Passive Intermodulation in Microwave Filters: Experimental Investigation

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Outline

- Overview of physical mechanisms in PIM generation
- PIM in microwave cavities and filters
- Experimental investigation of PIM produced in coaxial cavities
- Evaluations of PIM in filters and duplexers through non-linear circuit simulations
- Some case histories
- Conclusions
Generation of PIM in microwave cavities

1) **Due to the materials**
   - Ferromagnetism
   - Contacts between metals (even identical!)
   - Galvanic Silver plating (?)

2) **Due to the cavity structure**
   - Shape and dimensions
   - Tuning structure
   - Input/output coupling system
   - Input/output connectors

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Passive Intermodulation (PIM) and base station combiners

Passive intermodulation in cellular base station duplexers arises from the very weak non-linearity produced in the filters cavities.

Intermodulation generated by the TX filter may fall into the RX band; then, reaching the LNA input, it worsen the overall performances of the system.

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GSM Frequencies
- TX Band: 935 – 960 MHz
- RX Band: 890 – 915 MHz
**Passive Intermodulation Typical Requirements**

<table>
<thead>
<tr>
<th></th>
<th>Input power</th>
<th>PIM in RX band</th>
</tr>
</thead>
<tbody>
<tr>
<td>GSM</td>
<td>2 x 43dBm</td>
<td>-120dBm (3rd order)</td>
</tr>
<tr>
<td>PCS 1900 DCS 1800</td>
<td>2 x 47dBm</td>
<td>-118dBm (3rd order)</td>
</tr>
<tr>
<td>UMTS</td>
<td>2 x 46dBm</td>
<td>-120dBm (7th order)</td>
</tr>
</tbody>
</table>

**Experimental study on PIM generated by microwave coaxial cavity**

**Purpose:**
To investigate the dependence of PIM on the cavity parameters

**Methodology:**
Fabrication and measurements on suitably designed test cavities

**Question:**
How to design the test cavities?
A simple circuit model for describing PIM generation in resonators

**Heuristic Assumption:** non-linearity associated to the cavity dissipation

\[
L_{eq} = \frac{1}{2} \frac{\partial X}{\partial \omega}, \quad C_{eq} = \frac{1}{\omega^2 L_{eq}}, \quad R_p = R(i)
\]

\[
Q_0 = \frac{\omega_0 L_{eq}}{r_0}, \quad Q_L = \frac{\omega_0 L_{eq}}{2R_0 + r_0} \equiv \frac{\omega_0 L_{eq}}{2R_0}
\]

\[R_p\] is a non-linear resistor described by the following I-V characteristic:

\[
v = r_0 \cdot i + r_3 \cdot i^3 + \ldots \equiv r_0 \cdot i \cdot \left(1 + x \cdot i^2\right) \quad x = \frac{r_3}{r_0}
\]

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Two-tone characterization

\[
X(f) \equiv X(f_0) \left[2\left(\frac{f}{f_0} - 1\right)\right] = X(f_0) F_n(f)
\]

**Input tones:**

- Frequencies: \(f_1, f_2\)
- Amplitude (volt.): \(V_0\)

Input available power (\(P_{av}\)): \(V_0^2 / 8R_0\)
Simplified circuit analysis

Output power at \( f_1, f_2 \):

\[
P_{k(1)} = \frac{P_{av}}{(1 + Q_L/Q_0)^2} \alpha_k^2
\]

Output power at \( 2f_1 + f_2 \) (PIM):

\[
P_{k(3)} = \frac{9 P_{im}^3}{4 P_x^2} \left( \frac{Q_L}{Q_0} \right)^{2k} \left( 1 + \frac{Q_L}{Q_0} \right)^6
\]

\[
\alpha_k = \frac{1}{\sqrt{1 + \left( Q_L F_n (f_{k(1)}) \right)^2}}, \quad P_x = \frac{1}{2} \frac{f_0}{x}, \quad A_k = \frac{\alpha_k \alpha_2}{\sqrt{1 + \left( Q_L F_n (f_{k(3)}) \right)^2}}
\]

Evaluation on PIM with the simplified model

**Model parameters:**

- Resonant frequency \( f_0 \)
- Loaded and unloaded Qs
- Intrinsic PIM (\( P_x \))
- Input power

\[
(P_{th})_{dBm} = 3(P_{dir})_{dBm} - 2(P_x)_{dBm} + 40\log \left( \frac{3 Q_L}{2 Q_0} \right) - 60\log \left( 1 + \frac{Q_L}{Q_0} \right) + 20\log (\alpha_k A_k)
\]

For an ideal cavity (\( r_2 = 0 \)): \( P_x \rightarrow \infty, \ P_{IM} \rightarrow 0 \)
Dependence of $P_{IM}$ on the model parameters

- Decreases of 2 dB/dB with $P_x$
- Increases with $Q_L/Q_0$ for $Q_L/Q_0 << 1$, then decreases
- Increases of 3 dB/dB with $P_{in}$

Parameters to be varied in the test cavities

- Unloaded Q (cavity volume)
- Loaded Q (Input/Output coupling level)
- Intrinsic non-linear parameter $P_x$:
  - cavity shape
  - coupling structure
  - tuning element
  - Silver plating
Physical structure of the test cavities (GSM TX band)

**Cavity type:** Coaxial with capacitive loading  
**Outer cross section:** square  
**Tuning element:** screw into the inner conductor

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**Dimensions of the built cavities and varied parameters**

- Width of the cavity: 22.5 or 45 mm (changes $Q_0$)
- Section of inner conductor: circular or square
- Input/Output coupling: capacitive or inductive (tap).
- Loaded Q: 15, 25, 40 (by changing the in/out coupling)
- Tuning: with or without the screw

**Total built cavities: 30**
Does filter plating affect PIM?

Skin depth in silver around 1 GHz is about 1\(\mu\); so 5\(\mu\) of silver thickness should be sufficient (no contact between different conductors). However:

- The realizable silver thickness is not uniform inside the cavity (less at the bottom)
- Irregularities and impurities on the surface are possibly generated by the plating process
- Contacts between silvered and not-silvered parts become unavoidable (tuning screws)

**Conclusion:** PIM has been measured before and after silver plating the test cavities (5\(\mu\) tick.)

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**PIM Measurement (two-tone test)**

*Measurement test set:* Summitek mod. S1 900A (transmission set-up)

![Diagram](image)

**Instrument noise floor:** -130 dBm

**Choice of the two-tone frequencies**

- Tone \(f_1\) must be near the lowest end of the TX band (935 MHz)
- Tone \(f_2\) is around 956 MHz, in order to obtain the lower 3\(^{\text{rd}}\) order intermodulation product inside the RX band (< 915 MHz)
- Cavities are tuned at about \((f_1+f_2)/2\)
Measurement results (sample)

Comments on measurement results (1)

- PIM dependence on $Q_L$ seems similar to that estimated by the model
- The increase of the cavity size reduces PIM (as $Q_0$ increases)
- The rod cross section (square or circular) does not seem to affect PIM
- Capacitive coupling has better performances than tap coupling
Comments on measurement results (2)

- Tuning screws strongly increase PIM (5-15 dB)
- Measured PIM after silver plating seems to increase (especially with tap coupling and tuning screws).

Dependence of PIM on input Power

3rd order polynomial model not sufficiently accurate!

Dashed lines: Slope 2dB/dB
Matching PIM vs. $P_0$

Non-linear function for the I/V characteristic:

$$I = g_0 \cdot \left(1 + k_1 \tanh(k_2 V)\right) \quad g_0 = \frac{B_{eq}}{Q_0}$$

$\begin{array}{c}
\begin{bmatrix}
33 & 34 & 35 & 36 & 37 & 38 & 39 & 40 & 41 & 42 \\
\end{bmatrix}
\end{array}$

Simulator: ADS (Harmonic Balance)

Conclusions (first part)

- For reducing intrinsic PIM of a cavity:
  - no tuning screws
  - no soldering in the structure (avoid tap coupling)
  - thickness of silver plating at least 3-5 times the skin depth (for avoiding the influence of the adhesive layer, typically realized with nickel)
- The dependence of PIM on $Q_L$ and $Q_0$ has been demonstrated
- The shape of the inner rod (square or circular) does not seem to affect PIM
- A $3^{\text{rd}}$ order model is not sufficient to match PIM vs. $P_0$
Overall PIM generated in a duplexer

Reference Filters

**TX FILTERS**
- Lower passband frequency (MHz): 924.00
- Upper passband frequency (MHz): 960.50
- Return Loss (dB): 22.00
- Number of resonators: 10
- Unloaded Q of resonators: 2000.00
- External Q: 24.65
- Number of Transmission Zeros: 2
- Frequencies (MHz): 917.20 918.50

**RX FILTERS**
- Lower passband frequency (MHz): 878.00
- Upper passband frequency (MHz): 918.50
- Return Loss (dB): 16.00
- Number of resonators: 10
- Unloaded Q of resonators: 2000.00
- External Q: 27.18
- Number of Transmission Zeros: 2
- Frequencies (MHz): 924.50 926.30

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Equivalent circuit for the resonators

\[ R_0 = Q_0 \frac{2}{B_0}, \quad C_{eq} = \frac{B_0}{\omega_0}, \quad L_{eq} = \frac{1}{\omega_0^2 C_{eq}} \]

\[ g_0 = \frac{B_0}{Q_0}, \quad g_2 = \frac{g_0^2}{2P_x} \]

- \( f_0 = 935 \text{ MHz} \)
- \( f_1 = 931.65 \text{ MHz} \)
- \( Q_0 = 2700 \)
- \( f_2 = 938.35 \text{ MHz} \)
- \( B_0 = 1.55 \text{ S} \)
- \( P_x = 100 \text{ dBm} \)
Duplexer linear response

N.B. Ideal inverter has been employed in the filters equivalent circuit

Non linear analysis (Harmonic Balance)

TX input:
two-tone (930 MHz, 950 MHz), 43 dBm/tone
HB analysis: 5 harmonics/tono, max mix order 9
Non-linearity in all resonators (both TX and RX filters)
PIM at RX out vs. frequency

Blue curve: non linearity in both filters  Purple curve: non linearity in TX filter only

PIM is due to the TX filter only

Contribution to PIM from TX resonators

Only the first 4 resonators from ANT node give a contribute to PIM
PIM vs. Filters topology

Triplets close to the ANT node produce lower PIM!

Some Case Histories
Problems with silver plating

Poor silver plating: PIM 100dBm 2x45dBm

Solution: lateral hole to improve silver plating → PIM 115dBm 2x45dBm

Resonators design

Resonator too loaded and with thin ring
→ PIM 105dBm 2x43dBm

Solution: increase depth of cavity and resonator ring → PIM 120dBm 2x43dBm
Dissimilar metals

Stainless steel screws in silver-plated cavity
\[ \text{PIM 110dBm 2x45dBm} \]

Solution: shorter screws
\[ \text{PIM 125dBm 2x45dBm} \]

Conclusions:
“Good Rules” for making low PIM filters
- Wide resonator ring
- Deep cavities and not too loaded resonators
- No sharp corners
- No contact between dissimilar metals
- Attention to the position of cross couplings
- Short tuning screws in the cavities
  - Cleaning
  - Attention to solder joints
  - Good silver plating
  - Ensure good contacts