Measurement and modeling of passive intermodulation in isolators and circulators

Jacques Sombrin, Geoffroy Soubercaze-Pun, Jérôme Puech,
Aurélie Boisse, Julien Marijon, Éric Laroche

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Outline

- Context of renewed interest for high power circulators and isolators in telecommunications
- Passive intermodulation measurements with 2 carriers
- Magnetic hysteresis model
- Behavioral Hammerstein model
- Validation of the model with 3 carriers
- Link to fractal dimension of sintered ferrite material
- Conclusion and future work

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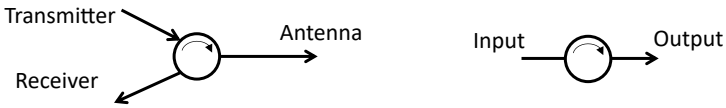
Circulators and isolators



- Non-reciprocal devices using a ferrite polarized by a strong static magnetic field
- Power transmitted only in one direction in isolator
- Isolators used in microwave payloads and functions to improve impedance matching and isolation between devices at less than 1 watt power
- Circulator used in Radar (1 carrier, transmission and reception at different times)
- **Not used at higher power in multi-carrier telecoms because of non-linearity except in some particular cases:**
  - Isolators at the output of telecom amplifiers because passive products << active products (amplifiers are followed by OMUX filter, low-pass filter and Rx/Tx diplexer)
  - In some output Multiplexers (no longer used, only if no other solution, followed by diplexer)

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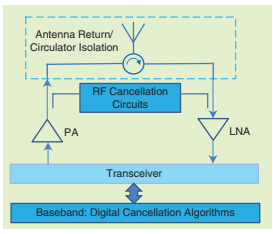
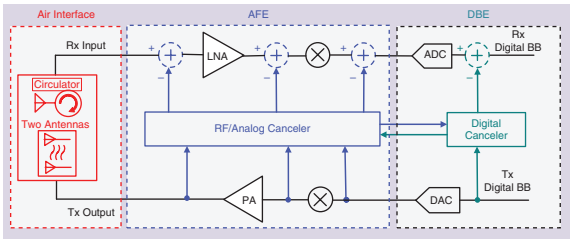
Use in Rx/Tx and in active antennas

- Circulators could be used between transmit amplifiers, antennas and receive amplifiers in telecoms multicarrier case, particularly for two-ways or full duplex systems, active antennas and MIMO systems
- Recent publications
- 4 articles in
- IEEE Microwave Magazine
- February 2019





- Active inter-modulations from the transmit amplifier can be reduced by a filter
- Passive inter-modulations in the receive bandwidth cannot be filtered out
- Possible active cancellation by analog and/or digital circuits
- **Measurements and models are necessary**
- **Measures by Cobham in a CNES study particularly for more precise modeling**

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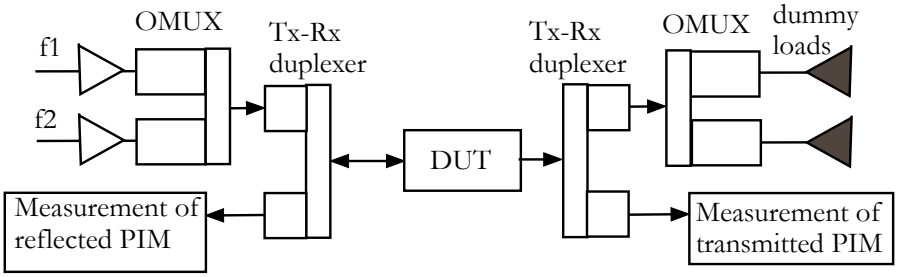
Full test bench for transmitted and reflected PIM measurement



- Test bench calibrated for very small IM products
- Use of synthesizers with low amplitude, phase and frequency noise
- Noise bandwidth around carriers multiplied by order in IM products

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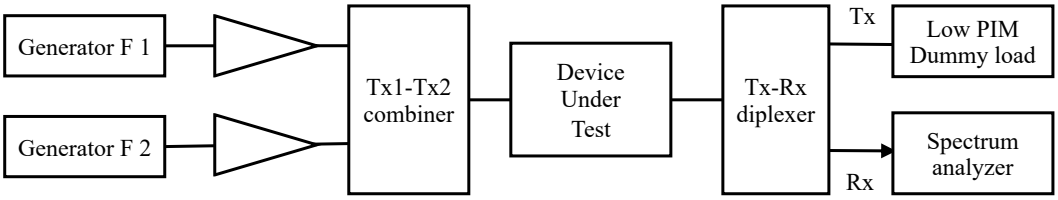
Simplified test bench, transmission only



- Measurement in transmission only of 2-carrier IM products of orders 3, 5, 7 and 9
- Low PIM dummy load (long lossy coaxial cable, no reflections, no PIM reflected)
- Only one Tx1/Tx2 diplexer and one Tx-Rx diplexer needed

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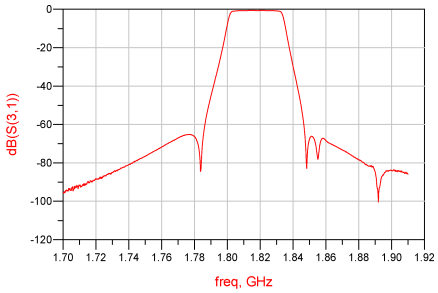
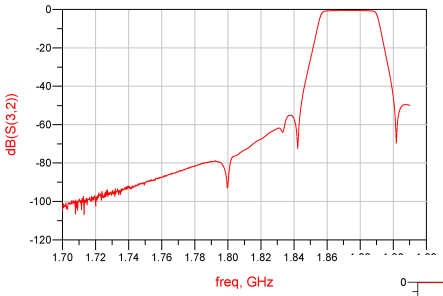
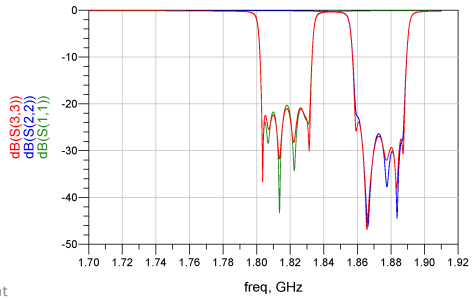
Tx1-Tx2 combiner







- Tx1 bandwidth 1804-1832 MHz
- Tx2 bandwidth 1859-1888 MHz

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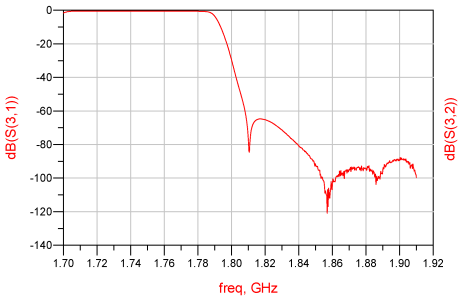
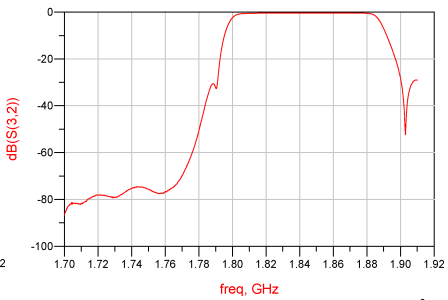
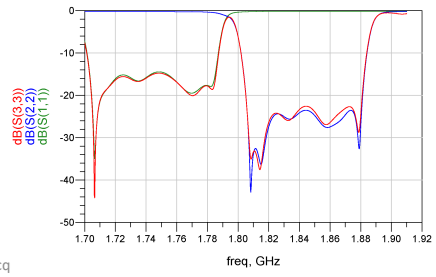
Tx-Rx diplexer







- Rx bandwidth 1705-1787 MHz
- Tx bandwidth 1806-1880 MHz

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3 configurations of frequencies

f1	f2	2f1-f2	2f2-f1	3f1-2f2	3f2-2f1	4f1-3f2	4f2-3f1	5f1-4f2	5f2-4f1
1832	1859	1805	1886	1778	1913	1751	1940	1724	1967
1823	1861	1785	1899	1747	1937	1709	1975	1671	2013
1815	1870	1760	1925	1705	1980	1650	2035	1595	2090

- Measurement of 2-carrier IM products of orders 3, 5, 7 and 9

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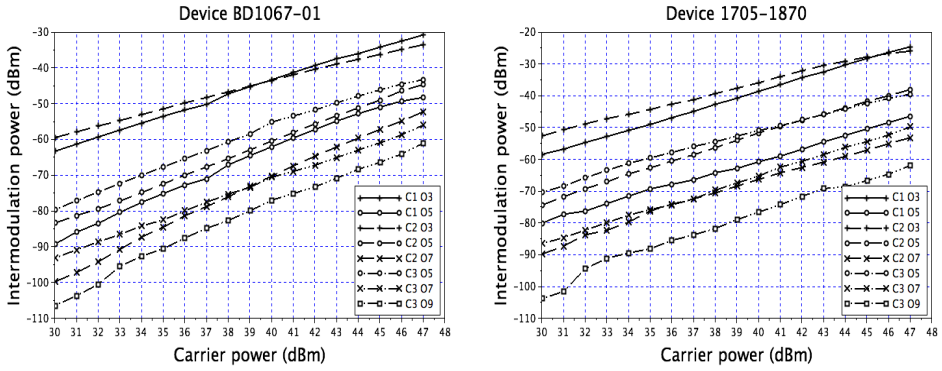
Measurements of orders 3, 5, 7 and 9



- Two isolators give similar curves
- Slopes of all orders around 2.5 dB/dB. Coherent with many published measurements
- Difficult to simulate with a classical model (polynomial, integer series, Taylor development, rational function or Padé development)

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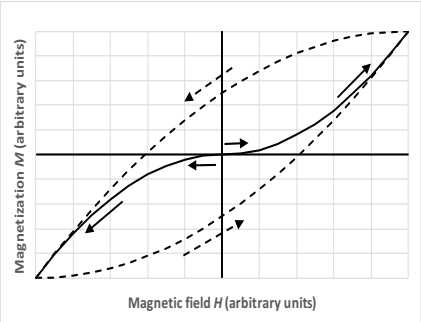
Magnetic hysteresis (1)

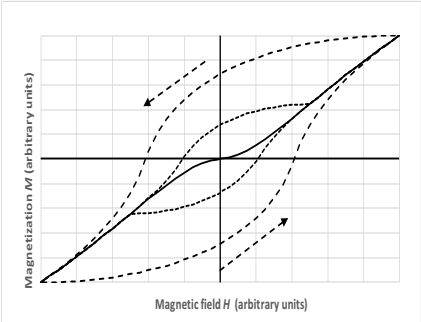
- Measure of magnetization $M(H)$ of an iron filing bar versus applied magnetic field H by Ewing in 1885 (Ewing invented the word hysteresis) [Ewing 1885]
- Measure and first theory by Rayleigh in 1887 [Rayleigh, 1887]
- Magnetic induction B depends on magnetic field and on material
- $B = \mu H$ can be written $B = \mu_0 H + M(H) = \mu_0 [H + J(H)]$
- Linear part of $M(H)$ can be removed
- Non-linear part depends on the square of H [Rayleigh, 1887]
- It is anti-symmetric: $M(H) = \text{signe}(H).|H|^2 = H.|H|$
- Order 2 and higher derivatives are discontinuous
- Harmonic power depends on the square of input power

[Ewing 1885] J. A. Ewing, "Experimental Researches in Magnetism", *Philosophical Transaction R. Soc. London,* 1885 **176**, January 1885, pp. 523-640

[Rayleigh 1887] Lord Rayleigh, "Notes on electricity and magnetism – III. On the behaviour of iron and steel under the operation of feeble magnetic forces", *Philosophical Magazine and Journal of Science*, March 1887, pp. 225-245

Magnetic hysteresis(2)

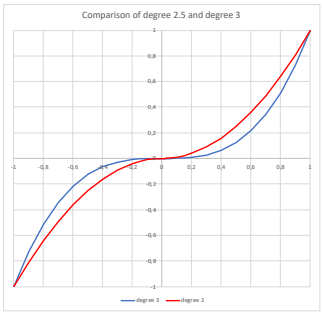


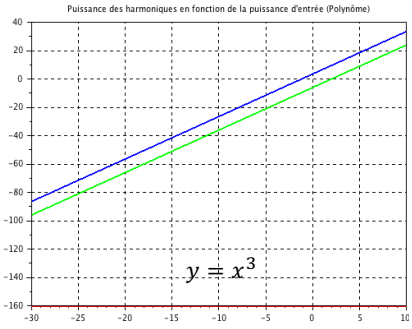


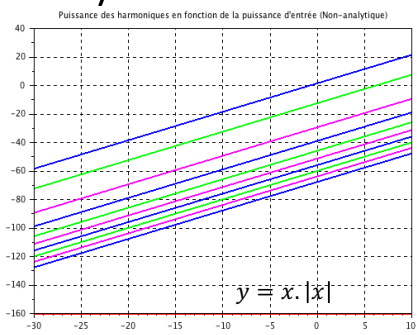
- When changing the direction of field H variation, M does not retrace the same curve => Hysteresis cycle
- Odd harmonics power computed by Rayleihgh in 1887
- Second curve with magnetic saturation at high field via the multiplication by a Padé like term, following Néel approach [Néel 1948]

[Néel 1948] L. Néel, "La loi d'approche en α/H et une nouvelle théorie de la dureté magnétique", *Journal Physique Radium*, May 1948, Vol. 9, No. 5, pp. 182-192

Difference with classical theory







[Sombrin 2013-1] J. Sombrin, "Non-analytic at the origin, behavioral models for active or passive non-linearity", *International Journal of Microwave and Wireless Technologies*, 2013, 5(2), pp. 133–140

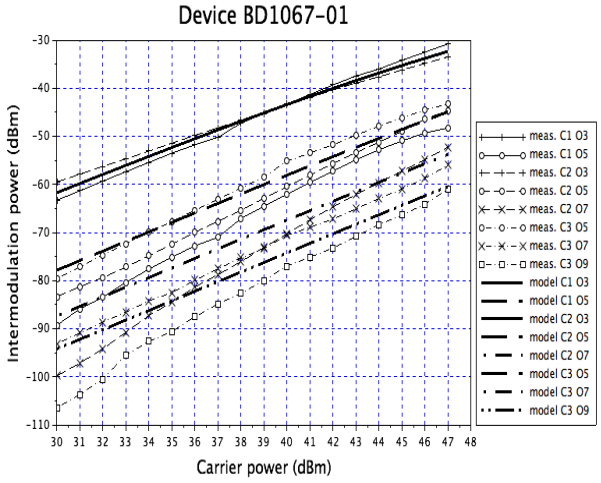
[Sombrin 2013-2] Sombrin, Soubercaze-Pun, Albert, "New models for passive non linearities generating intermodulation products with non-integer slopes", *EuCAP 2013*, Gotegorg, Sweden

[Sombrin 2013-3] Sombrin, Soubercaze-Pun, Albert, "Modélisation et prédiction des produits d'intermodulation passifs", *JNM 2013*, Paris

[Sombrin 2013-4] Sombrin, Soubercaze-Pun, Albert, "Discontinuity at origin in Volterra and band-pass limited models", *IMS 2013*, Seattle, USA

[Sombrin 2013-5] J. Sombrin, Soubercaze-Pun, I. Albert, "Multicarrier Passive Inter-Modulation Prediction from 2-Carrier Measurements", *31st AIAA International Communication Satellite Systems Conference*, October 14-17 , 2013, Florence

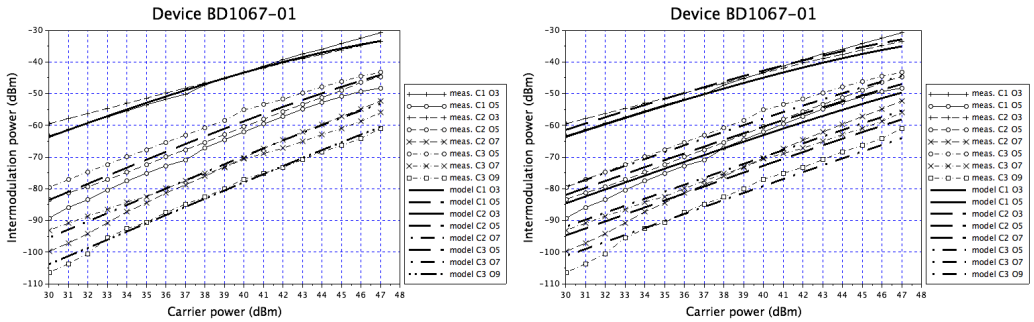
Physical model of isolator PIM



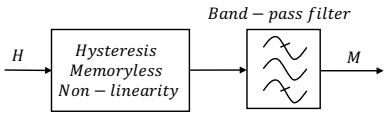
- Simulation of hysteresis with saturation
- For sinusoidal signal or for 2-carrier
- Computation of IM products power
- Error due to model slope that is nearly 2 dB/dB (except near saturation)
- Correct model for iron, steel and Nickel alloys giving slopes of 2 dB/dB as measured in [Henrie,2016]
- Less correct for ferrite isolator

[Henrie, 2016] J. Henrie, US 9,306,261 B2 Patent, 2016

Behavioral models of isolator PIM



- Slopes around 2,5 dB/dB
- Products power depends slightly on frequency
- Hammerstein model with slope 2,3 dB/dB
- Also tested a model with two different non-integer exponents



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Validation of the non-analytical model

- Predictions of the non-analytical model are different from the classical (polynomial) model for multi-carrier signals
- Using the classical model (and generally for amplifiers), when adding carriers and keeping the same carrier power, the power of products from previous carrier does not change
- Using the non-analytical model with a slope lower than 3 dB/dB, when adding carriers, the power of products from previous carriers decreases
- **Validation with 3 carriers**

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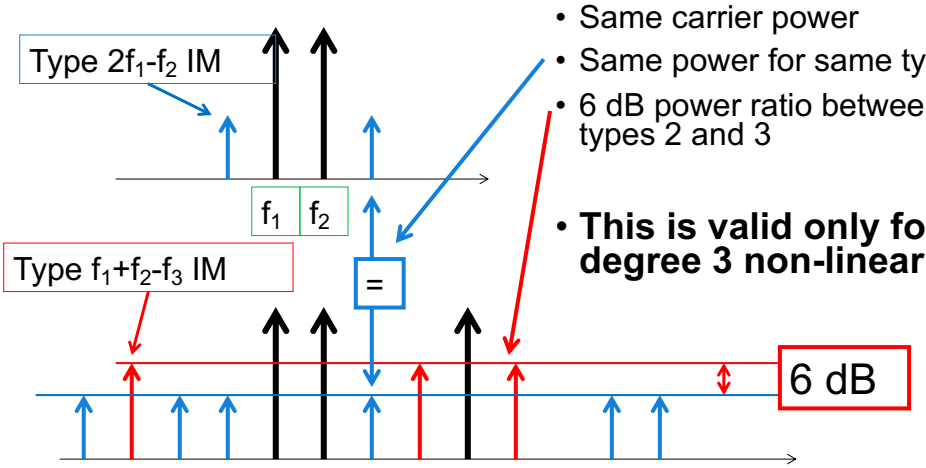
Comparison of 2-carrier and 3-carrier IM



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

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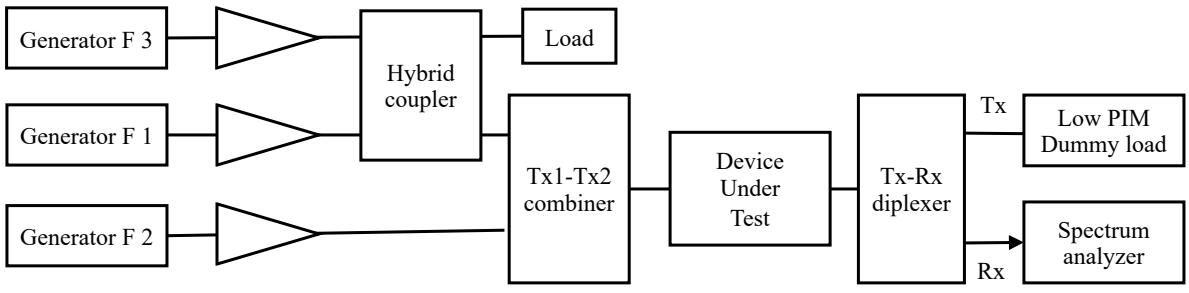
Modification of the test bench for 3 carriers



- Third carrier is added to first one through hybrid coupler
- Possible active and passive IM between both carriers are filtered by Tx combiner
- Reduced possibilities, measurement of 3rd and 5th order PIM

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3 configurations of frequencies

f1	f2	f3	2f1-f2	2f2-f1	2f3-f2	2f2-f3	f1+f3-f2	f1+f2-f3	f3+f2-f1	3f1-2f2	3f3-2f2	2f3+f1-2f2	f3+2f1-2f2
1810	1859	1820	1761	1908	1781	1898	1771	1849	1869	1712	1742	1732	1722
1810	1859		1761	1908						1712			
	1859	1820			1781	1898					1742		

- With 3 carriers, measurement of 3 order 3 IM products and 4 order 5 IM products
- With 2 carriers, measurement of 1 order 3 IM product and 1 order 5 IM product

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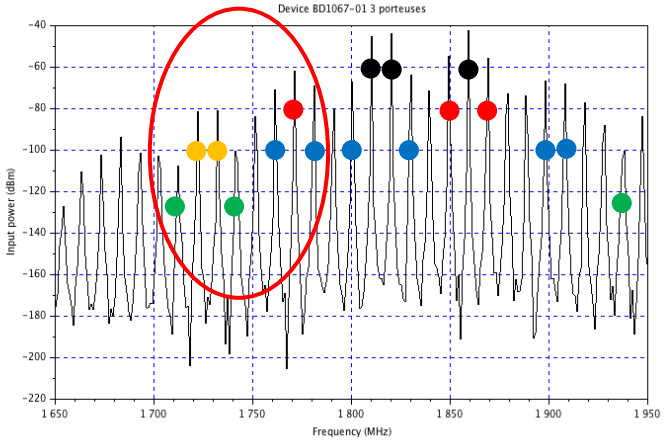
Spectrum of 3-carrier simulation



- Carriers
- 2-carrier order 3 PIM
- 2-carrier order 5 PIM
- 3-carrier order 3 PIM
- 3-carrier order 5 PIM
- Products measured in Rx bandwidth

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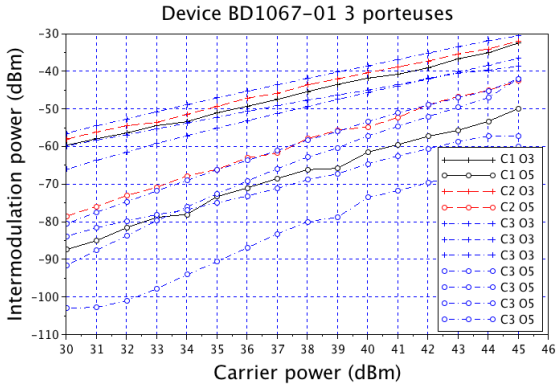
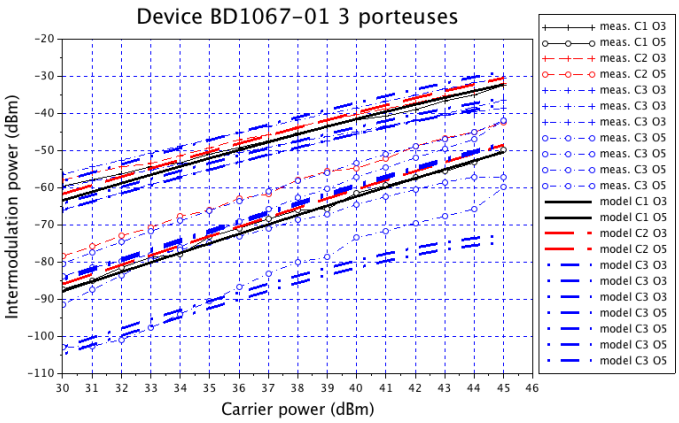
Measurement and Hammerstein model



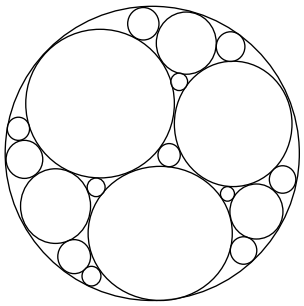


Results

- Decrease of 2-carrier PIM power from 2-carrier to 3-carrier case => degree of NL is less than 3
- Change of slope on some PIM products to be explained
  - higher order PIM products recombination,
  - memory effects, temperature,
  - IM between F1 and F3 in hybrid coupler,
  - …
- Good model fit for order 3
- Correctly explain the decrease of PIM power from 2-carrier case to 3-carrier case
- Model to be improved for order 5

Open problems for a better physical model

- Explain the theoretical degree (and slope) of 2 in Rayleigh law of magnetism
- Explain the slope of around 2.3 to 2.5 dB/dB for measurements of ferrite isolators instead of the theoretical slope of 2 dB/dB
  - Optimized ferrite material is sintered from powders with varied granulometry to minimize voids and get small grains and highest possible saturation
  - The magnetic energy stored in a piece of magnetic material is proportional to the total surface of the grains (magnetic domains)
  - The fractal dimension (Hausdorff dimension) of the grain surface in some ferrite samples has been measured with X-rays and is between 2.3 and 2.5
    - Fractal dodecahedron or fractal pyramid: 2.32
    - Apollonian sphere (3D extension of Apollonian gasket): 2.47



- $\frac{dM}{M} = r\frac{dH}{H}$ => $\frac{d\log(M)}{d\log(H)} = r = \frac{\log(S)}{\log(D)}$ = Hausdorff dimension ?
- Explanation or just a coincidence ????

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Conclusion and future work

- Much better results with Hammerstein-hysteresis behavioral model than with any classical model
- Validation of the model with 3 carriers

- Define some additional measurements to investigate remaining differences between model and measurements
- Improve the model for order 5 with 3 carriers
- Measurements at Ku Band with low PIM triplexer
- Transform behavioral model in a physical model
- Apply fractal dimension to other types of physical causes of PIM such as roughness of waveguide flanges or micro-strip lines edges

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