Higher Dynamic Measurement of Antenna Passive Intermodulation Products, using Ray Optics

Jacques Sombrin

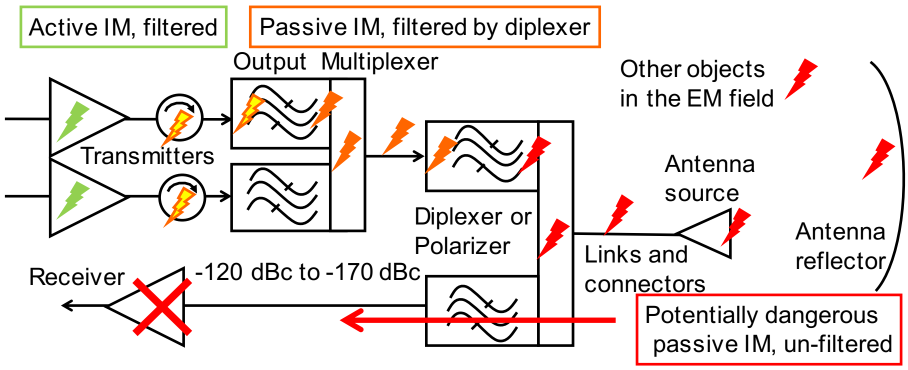
TESA Laboratory, Toulouse

Outline of talk

- Passive Inter-Modulation phenomenon
- State of the art PIM test benches
  - Need for higher dynamic measurements
- Linear reflection and refraction of plane waves
- Non-linear reflection of waves
  - Second harmonic and sum frequency
  - Third order IM products
  - Improvement of measurement dynamics
  - Proof of concept and first measurements
- Conclusion

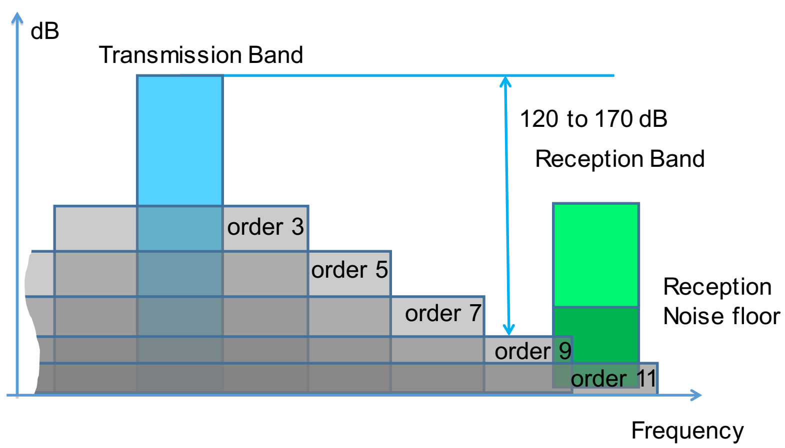
Passive intermodulation (PIM) generation

- 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



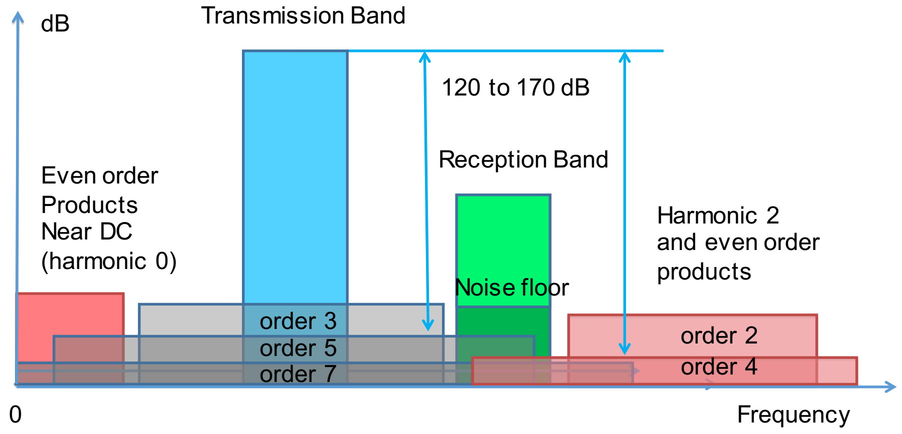
Passive intermodulation noise spectrum

Odd order IM products only



Passive intermodulation noise spectrum

Odd and even order IM products



12/04/2016 EuCAP 2016, Davos Copyright Jacques Sombrin 5

Overview of IM frequency and phase relations

- Frequencies and phases of of IM products of p carriers are given by:

$$f_{m_1,\dots,m_p} = |m_1 f_1 + m_2 f_2 + \cdots + m_p f_p|$$
$$\phi_{m_1,\dots,m_p} = |m_1 \phi_1 + m_2 \phi_2 + \cdots + m_p \phi_p|$$

With $m_i \in \mathbb{Z}$ (positive, negative or null integers)

- Harmonic number is:

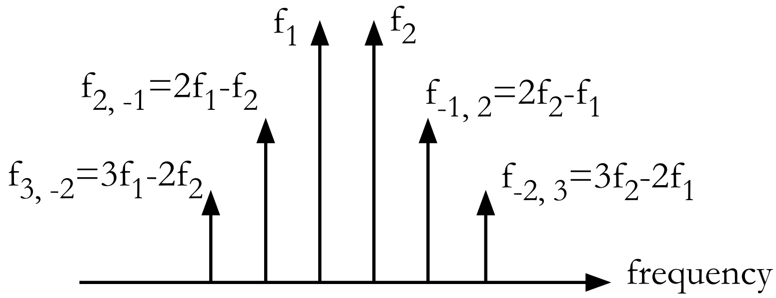
$$H = \left|\sum_{i=1}^{p} m_p\right|$$

- Order of IM is:

$$O = \sum_{i=1}^{p} |m_p|$$

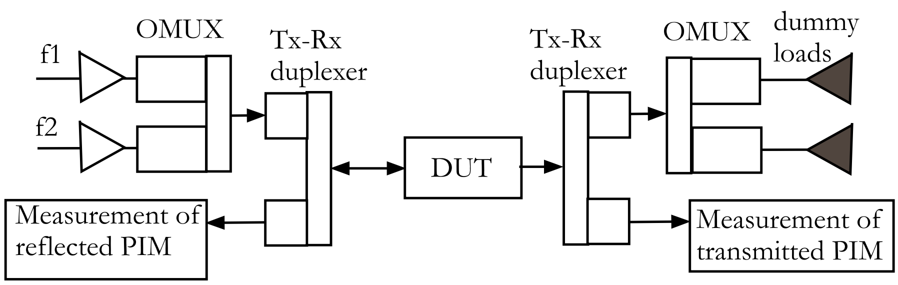
12/04/2016 EuCAP 2016, Davos Copyright Jacques Sombrin 6

Spectrum of IM products around 2 carriers



- Frequencies of products generated by 2 CW carriers are easy to compute
- Spread in frequency around carriers' frequencies

Frequency selectivity in test bench



- Test equipment (OMUX, duplexer) must be PIM free
- Patent EP0309350B1 (1988) US 4918684 (1990)
- Frequency selectivity is not always sufficient for some products

Use spatial selectivity

Need for higher dynamic measurement

- Requirements for antennas generally ask for passive intermodulation products levels that will increase the noise level in the receiver by much less than 0.1 dB. This means that in normal operation, IM level is at least 17 dB lower than the receiver own noise
- Measurement with pure continuous wave carriers, with minimum phase and amplitude noise.
- Not always sufficient as high order PIM are spread by phase and frequency noise multiplied by PIM order
- Higher dynamic in measurement would permit to measure slope different from classical 3dB/dB slope
- Allow to relax specification
- Allow to use lighter or cheaper technology for reflectors

Phases of plane waves

- Phases of plane waves depend on position and time by way of their wave-vector $\vec{k}$ and radian frequency ω
- At a position $\vec{r}$, the phase of wave i is given by:

$$\phi_i = \omega_i t - \overrightarrow{k_i}\vec{r} + \varphi_i$$

$$\phi_i = \omega_i t - k_x x - k_y y - k_z z + \varphi_i$$

- With:

$$k_i = \left|\overrightarrow{k_i}\right| = \frac{2\pi}{\lambda_i} = \frac{\omega_i}{c}$$

Phases of IM products

- The phase of an IM product created by 2 plane waves at position $\vec{r}$ is given by:

$$\phi_{m,n} = m\left(\omega_1 t - \overrightarrow{k_1}\vec{r} + \varphi_1\right) + n\left(\omega_2 t - \overrightarrow{k_2}\vec{r} + \varphi_2\right)$$

- The length of the wave-vector is:

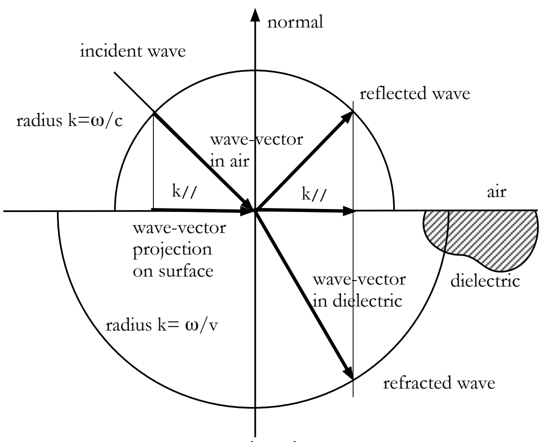
$$k_{m,n} = \frac{\omega_{m,n}}{c} = \frac{m\omega_1 + n\omega_2}{c} = mk_1 + nk_2$$

- If all plane waves come from the same direction, wave-vectors are aligned and we have:

$$\overrightarrow{k_{m,n}} = m\overrightarrow{k_1} + n\overrightarrow{k_2}$$

But this is not true if incident directions are different

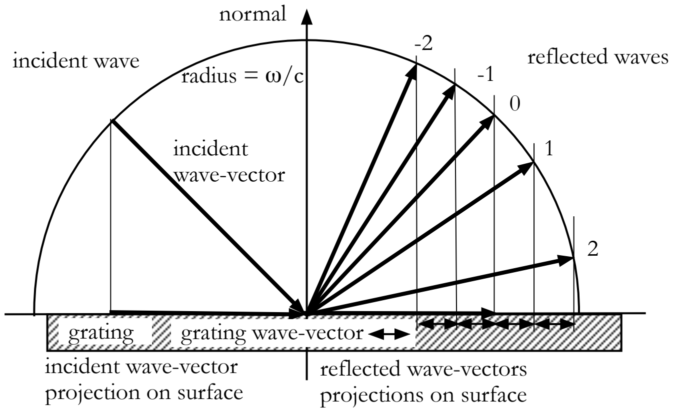
Linear reflection and refraction on a plane (using ray optics)



Identical wave-vector projections on the plane

Brewster angle: no refraction if length lower than projection: $k = |\vec{k}| < k_{\parallel}$

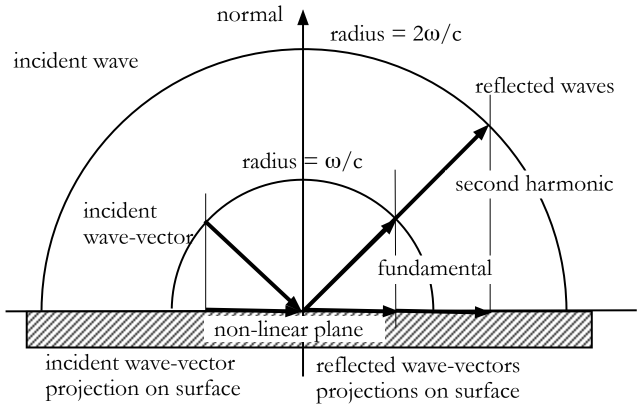
Non-linear reflection on a grating



- Addition of multiples of grating wave-vectors
- Spread of reflected beams at same frequency
- Can be applied to passive reflect-array

12/04/2016 EuCAP 2016, Davos Copyright Jacques Sombrin 13

Second harmonic reflection by a plane with homogeneous, distributed non-linearity



- Doubling of wave-vector and of wave-vector projection
- Same reflection angle as fundamental in non-dispersive medium

12/04/2016 EuCAP 2016, Davos Copyright Jacques Sombrin 14

Phases of IM products on a non-linear plane reflector

- Incident waves

$$\phi_i = \omega_i t - \overrightarrow{k_i}\vec{r} + \varphi_i$$

- Reflected waves phases and frequencies

$$\phi_{m,n} = |m\phi_1 + n\phi_2|$$
$$\omega_{m,n} = |m\omega_1 + n\omega_2|$$
$$f_{m,n} = |mf_1 + nf_2|$$

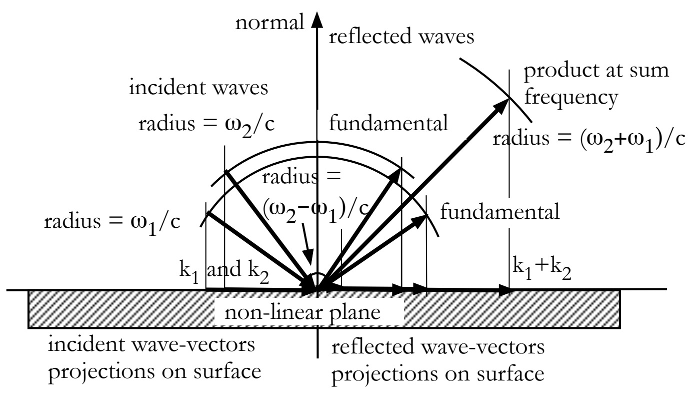
- Reflected wave-vectors projections on the surface

$$\overrightarrow{k_{m,n\,\parallel}} = m\overrightarrow{k_{m\,\parallel}} + n\overrightarrow{k_{n\,\parallel}}$$

- Reflected wave-vectors lengths

$$k_{m,n} = \left|\overrightarrow{k_{m,n}}\right| = \omega_{m,n}/c$$

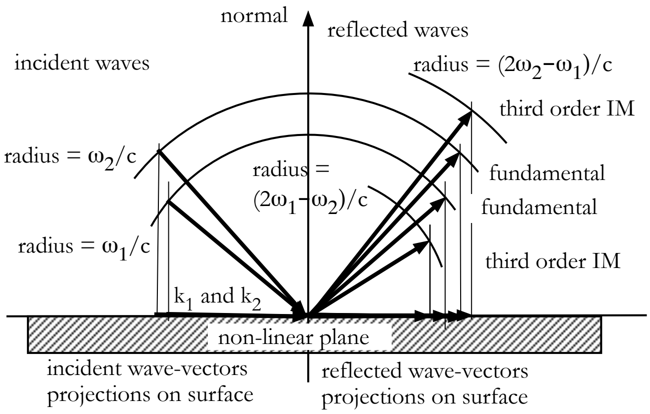
Non-linear sum frequency reflection



- Sum frequency wave-vector different from vector addition of wave-vectors
- Difference frequency may not propagate if length lower than projection: $k < k_\parallel$

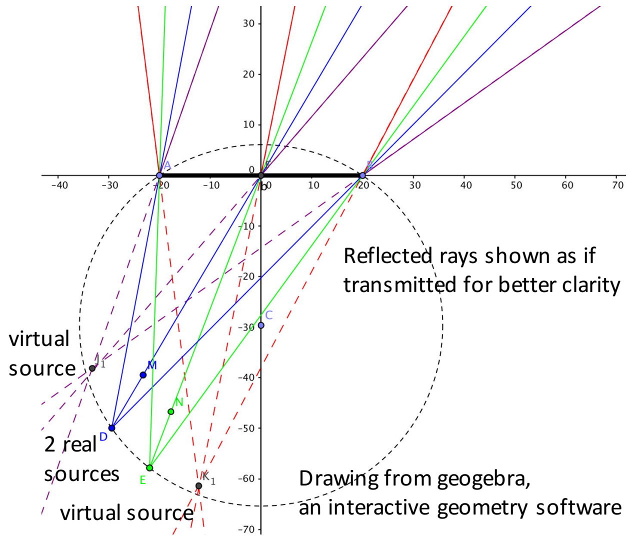
Bloembergen and Pershan, "Light waves at the boundary of nonlinear media", Physical Review, Vol. 128, No. 2, October 15, 1962, pp. 606-622

Propagation directions of carriers and IM products



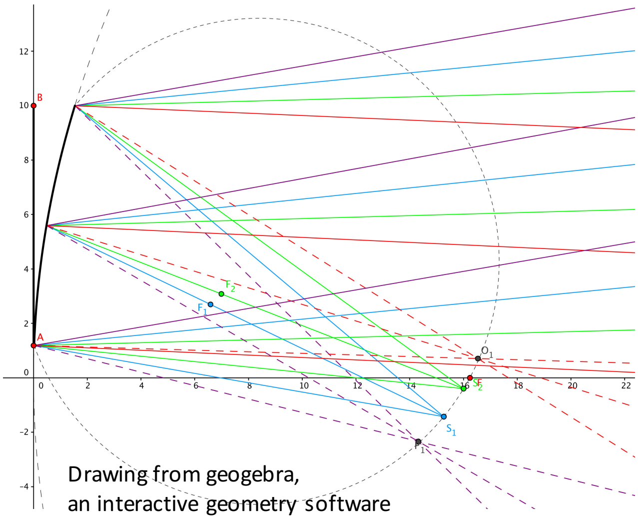
- Spreading of reflected directions for IM products if carriers' incident directions are different

Reflection of spherical waves on a finite plane reflector



- Different geometry on each point of the reflector
- Third order IM products seem to come from two virtual sources
- Position depends on real sources positions and on frequency of carriers

Reflection of spherical waves on a finite parabolic reflector



Drawing from geogebra, an interactive geometry software

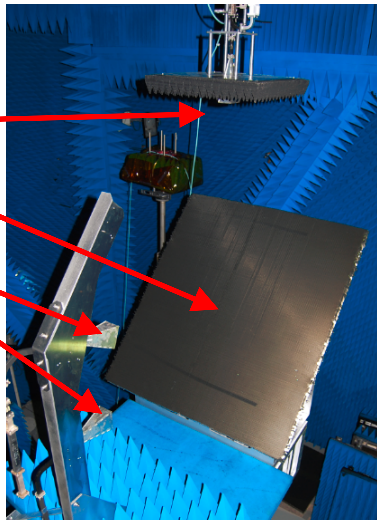
- Two feed horns near the focal point
- IM virtual sources also near the focal point
- IM products are focused beams
- Some IM may be directed toward some Rx horns of a multi-feed antenna

Improvement of measurement dynamics

- Maximum gain direction of reflected IM products diagram is different from the one of carriers
- In near field conditions, IM product fields exist where carrier fields are low
- By choosing correctly the position of the test antenna, we will be able to measure IM products near their maximum gain while the gain for carriers is lower, thus increasing the measurement dynamic
- PIM free test bench as each carrier is transmitted from a different feed horn
- Proof of concept at Thales Alenia Space near-field anechoic chamber shows a first improvement of 15 dB

Proof of concept test bench

- TAS anechoic chamber
- Near-field test range
- 1 mobile horn for Rx
- Al honeycomb panel
- 2 horns for Tx



Conclusion

- A method to compute the propagation direction of IM products by using ray optics has been presented
- It can be used to optimize the geometry of Antenna IM products test benches and to increase the measurement dynamic by using spatial filtering in addition to frequency filtering
- A proof of concept gave good first results

- In some cases, high IM power may be reflected in the direction of the focal source and this should be taken into account in the design of multi-feed antennas

Acknowledgements

- This study has been funded by CNES, the French Space Agency, in the frame of the Research and Technology Program (R&T)
- Patent filed by CNES
- Measurements are carried by Thales Alenia Space and funded by CNES R&T program

References

- Snell, Descartes, Huygens, Hamilton
- Franken, Hill, Peters, and Weinreich, "Generation of Optical Harmonics", Phys. Rev. Letters, Vol. 7, No. 4, 1961, pp. 118-120
- Armstrong, Bloembergen, Ducuing and Pershan, "Interactions between Light Waves in a Nonlinear Dielectric", Physical Review, Vol. 127, No. 6, 1962, pp. 1918-1932
- Bloembergen and Pershan, "Light waves at the boundary of nonlinear media", Physical Review, Vol. 128, No. 2, October 15, 1962, pp. 606-622
- Born and Wolf, "Principles of Optics", Pergamon Press, 1959, 4th edition, 1970