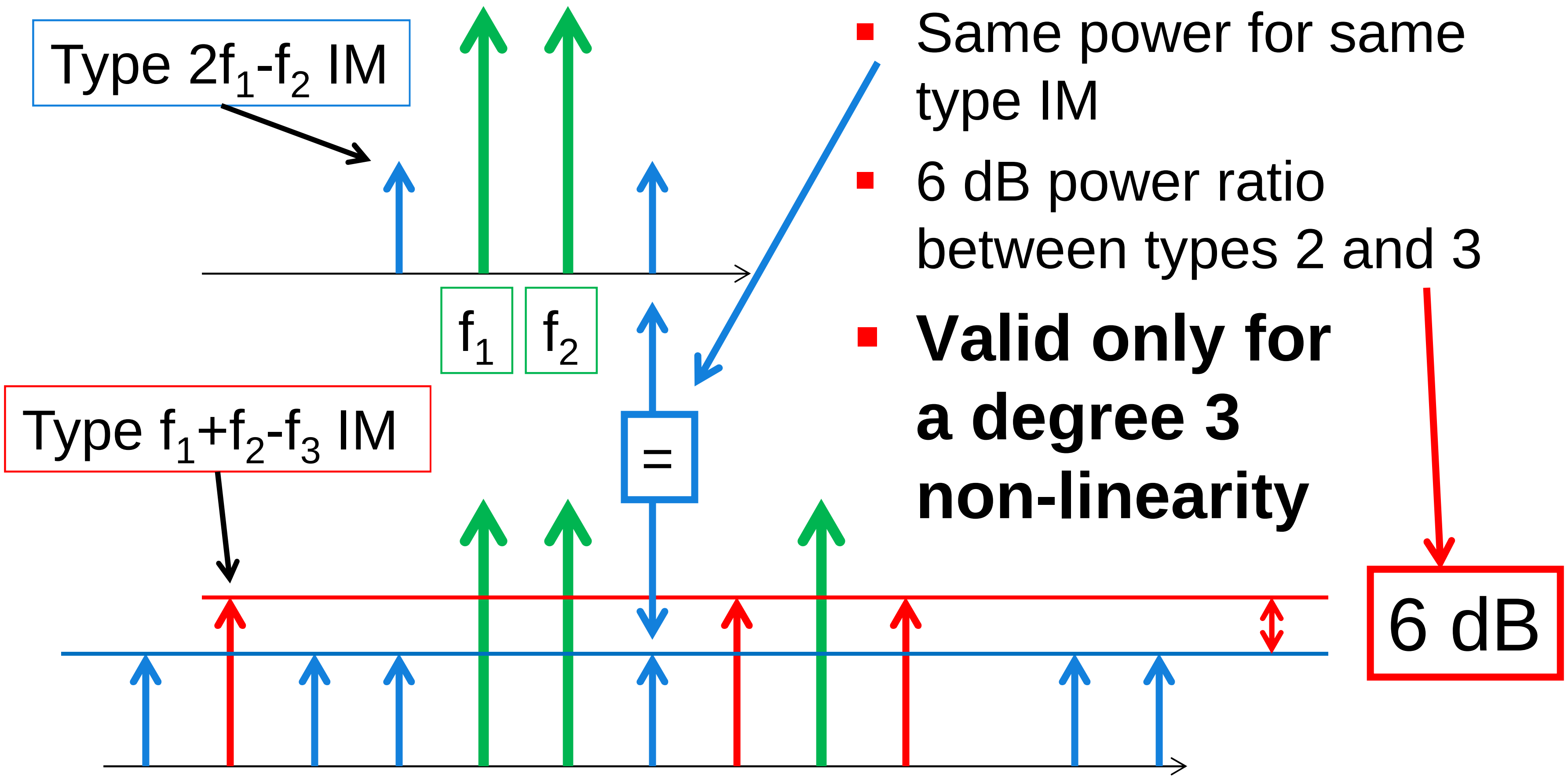


Input ratio in dB (-30 to +30)

Non-equal carriers IM power:
Results not sensitive enough



"Well known classical results"
Comparison of 2-carrier and 3-carrier IM



- Same carrier power
- Same power for same type IM
- 6 dB power ratio between types 2 and 3
- **Valid only for a degree 3 non-linearity**