Solid state broadband un-cooled noise generator with noise temperature below room temperature

by

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Overview

- Introduction
- Noise figure measurement uncertainty
- Schottky diode based noise generator
  - I/U characteristics
  - Noise model
- Implementation
- Application and measurements
- Conclusions

Introduction

- For absolute noise figure measurement a lot of problems/errors arise if e.g. NF < 1dB (= T_e < 75K) – even with sophisticated measurement equipment
- What are reasons/interdependencies for uncertainties?
- Could we lower the uncertainties for NF values below 1dB?

Noise figure measurement uncertainty

- Here only two contributions considered:

1. ENR calibration uncertainty:

AILTech 7615
enr = 15.5dB
Δenr = +/-0.3dB

Agilent/HP 346A
enr = 5.2dB
Δenr = +/-0.2dB

Agilent N4000A
enr = 6dB
Δenr = +/-0.15dB

2. Instrumentation error:

HP 8970A/B
Δy = +/-0.1dB

Agilent N8973A
Δy = +/-0.05dB

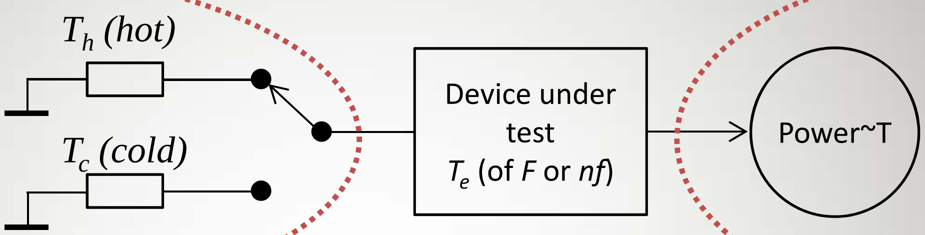
Noise figure measurement basics

- Y factor method

$$ENR = \frac{T_h - T_c}{T_0}$$

$$enr = 10 \cdot \log(ENR)$$

$$T_0 = 290K$$



$$Y = \frac{T_h + T_e}{T_c + T_e}$$

$$y = 10 \cdot \log(Y)$$

→ Noise factor:

$$F = \frac{ENR - Y \cdot (T_c / T_0 - 1)}{Y - 1}$$

or noise figure:

$$nf = 10 \cdot \log(F)$$

- nf uncertainty (see conference paper)

→ Combination of two uncertainties at actual set of parameters:

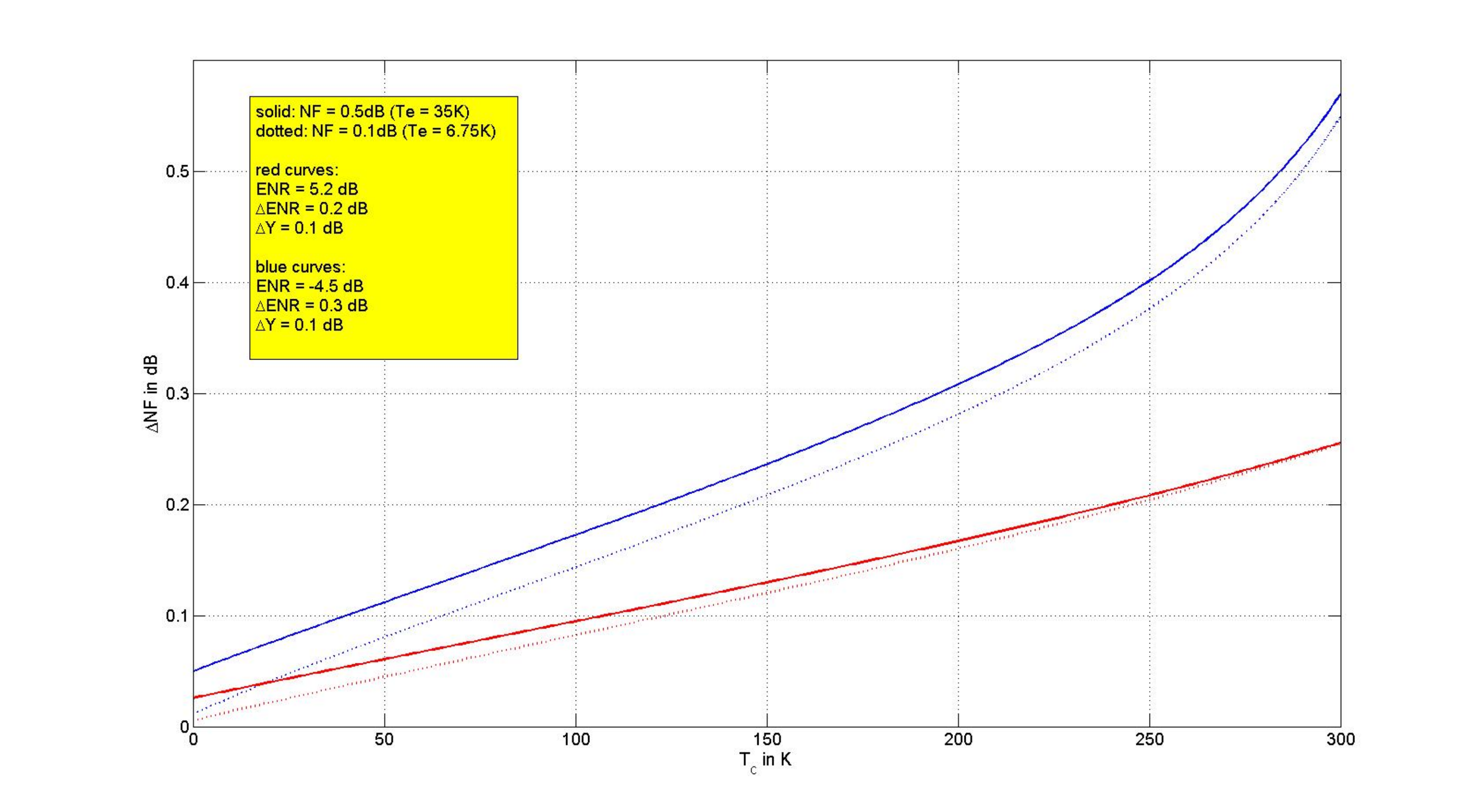
$$\Delta F = \sqrt{\left(\frac{\delta F}{\delta Y} \cdot \Delta Y\right)^2 + \left(\frac{\delta F}{\delta ENR} \cdot \Delta ENR\right)^2}$$

→ nf uncertainty in dB's:

$$\Delta nf = \frac{10}{\log(10)} \cdot \frac{\Delta F}{F}$$

Noise figure measurement uncertainty

- $\Delta nf = f(\Delta enr, \Delta y, T_c)$ for DUT nf = 0.5dB and nf = 0.1dB



→ enr could be much lower than 5dB to measure nf < 0.5dB

→ uncertainty dependent on absolut nf value

→ make T_c as low as possible!

How to lower T_c (and providing a matched load at the same time)?

- Cooled 50Ω resistor (liquid nitrogen→ T_c = ~80K)
- Looking at cold sky → RW3BP's cold horn…

Pro:
+ very low cold temperature T_c = ~15K

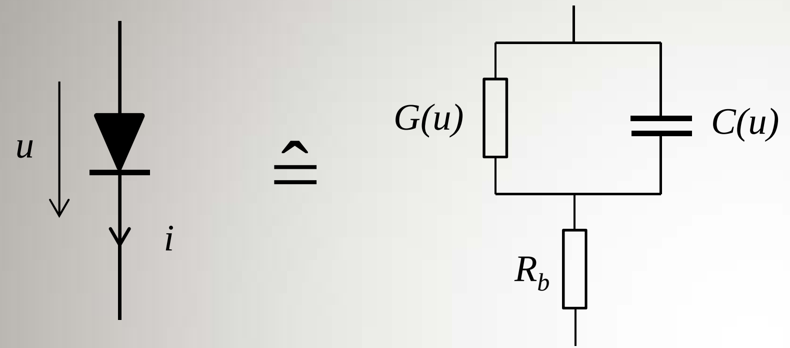
Con:
- huge effort
- small band (only 1296MHz or single other band)

- Solid-state Schottky diodes?

→ Mixture of shot (Schottky) and thermal (Johnson) noise

Schottky diode based noise generator

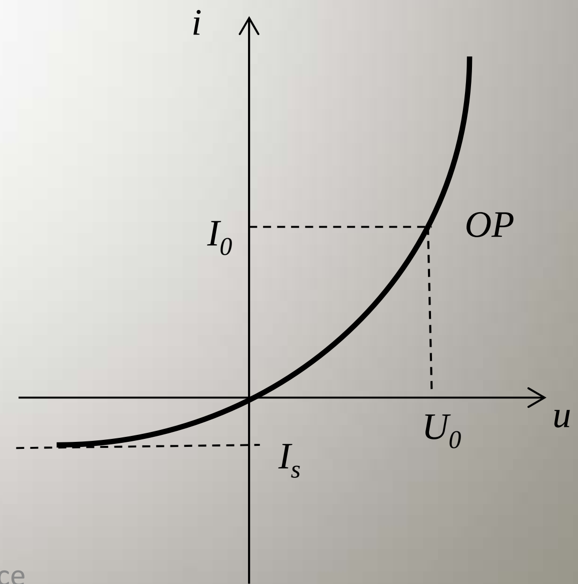
- Equivalent circuit of a Schottky diode



G(u): nonlinear conductance of junction
C(u): nonlinear capacitance of junction (very small, e.g. < 0.5pF → high f!)
R_b: bulk resistance (e.g. < 10Ω)

- I/U - characteristics

$$i(u) = I_S \cdot \left(\exp\left(\frac{q \cdot u}{\tilde{n} \cdot kT} \right) - 1 \right)$$



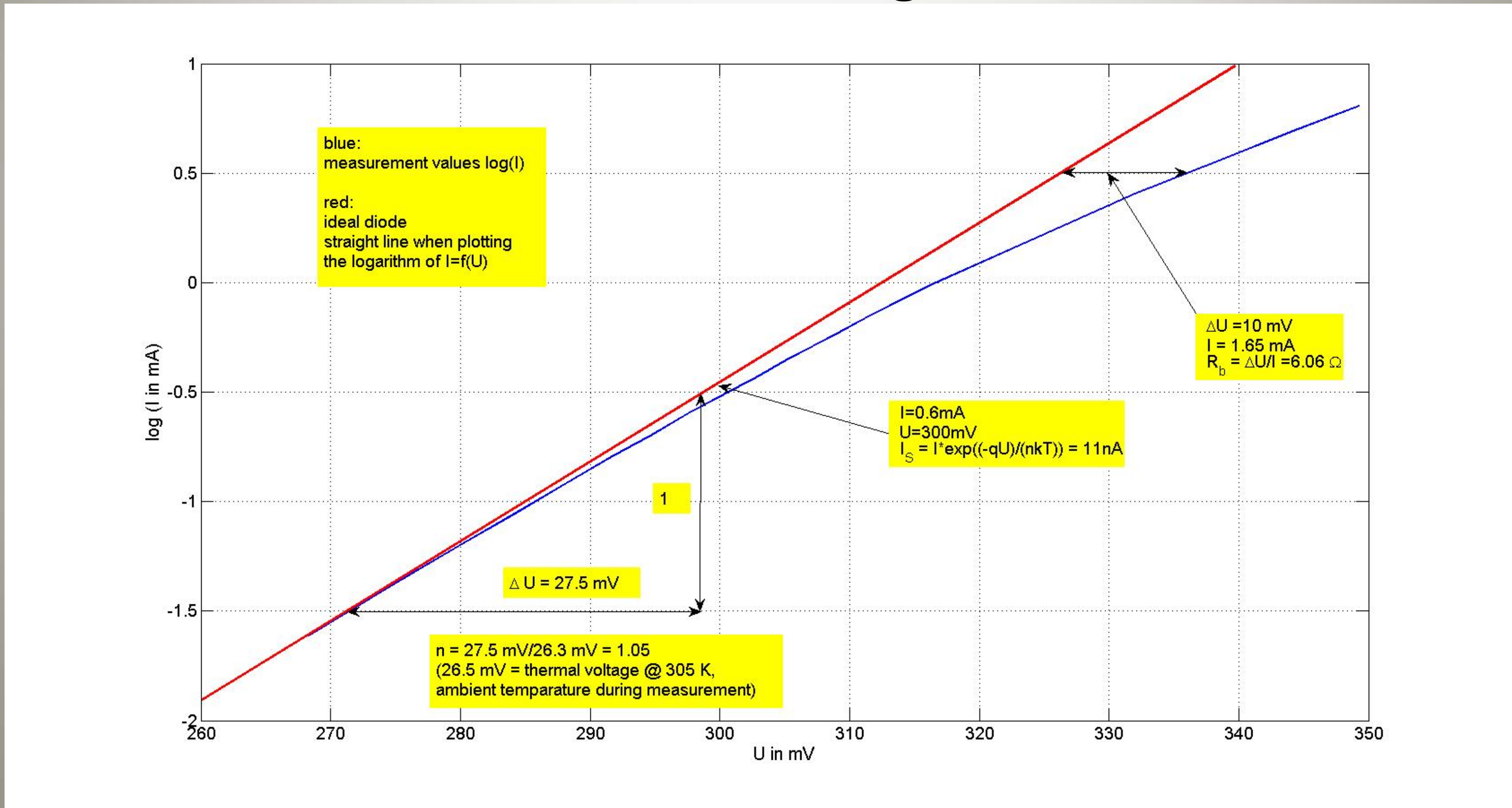
$\frac{kT}{q}$: temperature voltage (26mV at room temp.)

I_S : saturation current (e.g. < 0.1μA)

$\tilde{n}$: ideality factor to describe deviation from exponential, typical values 1…1.2

Schottky diode parameters ?

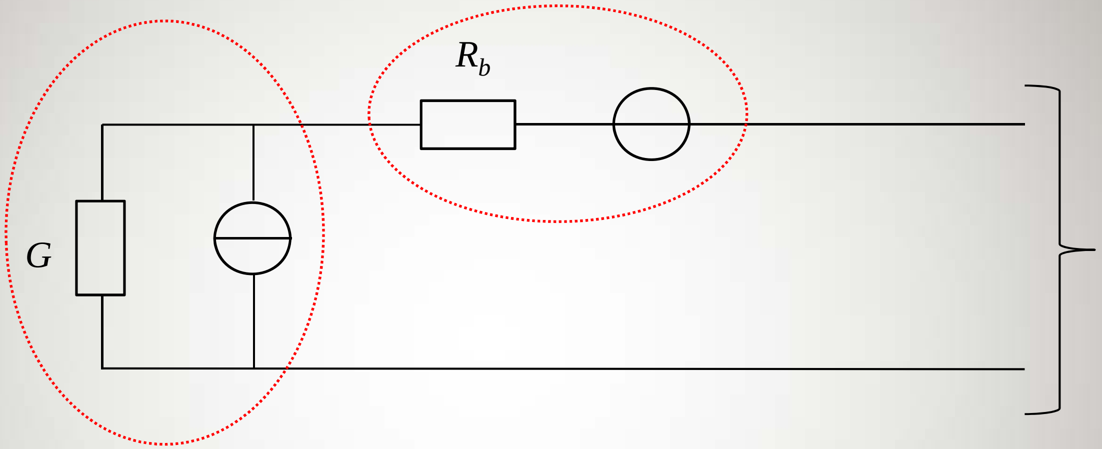
- From data sheet (SPICE parameters)
- Better: measurements, here Agilent HSMS-2823



Schottky diode noise model

thermal (Johnson) noise source:
random motion of charge carriers

shot (Schottky) noise source: charge carriers have to „climb“ a barrier



= diode terminals

Without bulk resistance [1]: $$\frac{T_{ef}^{*}}{T} = \frac{1}{2} \cdot \tilde{n} \cdot \left(1 + \frac{I_S}{I_0 + I_S}\right)$$

I_0: DC current at operating point

T : physical junction temperature (= ambient room temperature)

Overall noise temperature T_{ef} including bulk resistance [1]: $$\frac{T_{ef}}{T} = \frac{\frac{T_{ef}^{*}}{T} + R_b \cdot G}{1 + R_b \cdot G}$$

[1] Schiek, B.; Rolfes, I.; Siweris, H.-J.: *Noise in High-Frequency Circuits and Oscillators*, Wiley, 2006.

Steps towards Schottky diode noise generator

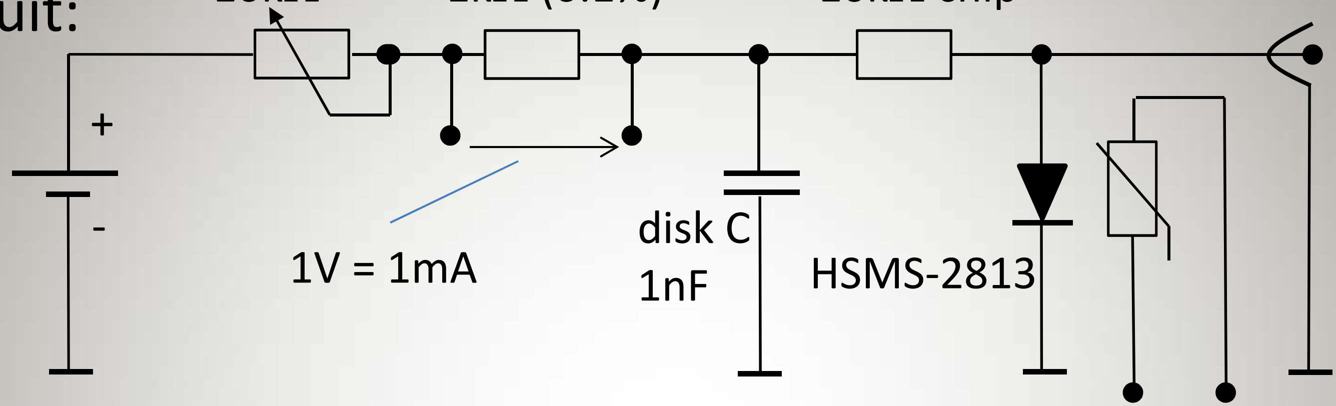
1. Make I/U measurements (DC measurement) at known ambient temperature to derive
   - Ideality factor
   - Saturation current
   - Bulk resistance
2. Align DC current through diode in order to make bulk resistance in series with differential junction resistance a pure 50Ω load (VNWA measurement) → $1/G + R_b = 50\Omega$
3. Apply equation of noise model to calculate effective noise temperature

↓

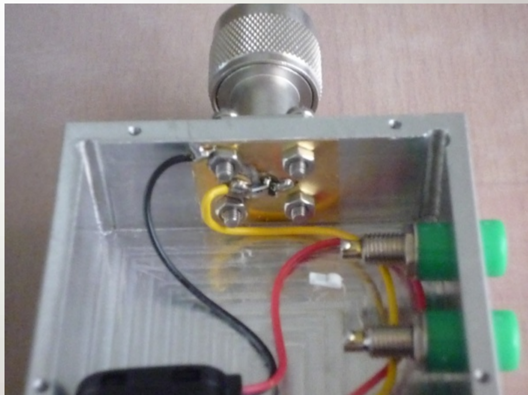
matched cold load with known noise temperature

Implementation

- Circuit:



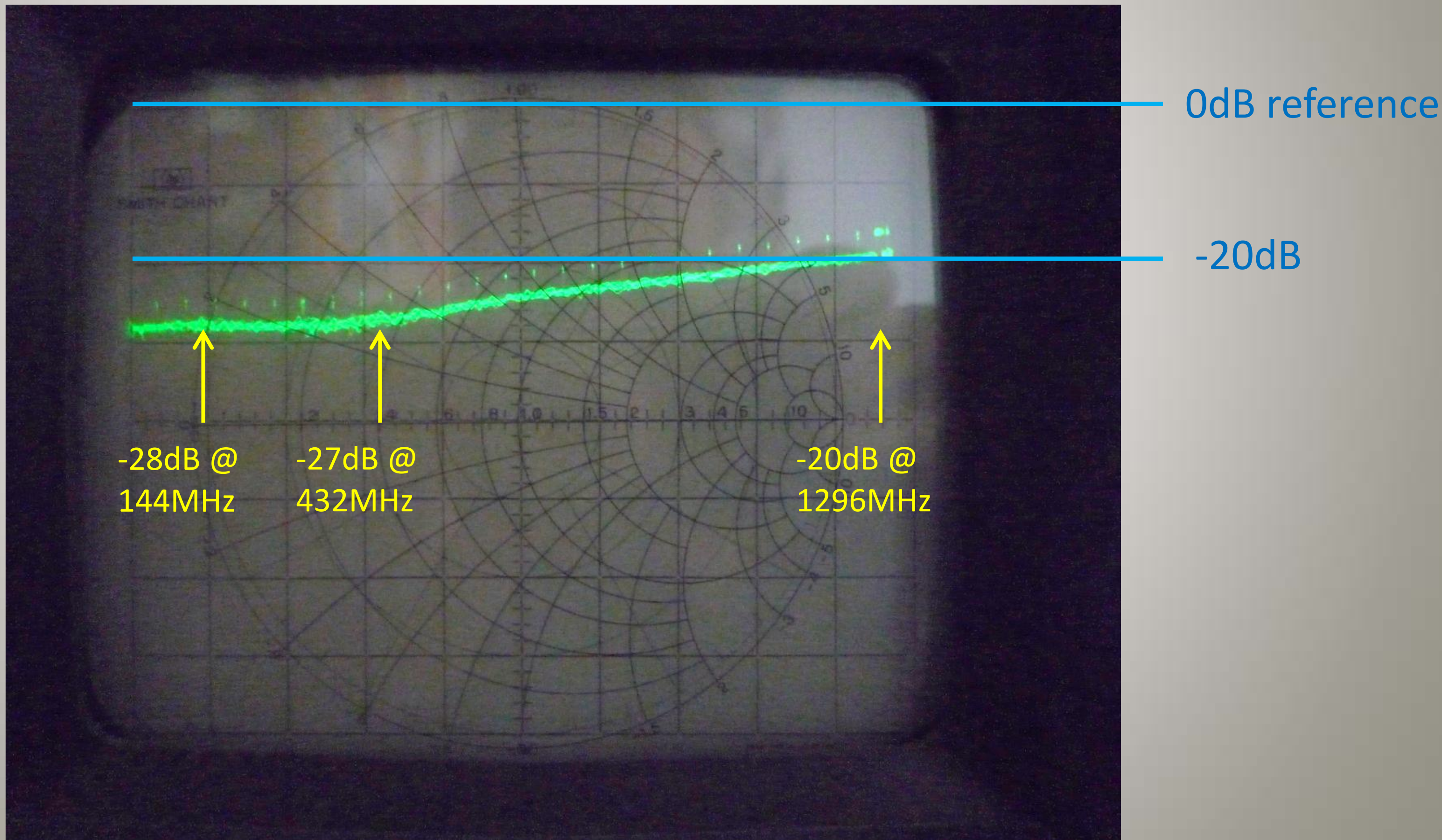
- Realization:



- Effective noise temperature (I_0=0.67mA, T=305K): 180K

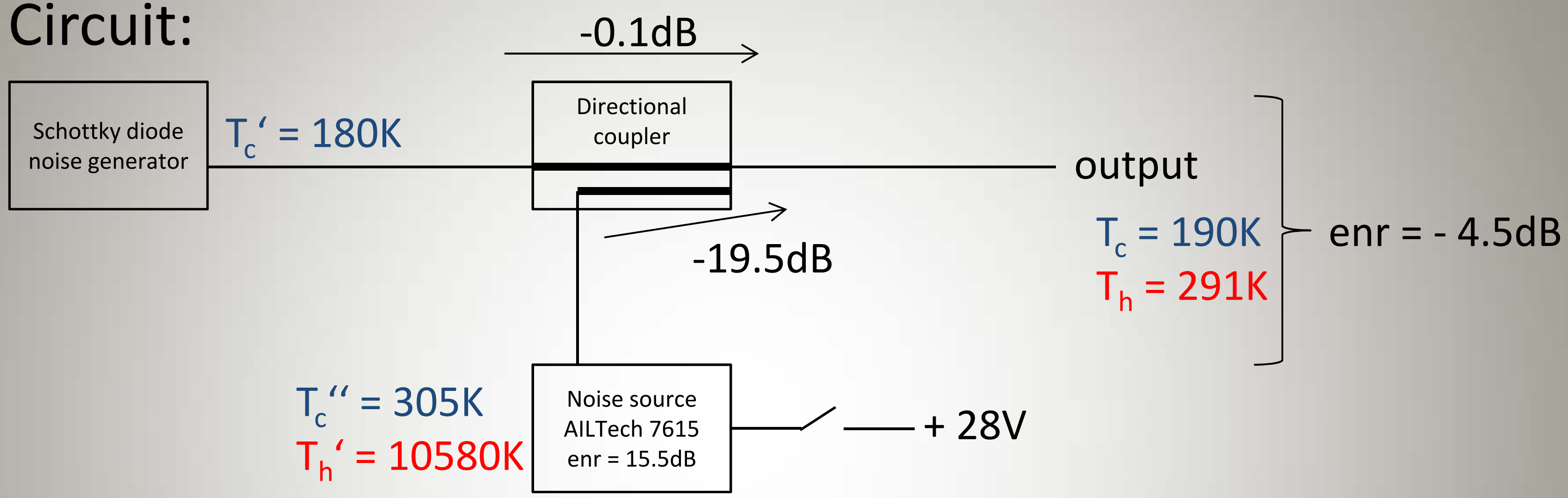
Return loss

- Attention: hold VNWA output low (< -20dBm) during measurement to avoid nonlinear distortion at diode!



Application

- Circuit:

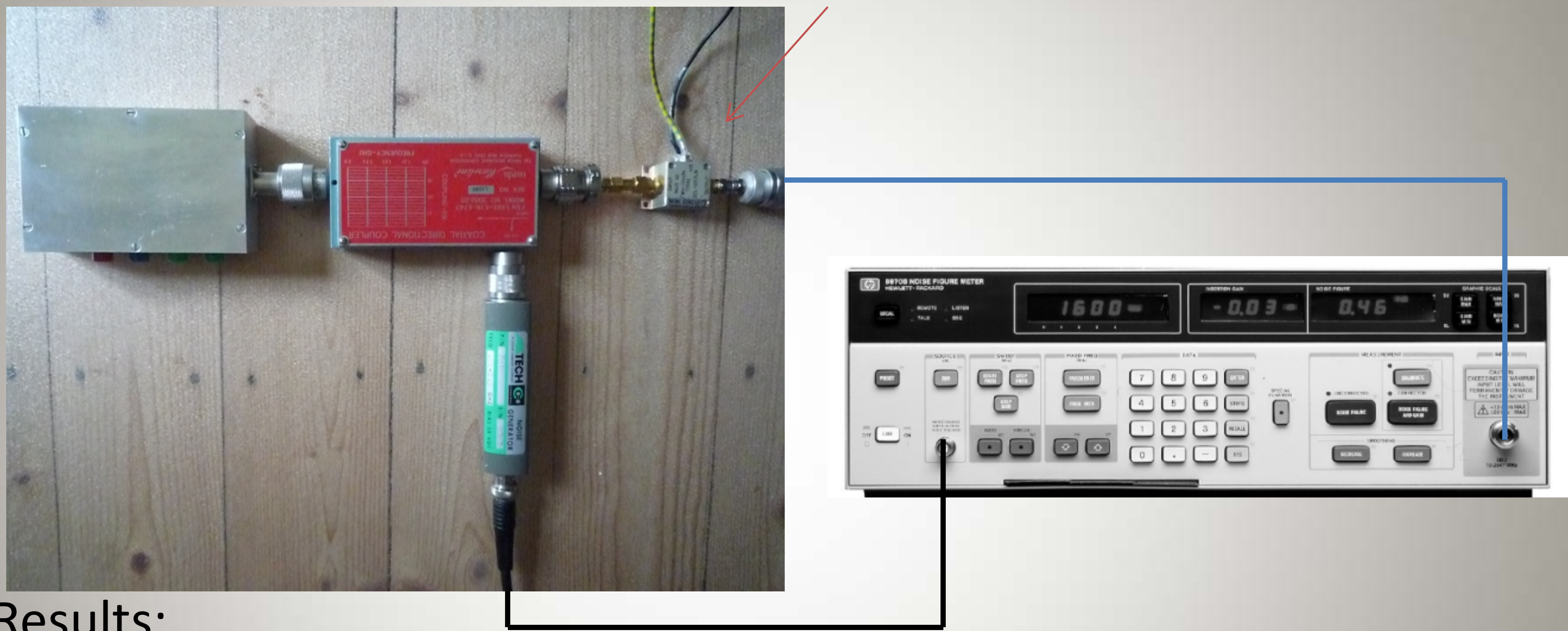


Standard noise source + Schottky diode noise source + coupler = „new“ noise source:

- enr = -4.5dB
- Δenr = 0.3dB (unchanged)
- T_c changed from ~305K to ~190K
- Due to -19.5dB coupling factor → in fact no gain error due to mismatched LNA (no change in reflection coefficient between „on“ and „off“ state of noise source)

Measurements

- Measurement of MCL ZEL-1217LN @1296MHz



- Results:
  - nf from datasheet: typically 1.1dB
  - measured with HP8970B & HP346A: 0.97dB
  - Measured with Schottky diode noise generator & Narda 1-2 GHz coupler & AILtech 7615: 1dB

Conclusions

- In Y-factor based nf measurements having T_c as low as possible is beneficial
- Matlab based tool to calculate nf uncertainties as function of enr and instrumentation (y-factor) uncertainty
- Schottky diode shows shot and thermal noise
- Realization of simple noise generator with $T_c < T_{amb}$
- Integration of new noise generator into usually used nf measurement setup very easy by means of directional coupler (low loss in main line!)
  - → nf uncertainties substantially lowered – not only by low T_c but:
  - → Change of reflection coefficient in on/off state of noise source decreased – especially of advantage for amplifiers with mismatched input („gain error“ lowered)
- Application of more expensive diodes for higher frequencies ?