Flicker noise of high-speed p-i-n photodiodes

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Outline

• introduction
• method
• background noise
• results

Work carried out at the JPL/CALTECH under NASA contract, with support from ARL and AOS/P/DARPA
p-i-n InGaAs photodiode

- Photoconductive region $\Rightarrow$ lowest C $\Rightarrow$ high speed
Signal and noise

microwave-modulated IR

\[ P_\lambda(t) = \overline{P}_\lambda [1 + m \cos 2\pi \nu_0 t] \]

microwave photocurrent with AM and PM noise

\[ i_{ac}(t) = \rho \overline{P}_\lambda m [1 + \alpha(t)] \cos [\omega_0 t + \phi(t)] \]

Virtually no information on AM/PM flicker is available

Motivations

- frequency distribution systems
depth space network, VLBI, inter-lab link
- laser metrology
- photonic oscillators (Leeson effect)
Experimental method (1)

- the photodiode output is insufficient to saturate a mixer
- a preliminary survey suggests that the photodiode phase flickering is lower than that of a microwave amplifier (typical amplifier flicker $-105$ dBrad$^2$/Hz at 1 Hz)
- we choose some similar photodiodes, with a max speed of some 12-15 GHz (Discovery Semiconductors, Fermionics, Lasertron)
- a single-photodiode interferometric (bridge) scheme can’t work because the equilibrium condition is difficult
interferometric (bridge) scheme
- low phase noise, limited by the noise figure of the $\Delta$ amplifier
- carrier rejection in $\Delta$ $\Rightarrow$ the $\Delta$ amplifier does not flicker
- rejection of the source noise


- the noise of the $\Sigma$ amplifier is not detected

Background noise (1)

- well understood:
  - phase-to-voltage gain [V/ rad]
  - thermal noise
  - shot noise

- experimentally determined or up-bounded:
  - contamination from AM noise (RIN)
  - flicker noise

\[ k_d = \sqrt{\frac{gP_\mu R_0}{\ell}} - \text{[dissip. loss]} \]

\[ S_{\phi t} = \frac{2FkT_0}{P_\mu} + \text{[dissip. loss]} \]

\[ = \frac{2FkT_0}{R_0\rho^2\bar{P}_\lambda m^2} + \text{[dissip. loss]} \]

\[ S_{\phi s} = \frac{4q}{\rho m^2\bar{P}_\lambda} \]

- power gain 
  (Δ ampli)
- \( P_\mu \) microw. pow.
- \( R_0 \) charact. resist. 
  (50 Ω)
- \( \ell \) ssb mixer loss
- \( F \) noise figure 
  (Δ ampli)
- \( kT_0 \) thermal energy 
  (4×10^{−21} J)
- \( q \) electron charge 
  (1.6×10^{−19} C)
- \( \rho \) responsivity [A/W]
- \( m \) modulation index
- \( P_\lambda \) optical power
Background noise (2)

low optical power => thermal noise >> shot noise

1. replace the detectors with microwave signals

2. terminate the input of the delta amplifier

... and take the worst case
Technical difficulties (1): crosstalk

- high EOM driving power (22 dBm)
- low photodiode output power (-26 dBm)
- finite isolation (100-120 dB?)
- even small fluctuations of the environment induce noise as a consequence of the fluctuating crosstalk
- work nighttime, when nobody is around

**Figure 3: Examples of environmental effects and experimental mistakes**

- **P**: photodiode noise
- **B**: background noise
- **W**: waving a hand 0.2 m/s, 3 m far from the system

![Graph showing S(f) vs. dBm^2/Hz](file plot719a.pdf)
Technical difficulties (2): reflections

- back reflections cause the spectrum to be polluted
- flares appear at random in some spectra, as shown
- unexplained physical mechanism

S: example of single spectrum, with optical connectors and no isolators
B: background noise
P: photodiode noise
Technical difficulties (3): reflections

- back reflections cause spectra to be polluted at random
- the average spectrum is smooth
- wrong slope
- it is difficult to identify and to discard polluted spectra

A: average spectrum, with optical connectors and no isolators
B: background noise
P: photodiode noise
Technical difficulties (4): fibers

- the path of the optical fibers affects the internal stresses, and in turn the reflections
- unpredictable effect on noise, which is not the photodiode noise
- trimming the system takes patience

F: after bending a fiber, 1/f noise can increase unpredictably
B: background noise
P: photodiode noise
Example of photodiode noise

DSC30-1k and HSD30

- connections are spliced
- isolators are inserted
- air-flow shielding
- myself > 3 m far away

avg m=40

... after patient adjustment
Some results

All the pair of two different photodiodes are compared

<table>
<thead>
<tr>
<th>photodiode</th>
<th>$S_\alpha$ (1 Hz) estimate</th>
<th>$S_\alpha$ (1 Hz) uncertainty</th>
<th>$S_\varphi$ (1 Hz) estimate</th>
<th>$S_\varphi$ (1 Hz) uncertainty</th>
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</thead>
<tbody>
<tr>
<td>HSD30</td>
<td>-122.7</td>
<td>-7.1 +3.4</td>
<td>-127.6</td>
<td>-8.6 +3.6</td>
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<tr>
<td>DSC30-1K</td>
<td>-119.8</td>
<td>-3.1 +2.4</td>
<td>-120.8</td>
<td>-1.8 +1.7</td>
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<tr>
<td>QDMH3</td>
<td>-114.3</td>
<td>-1.5 +1.4</td>
<td>-120.2</td>
<td>-1.7 +1.6</td>
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<tr>
<td>unit</td>
<td>dB/Hz</td>
<td>dB</td>
<td>dBrad$^2$/Hz</td>
<td>dB</td>
</tr>
</tbody>
</table>

**estimated uncertainty**

- 0.5 dB random, affects the differences
- 1 dB systematic, affects all values in the same way (non amplified by the three-corner method)
Conclusions

• the photodetectors we measured are similar in AM and PM 1/f noise

• the 1/f noise is about $-120 \text{ dB}[\text{rad}^2]/\text{Hz}$

• other effects are easily mistaken for the photodetector 1/f noise

• environment and packaging deserve attention in order to take the full benefit from the low noise of the junction