Phase Noise in RF and Microwave Amplifiers

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Outline

• Noise types (white and flicker)
• Amplifier networks
• Experiments
• Conclusions

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AM-PM noise types

- **Parametric noise**
  - environmental: temperature, 50 Hz B fields, power supply, acoustic, radiation
  - internal: flicker (1/f), rnd walk (1/f²), drift

- **Additive noise**
  - environmental: noise originates near DC
  - internal: RF leakage
  - white: noise originates around ν₀

file: amp-noise-tree

AM-PM noise
The difference between additive and parametric noise

**Additive Noise**
- Input: $u(t)$
- Output: $v(t)$
- Noise: $z(t)$
- The noise sidebands are independent of the carrier

**Parametric Noise**
- Input: $u(t)$
- Output: $v(t)$
- Noise: $z(t)$
- The noise sidebands are proportional to the carrier
White noise in cascaded amplifiers

White noise is chiefly the noise of the first stage

\[ N_e = F_1 kT_0 + \frac{(F_2 - 1)kT_0}{A_1^2} + \frac{(F_3 - 1)kT_0}{A_2^2 A_1^2} + \ldots \]

\[ F = F_1 + \frac{(F_2 - 1)}{A_1^2} + \frac{(F_3 - 1)}{A_2^2 A_1^2} + \ldots \]

Friis formulae

H. T. Friis, Proc. IRE 32 p.419-422, jul 1944

Noise is chiefly that of the 1st stage

### Friis formula for phase noise

\[ b_0 = \frac{F kT_0}{P_0} \quad \text{white phase noise} \]

\[ b_0 = \frac{F_1 kT_0}{P_0} + \frac{(F_2 - 1)kT_0}{A_1^2 P_0} + \frac{(F_3 - 1)kT_0}{A_2^2 A_1^2 P_0} + \ldots \]
Parametric noise in cascaded amplifiers

There is a nonlinear model that gives exactly the same results, see Chap. 2 of E. Rubiola, *Phase Noise and Frequency Stability in Oscillators*, Cambridge 2008, ISBN 978-0521-88677-2

**Flicker: the two amplifiers are independent**

\[
\mathbb{E}\{\alpha^2\} = \mathbb{E}\{\alpha_1^2\} + \mathbb{E}\{\alpha_2^2\}
\]

\[
\mathbb{E}\{\varphi^2\} = \mathbb{E}\{\varphi_1^2\} + \mathbb{E}\{\varphi_2^2\}
\]

\[
S_\alpha = S_{\alpha_1} + S_{\alpha_2}
\]

**Environment: a single process drives the two amplifiers**

\[
\alpha = \alpha_1 + \alpha_2
\]

\[
\varphi = \varphi_1 + \varphi_2
\]

\[
\mathbb{E}\{\alpha^2\} = \mathbb{E}\{(\alpha_1 + \alpha_2)^2\}
\]

\[
\mathbb{E}\{\varphi^2\} = \mathbb{E}\{(\varphi_1 + \varphi_2)^2\}
\]

Yet there can be a time constant, not necessarily the same for the two devices.
The phase flicker coefficient $b_{-1}$ is about independent of power.

The flicker of a branch is not increased by splitting the input power.

At the output,
- the carrier adds up coherently
- the phase noise adds up statistically

Hence, the 1/f phase noise is reduced by a factor $m$

Only the flicker noise can be reduced in this way.
Volume law

The analysis of the parallel amplifier suggests that:

For a given technology, the flicker coefficient $b^{-1}$ should be proportional to the inverse of the volume of the active region.

Gedankenexperiment

- Flicker is of microscopic origin because it has Gaussian PDF (central limit theorem)
- Join the $m$ branches of a parallel device forming a compound
- Phase flicker is proportional to the inverse size of the amplifier active region
Parametric noise in regenerative amplifiers

R. Boudot, E. Rubiola, arXiv:1001.2047v1, Jan 2010. Submitt. IEEE Transact. MTT

\[ A = \frac{A_0}{1 - A_0\beta} \]

\[ A = A_0^m \Rightarrow \beta = \frac{A_0^{m-1} - 1}{A_0^m} \]

- Short roundtrip time, vs. flicker time frame
- Quasi-static analysis holds

\[ S_\varphi(f) [\text{rad}^2/\text{Hz}] \]

\[ A \to \frac{A_0 e^{j\psi}}{1 - A_0\beta e^{j\psi}} \]

\[ A = \frac{A_0}{1 - A_0\beta} \left[ 1 + j \frac{1}{1 - A_0\beta} \psi \right] \]

\[ \varphi(t) = \frac{1}{1 - A_0\beta} \psi(t) \]

\[ (b-1)_{RA} = \left[ \frac{1}{1 - A_0\beta} \right]^2 (b-1)_{\text{ampli}} \]

\[ (b-1)_{RA} = m^2 (b-1)_{\text{ampli}} \]
Measurement methods

Saturated mixer (common laboratory practice)

Bridge (interferometer)

E. Rubiola, V. Giordano, Rev. Sci. Instrum. 73(6) pp.2445-2457, June 2002
# Flicker noise of some amplifiers

R. Boudot, E. Rubiola, arXiv:1001.2047v1, Jan 2010. Submitted IEEE Transact. MTT

| Amplifier           | Frequency (GHz) | Gain (dB) | $P_{1\,\text{dB}}$ (dBm) | $F$ (dB) | DC bias | $b_{-1}$ (meas.) (dB/√Hz) |
|---------------------|----------------|-----------|---------------------------|---------|---------|--------------------------|
| AML812PNB1901       | 8 – 12         | 22        | 17                        | 7       | 15 V, 425 mA | −122                     |
| AML412L2001         | 4 – 12         | 20        | 10                        | 2.5     | 15 V, 100 mA | −112.5                   |
| AML612L2201         | 6 – 12         | 22        | 10                        | 2       | 15 V, 100 mA | −115.5                   |
| AML812PNB2401       | 8 – 12         | 24        | 26                        | 7       | 15 V, 1.1A  | −119                     |
| AFS6                | 8 – 12         | 44        | 16                        | 1.2     | 15 V, 171 mA | −105                     |
| JS2                 | 8 – 12         | 17.5      | 13.5                      | 1.3     | 15 V, 92 mA  | −106                     |
| SiGe LPNT32         | 3.5            | 13        | 11                        | 1       | 2 V, 10 mA   | −130                     |
| Avantek UTC573      | 0.01 – 0.5     | 14.5      | 13                        | 3.5     | 15 V, 100 mA | −141.5                   |
| Avantek UTO512      | 0.005–0.5      | 21        | 8                         | 2.5     | 15 V, 23 mA  | −137                     |
Phase noise vs. power

- The $1/f$ phase noise $b_{-1}$ is about independent of power
- The white noise $b_0$ scales as the inverse of the power
- The corner frequency is misleading because it depends on power
Phase noise in cascaded amplifiers

R. Boudot, E. Rubiola, arXiv:1001.2047v1, Jan 2010. Submitt. IEEE Transact. MTT

The expected flicker of a cascade increases by:
3 dB, with 2 amplifiers
4.8 dB, with 3 amplifiers

White noise is limited by the (small) input power
Connecting two amplifier in parallel, a 3 dB reduction of flicker is expected.
Flicker noise in parallel amplifiers

E. Rubiola, *Phase Noise and Frequency Stability in Oscillators*, Cambridge 2008, ISBN 978-0521-88677-2

**Specification of low phase-noise amplifiers (AML web page)**

| amplifier            | parameters | phase noise vs. $f$, Hz |
|----------------------|------------|-------------------------|
|                      | gain $F$   | bias | power | $10^2$ | $10^3$ | $10^4$ | $10^5$ |
| AML812PNA0901        | 10  6.0    | 100  | 9      | −145.0 | −150.0 | −158.0 | −159.0 |
| AML812PNB0801        | 9   6.5    | 200  | 11     | −147.5 | −152.5 | −160.5 | −161.5 |
| AML812PNC0801        | 8   6.5    | 400  | 13     | −150.0 | −155.0 | −163.0 | −164.0 |
| AML812PND0801        | 8   6.5    | 800  | 15     | −152.5 | −157.5 | −165.5 | −166.5 |
| unit                 | dB dB mA dBm | dB/Hz |        |        |        |        |        |
Phase noise of a regenerative amplifier

R. Boudot, E. Rubiola, arXiv:1001.2047v1, Jan 2010. Submitt. IEEE Transact. MTT

Indirect measurement: The RA replaces the two-stage sustaining amplifier in a Opto-Electronic oscillator

- A RA is set for the gain of two cascaded amplifiers
- As expected, the RA flicker is 3 dB higher than the two amplifiers
- Indirect measurement through the frequency flicker
Environmental effects in RF amplifiers

E. Rubiola, *Phase Noise and Frequency Stability in Oscillators*, Cambridge 2008, ISBN 978-0521-88677-2

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It is experimentally observed that the temperature fluctuations cause a spectrum $S_\alpha(f)$ or $S_\phi(f)$ of the $1/f^5$ type.

Yet, at low frequencies the spectrum folds back to $1/f$. 
Correlation between AM and PM noise

R. Boudot, E. Rubiola, arXiv:1001.2047v1, Jan 2010. Submitt. IEEE Transact. MTT

The need for this model comes from the physics of popular amplifiers

- Bipolar transistor. The fluctuation of the carriers in the base region acts on the base thickness, thus on the gain, and on the capacitance of the reverse-biased base-collector junction.
- Field-effect transistor. The fluctuation of the carriers in the channel acts on the drain-source current, and also on the gate-channel capacitance because the distance between the `electrodes' is affected by the channel thickness.
- Laser amplifier. The fluctuation of the pump power acts on the density of the excited atoms, and in turn on gain, on maximum power, and on refraction index.

AM and PM fluctuations are correlated because originate from the same near-dc random process

$$a^2 + b^2 + c^2 + d^2 = 1$$
Conclusions

• The model predicts the noise of the amplifier and of networks

• First noise model of the regenerative (positive-feedback) amplifier

• Experimental data validate the model

• Correlation between AM noise and PM noise (needs further work)

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R. Boudot, E. Rubiola, arXiv:1001.2047v1, Jan 2010. Submitt. IEEE Transact. MTT

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