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A method for primary calibration of AM and PM noise measurements

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Outline

- Introduction
- Power measurements
- I-Q modulators and detectors
- Method and error budget
- Perspectives and conclusions

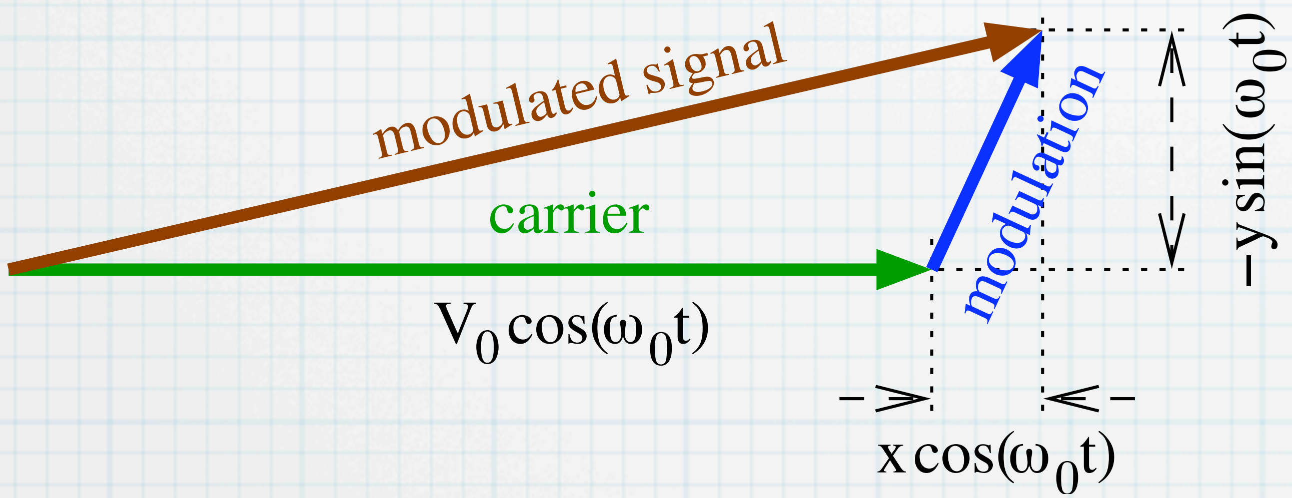
home page http://rubiola.org

The SI unit of angle

The **radian** is now considered a **derived unit** because an angle can always be defined in terms of the ***ratio of two homogeneous quantities***

(formerly, it was considered an auxiliary unit)

Electrical circuits => Phasors



In low-noise conditions

$$\alpha(t) = \frac{x}{V_0} \quad \text{and} \quad \varphi(t) = \frac{y}{V_0}$$

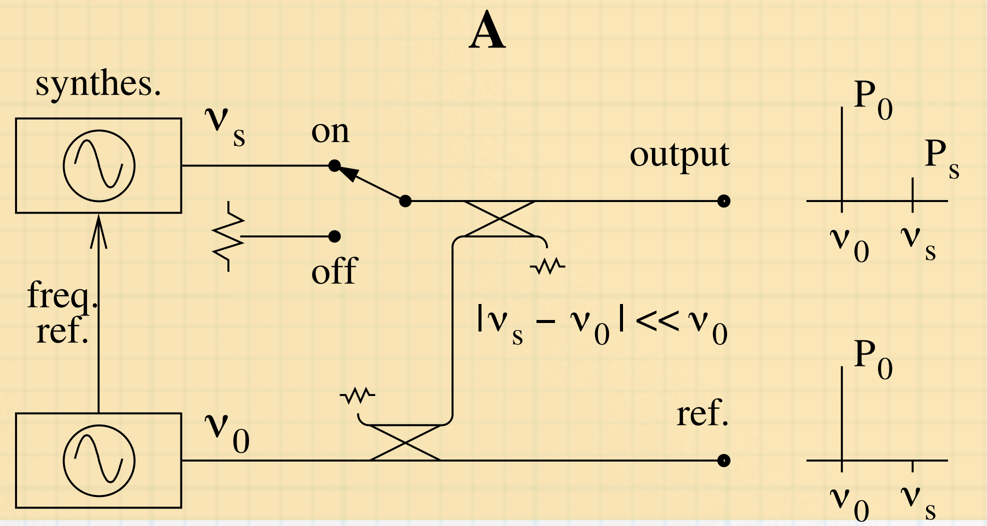
$|x/V_0| \ll 1$ and $|y/V_0| \ll 1$

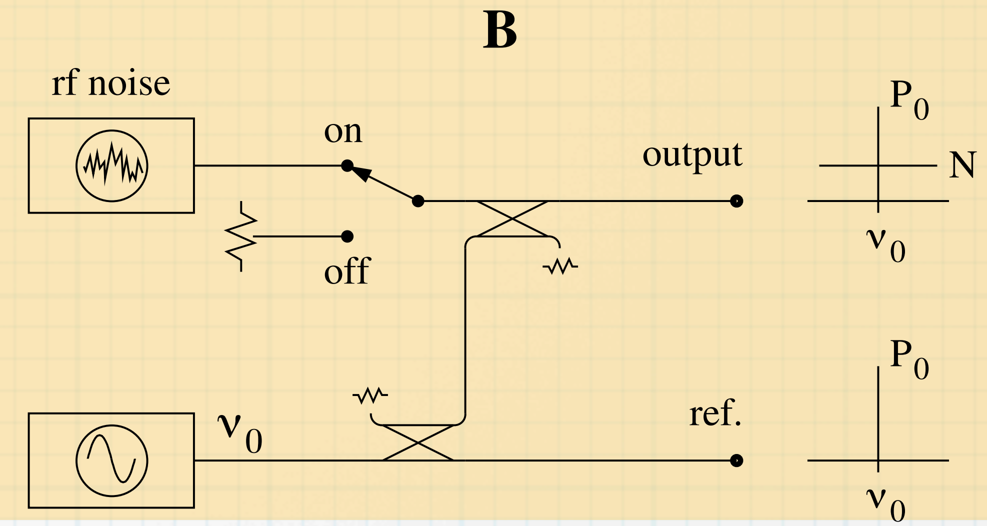
thus, $\arctan(y/x) \to y/x$

requirements for a derived measurement to be primary		
type of partial measurement	**allowed?**	**this work**
null measurement	always OK	needed
ratio measurement	always OK	needed
other primary measurement	OK	unused
significantly **more precise** measurement	tolerated	**needed**

State of the art

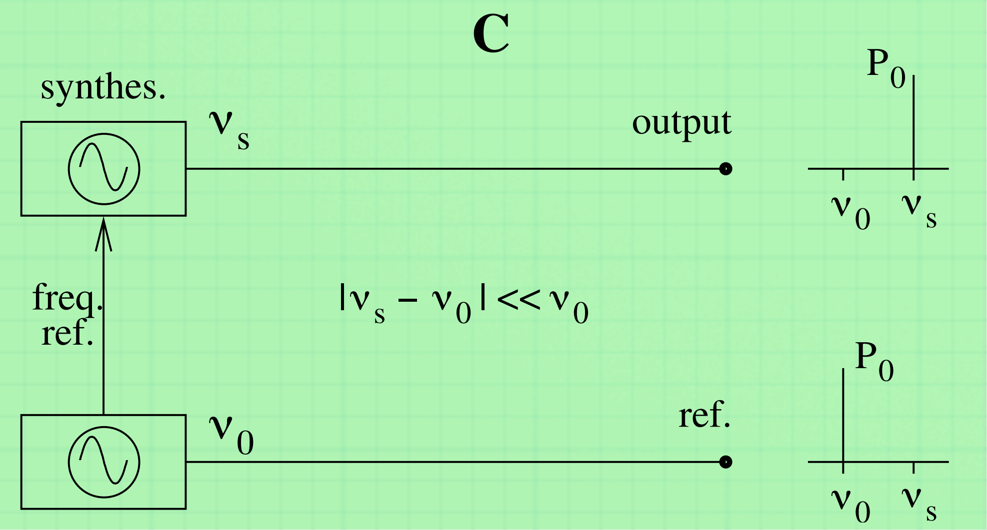
However accurate in practice, **A - B** are **incorrect**
because of the simultaneous presence of AM and PM.

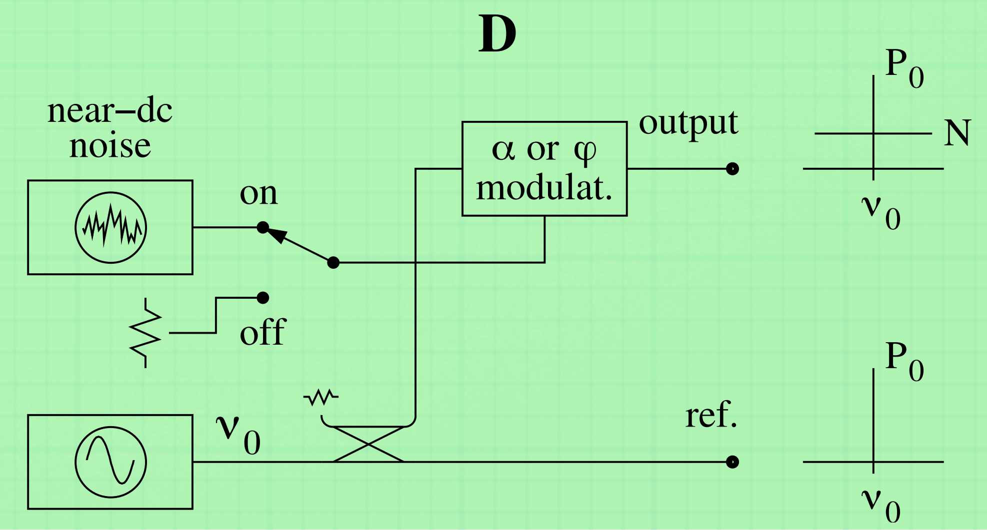




The problem is that the phase detector (saturated-mixer) is sensitive to AM
E. Rubiola, R. Boudot, IEEE Trans. UFFC **54** 5 p.926–932, may 2007

C - D are **correct** because only PM (or AM) is present

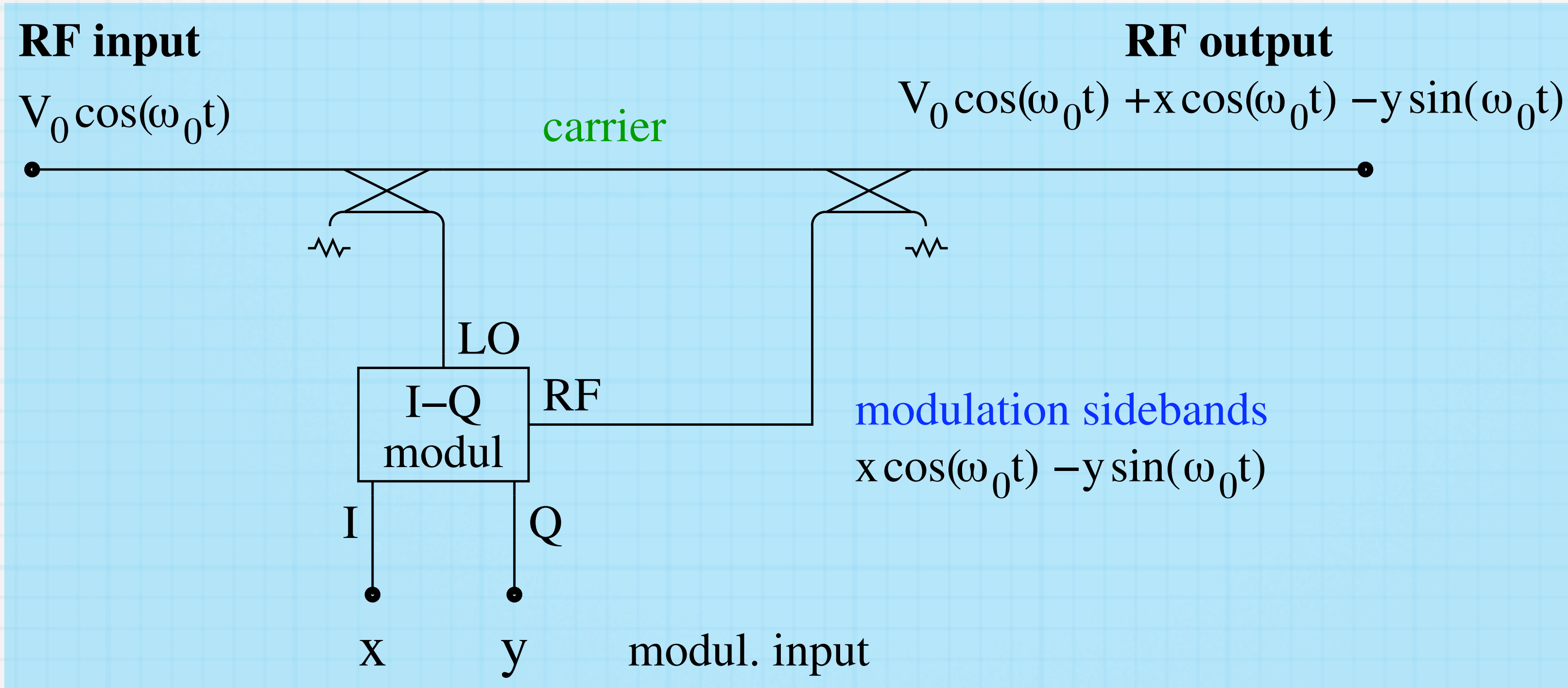




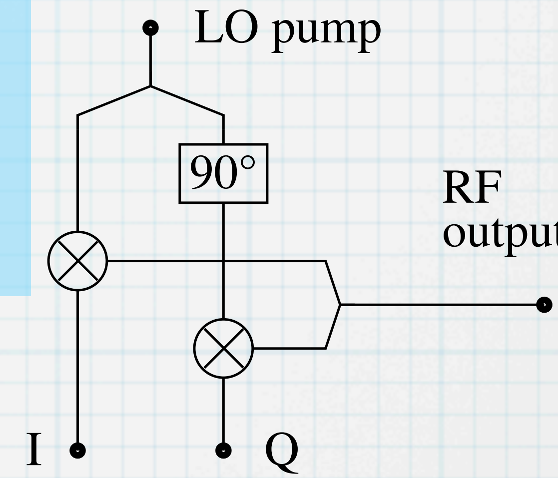
The calibrators are still to be referred to the SI unit rad

Primary laboratories declare 1–2 dB accuracy in PM noise measurements

Reference AM - PM modulator



I–Q modulator

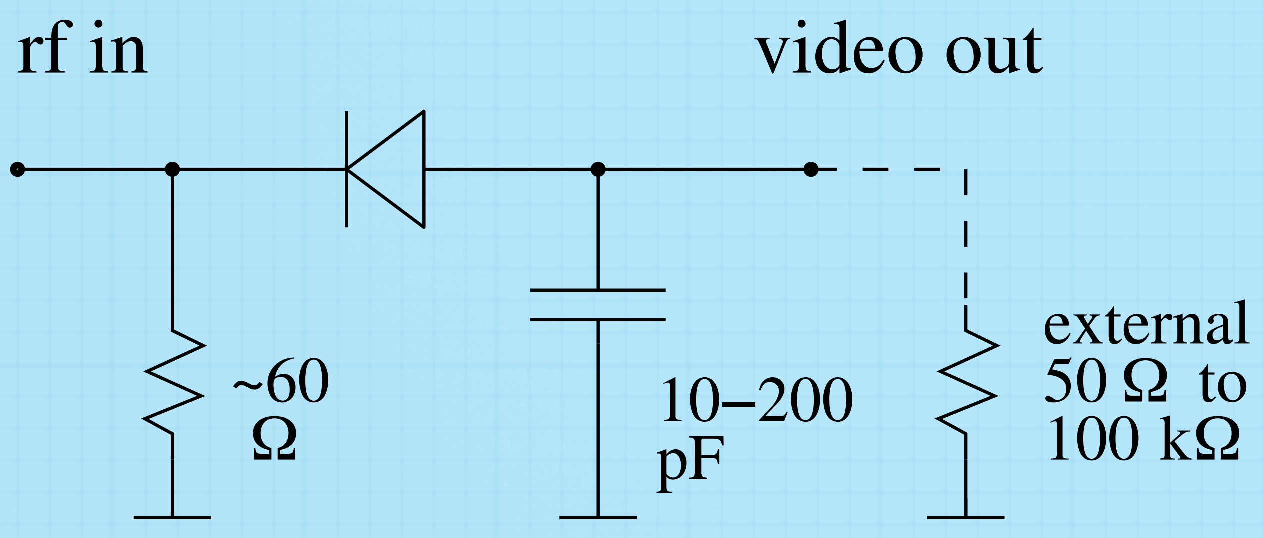


This scheme is similar to the single-mixer scheme (NIST)

The novelty is in the *calibration process*

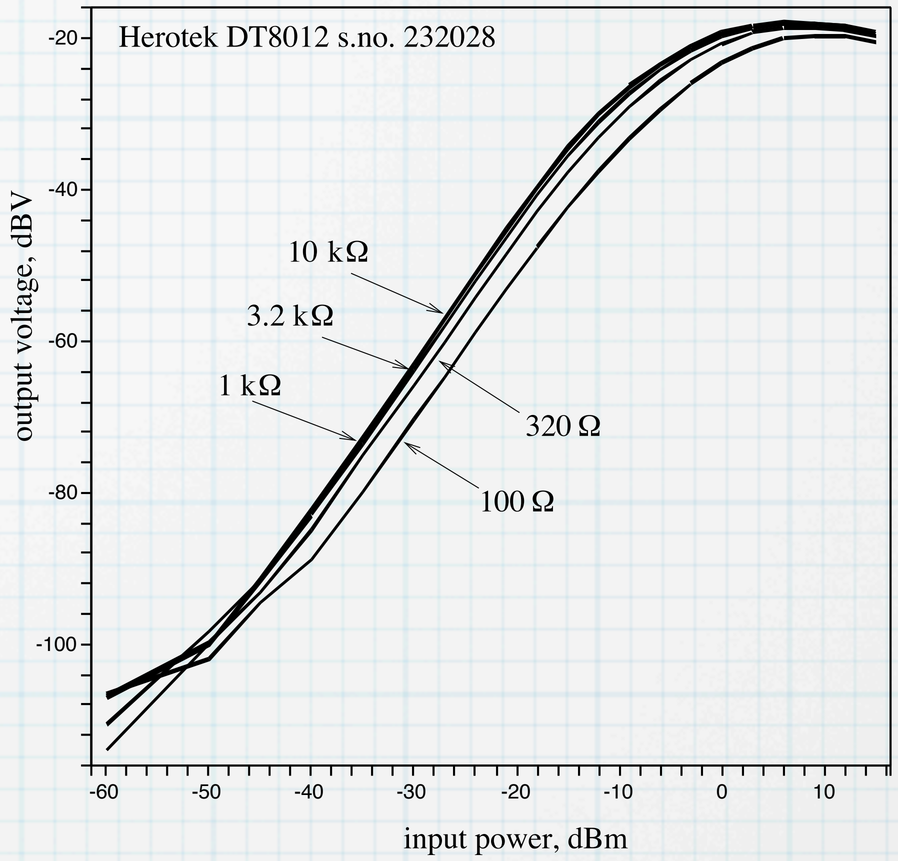
- fix the defects of the I-Q modulator (quadrature and symmetry)
- fix the arbitrary LO phase that derives from the layout
- calibrate the modulation index

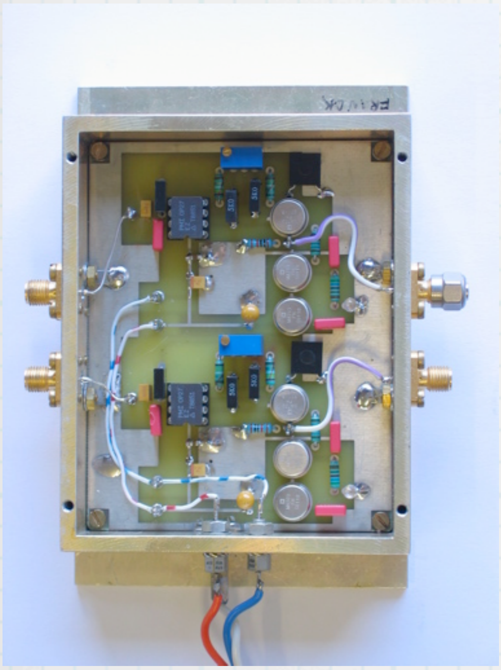
Power detector



law: $v = k_d P$

≥30 A^{-1} Schottky
≥300 A^{-1} Tunnel





Large video bandwidth: 10–100 MHz

Short storage time => Virtually no discriminator effect

A detected null of AM validates a phase modulator

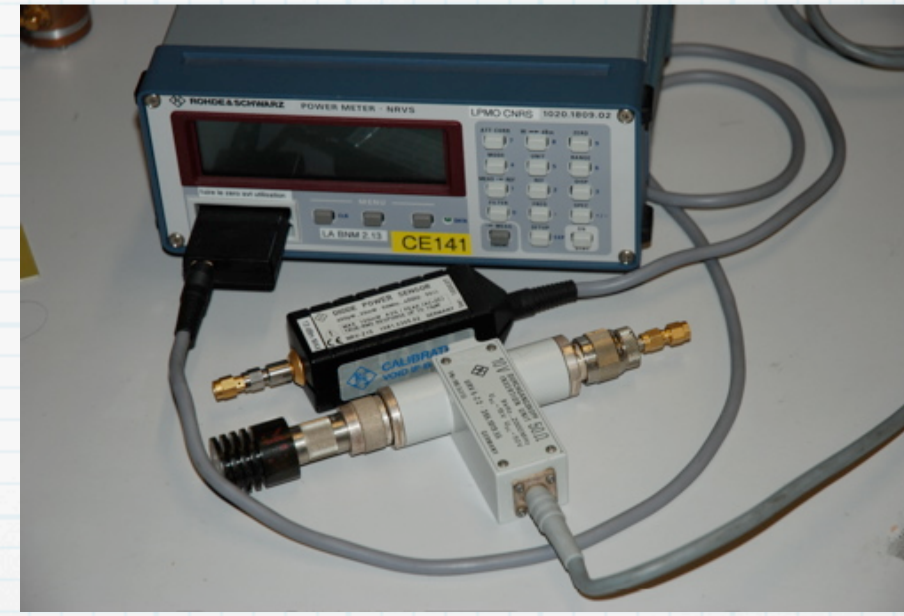
For best accuracy, use a lock-in amplifier
Need a low-noise dc amplifier

E. Rubiola, “The measurement of AM noise of oscillators,” arXiv:physics/0512082, dec 2005
E. Rubiola, F. Lardet-Vieudrin “Low flicker-noise amplifier ...” Rev. Sci. Instr **75** 5 p.1323–26,

Power meter and calibrated attenuator

Power meter

- We have two similar power meters and some probes
- The RF probe goes up to 2 GHz,
  the µwave probe starts at 50 MHz
  (overlap in the 50-2000 MHz region)
- Reproducibility within **0.01 dB, max 0.02** (observed)
  - changing the mainframe
  - replacing the probe with another of the same type
  - interchanging the RF probe with µwave one
- Similar accuracy is expected in differential meas.



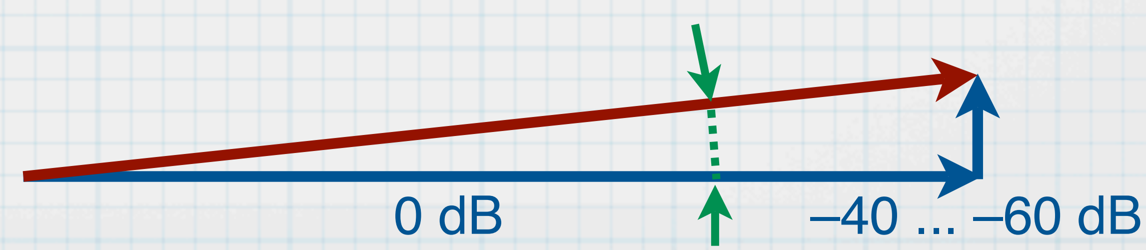
Reference attenuator

a reference attenuator with 40 dB attenuation and
0.05 dB accuracy is not difficult to obtain

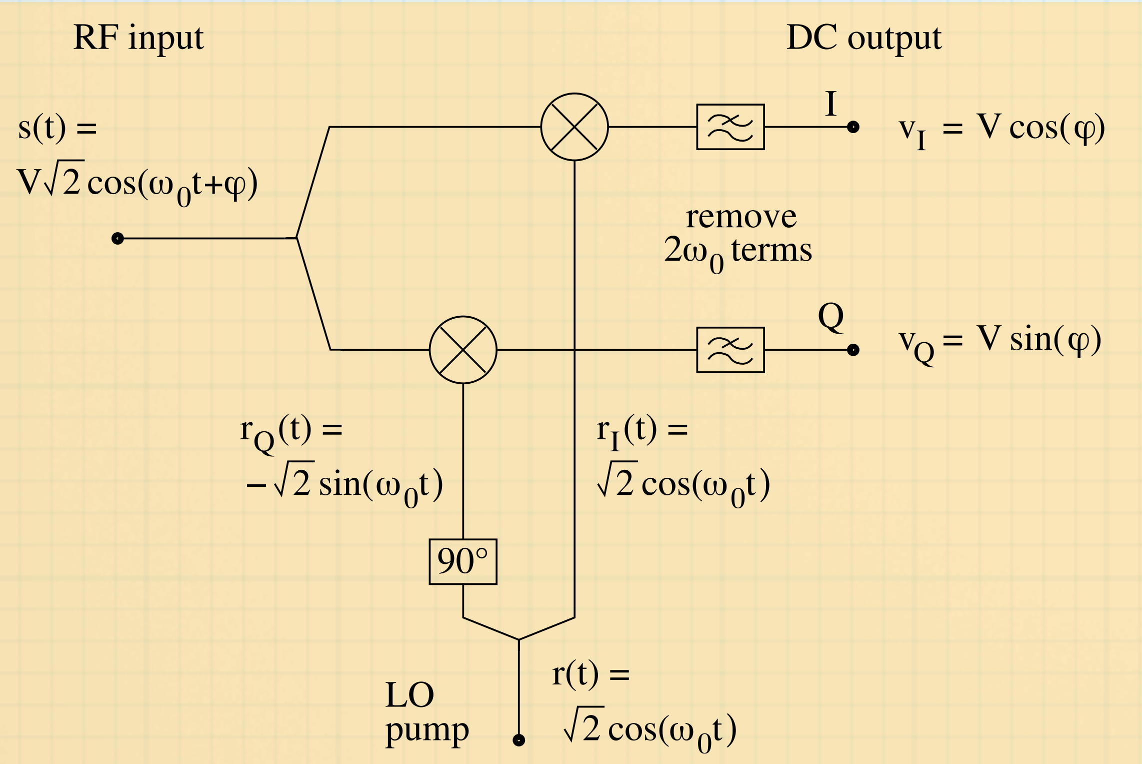
Power-ratio: 40–60 dB
Accuracy: 0.05 dB

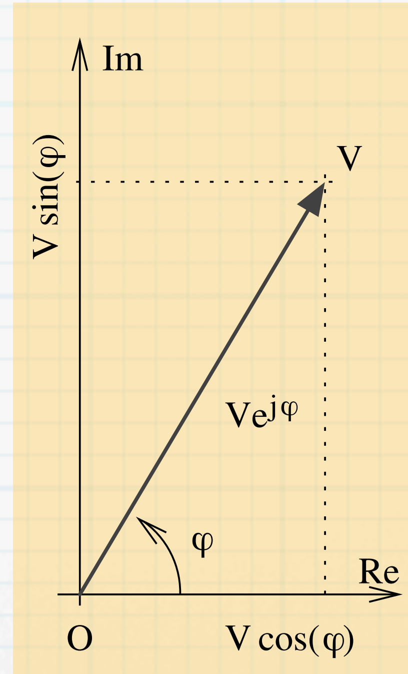
This should be achievable with off-the-shelf parts, at least at a set of frequencies.
A pinch of good luck may be useful

angle 0.05° ... 0.5°, accuracy 6×10^{-3}



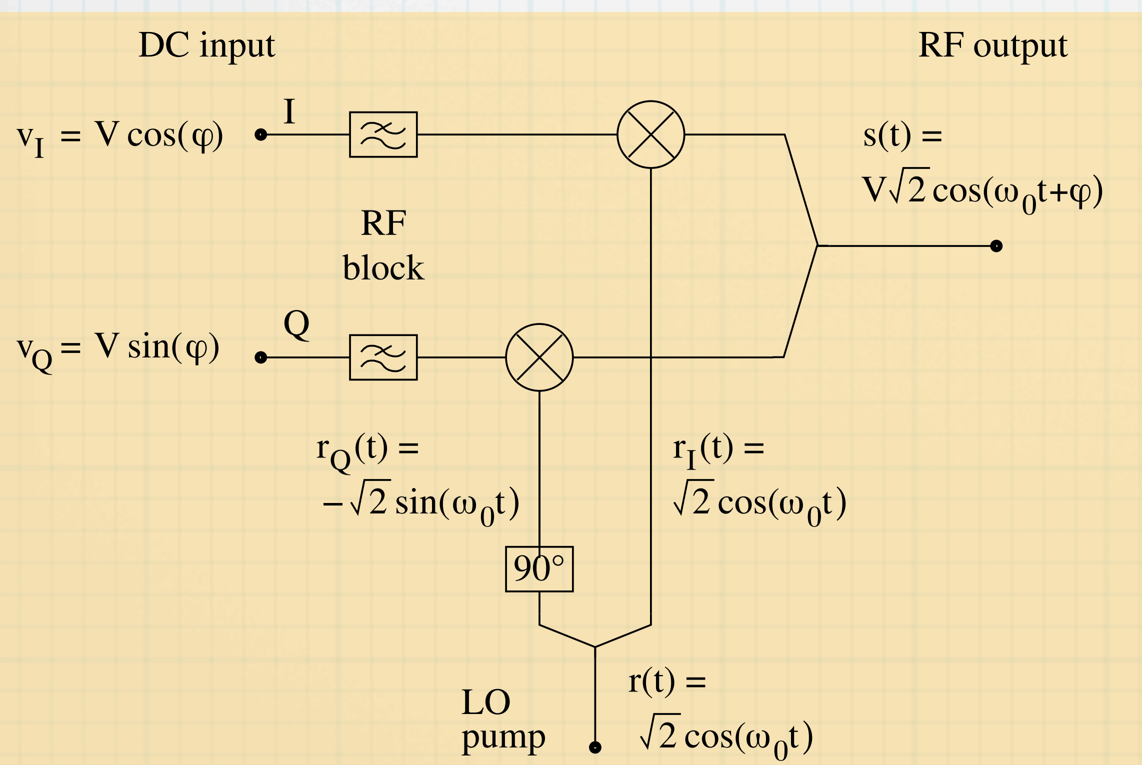
I-Q detector and modulator

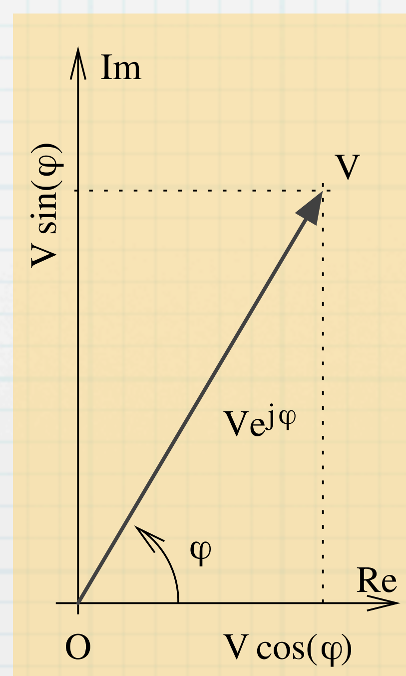




I-Q detector

Gets the **I** and **Q** components of the input phasor vs. the **Cartesian** frame defined by the **LO** pump



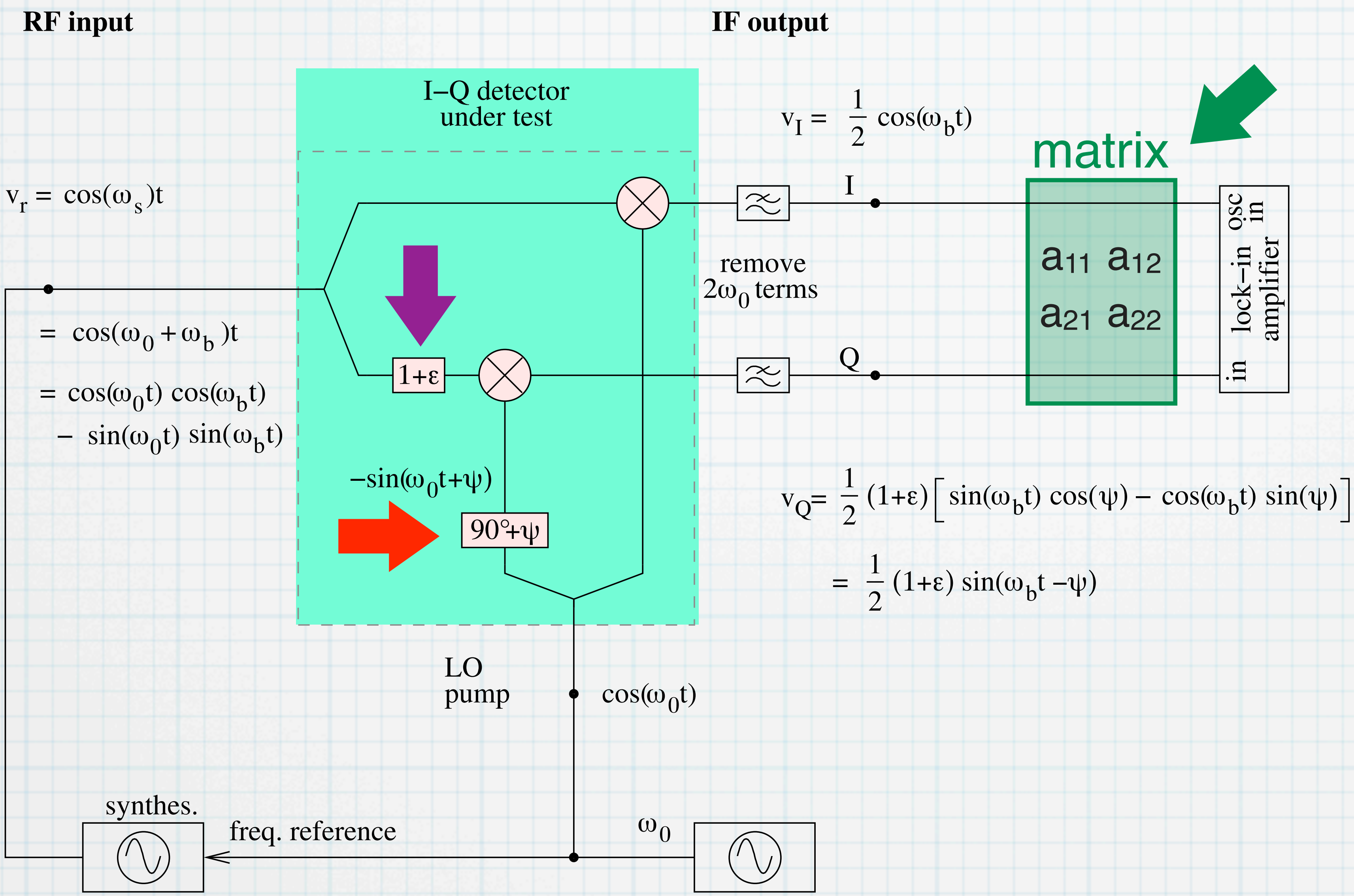


I-Q modulator

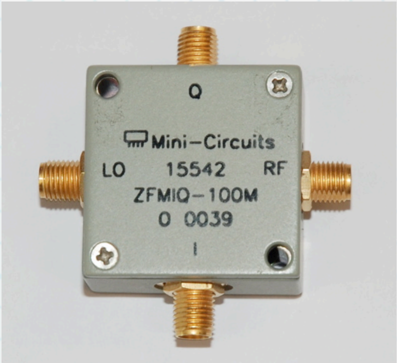
Combines the **I** and **Q** inputs into a phasor referred to a **Cartesian** frame is defined by the **LO** pump

E. Rubiola, “Tutorial on the double-balanced mixer,” arXiv/physics/0608211, aug 2006

Real I-Q detector

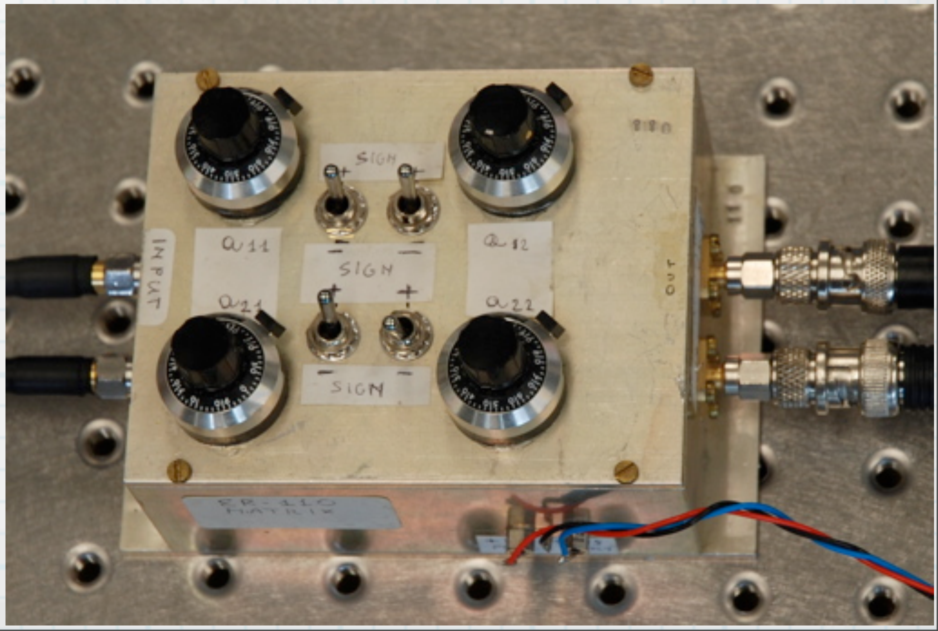


95–105 MHz I-Q



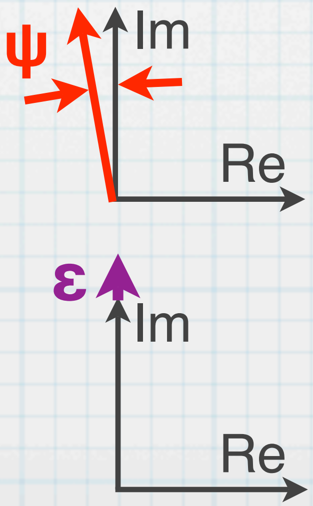
8–12 GHz I-Q

matrix

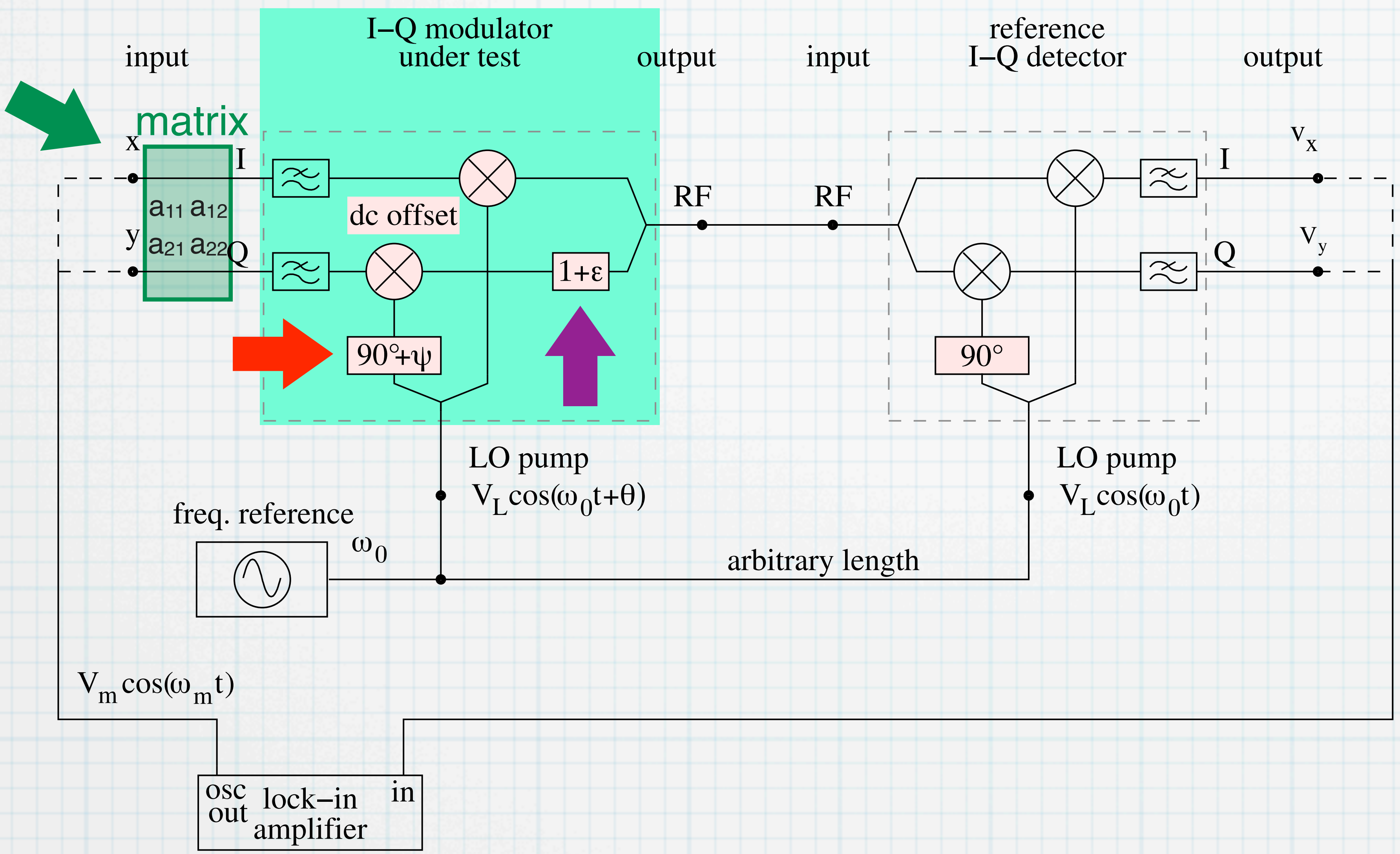


Problems & solutions

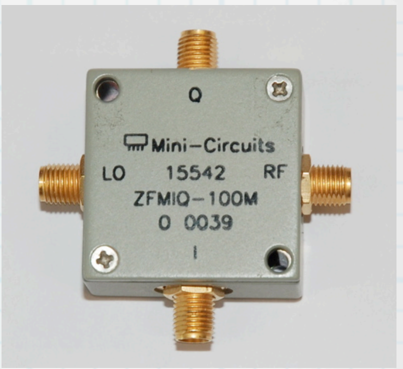
- quadrature error ψ
- amplitude asymmetry ε
- fix the errors with a matrix
- use the Gram Schmidt process
- the LO phase is still arbitrary



Real I-Q modulator



95–105 MHz I-Q



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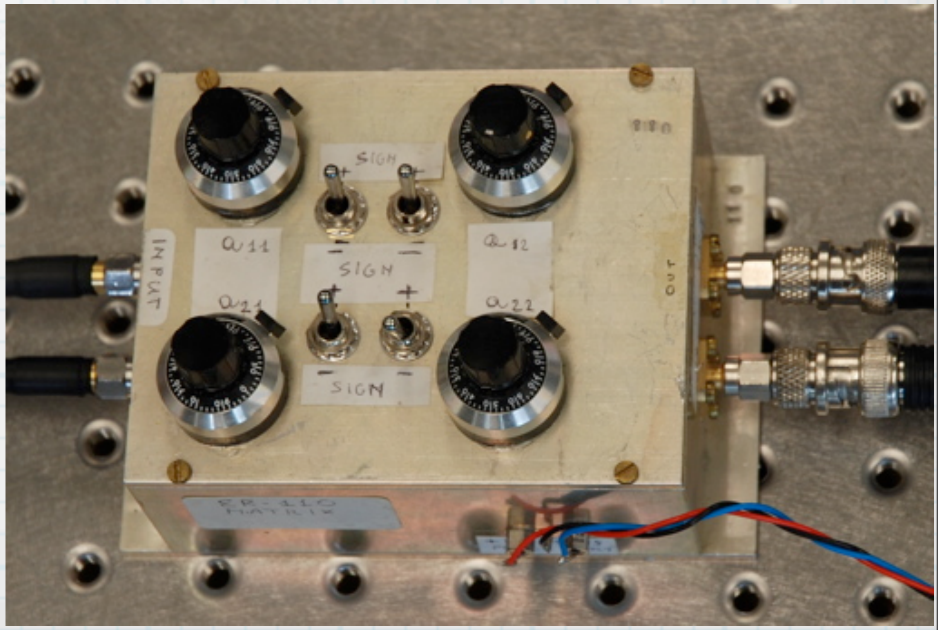

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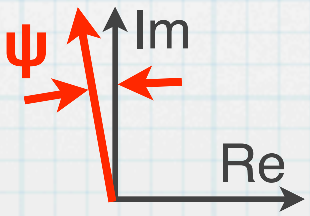
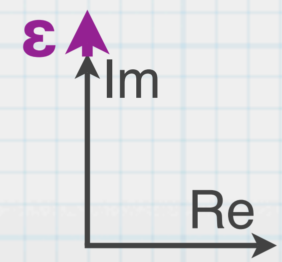
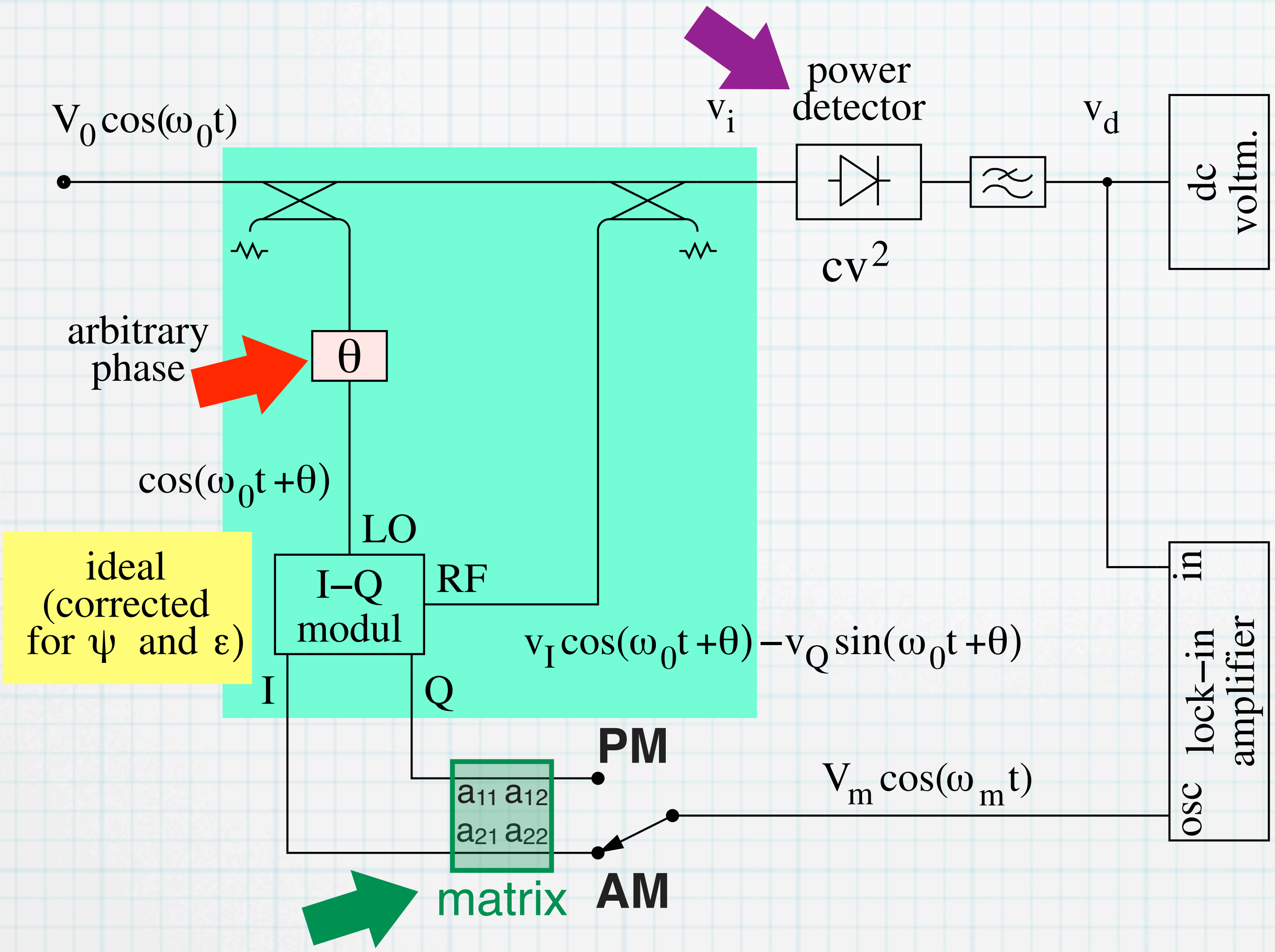




Setting up the reference modulator



$$V_{dc} = c\left[\frac{1}{2}V_0^2 + \frac{1}{4}V_m^2\right]$$

fundamental

I: $V_\omega = c\,V_m V_0 \cos(\theta)\cos(\omega_m t)$

Q: $V_\omega = -cV_m V_0 \sin(\theta)\cos(\omega_m t)$

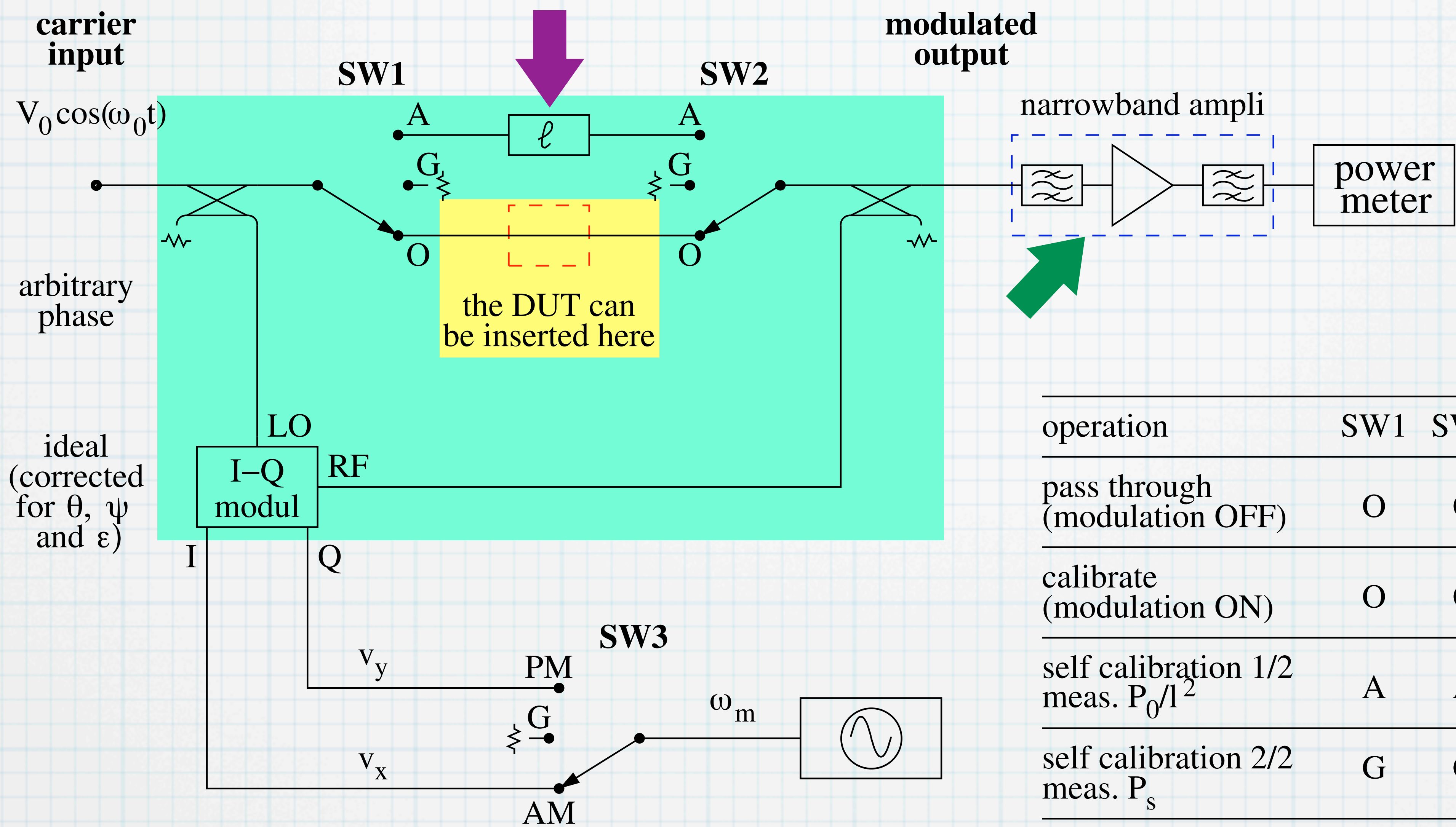
2nd harmonics

I,Q: $V_{2\omega} = \frac{1}{4}c^2 V_m^2 \cos(2\omega_m t)$

Problems & solutions

- the LO phase θ is still arbitrary
- this is fixed with a matrix that rotates the Cartesian frame by –θ
- pure PM is guaranteed by a null of the detected AM
- the corrected IQ guarantees the pure AM

Assessing the modulation depth



operation	SW1	SW1	SW1
pass through (modulation OFF)	O	O	G
calibrate (modulation ON)	O	O	AM/PM
self calibration 1/2 meas. P_0/l^2	A	A	G
self calibration 2/2 meas. P_s	G	G	AM/PM

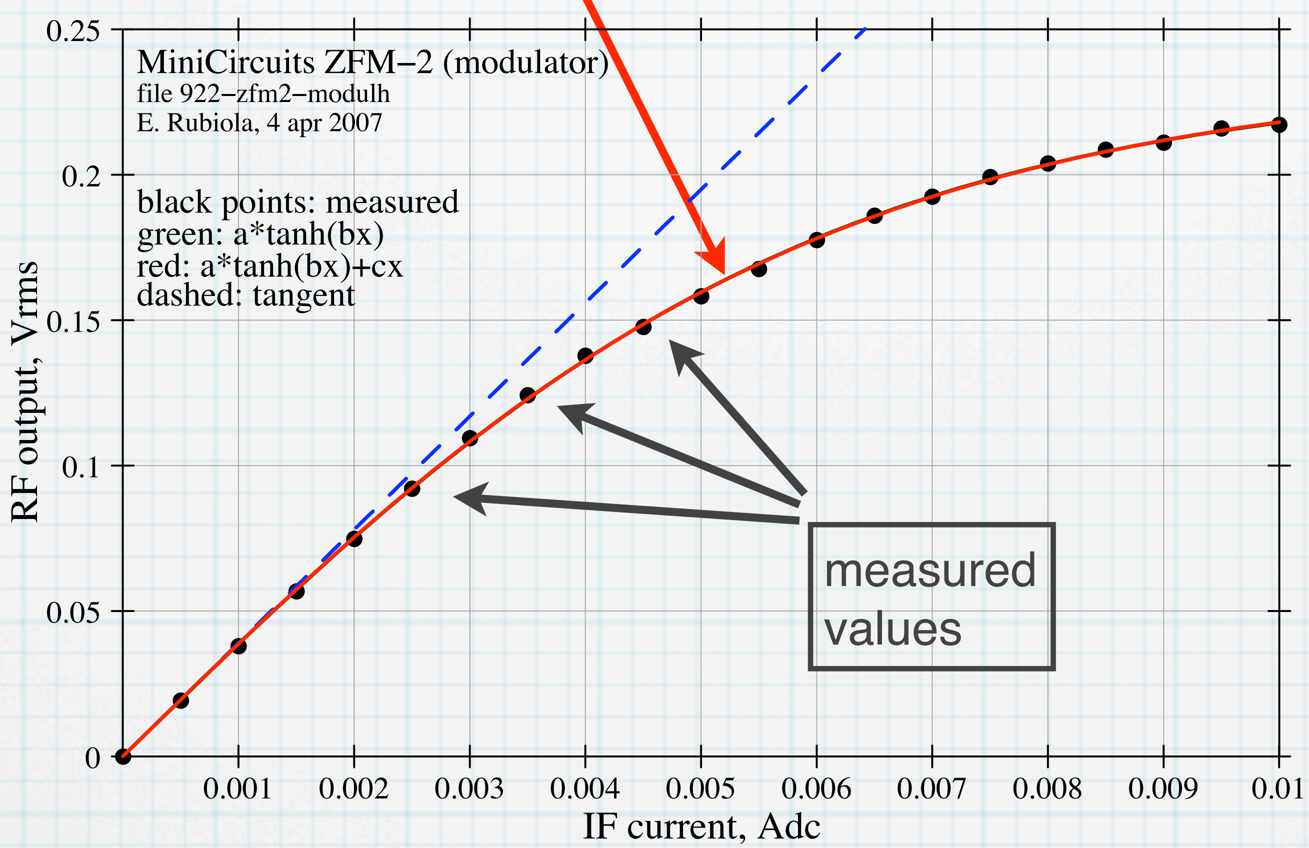
Problems & solutions

- measure the modulation depth as $P_{sidebands} / P_{carrier}$
- measure the carrier and the modulation separately
- need a reference attenuator for differential power measurement
- need a narrowband amplifier to limit the thermal noise of the power meter

Modulator linearity

$v_{RF} = a_1 \tanh(a_2 i_{IF})$ pure $\tanh(x)$ model

$v_{RF} = a_1 \tanh(a_2 i_{IF}) + a_3 i_{IF}$ $\tanh(x)$ model with dissipation



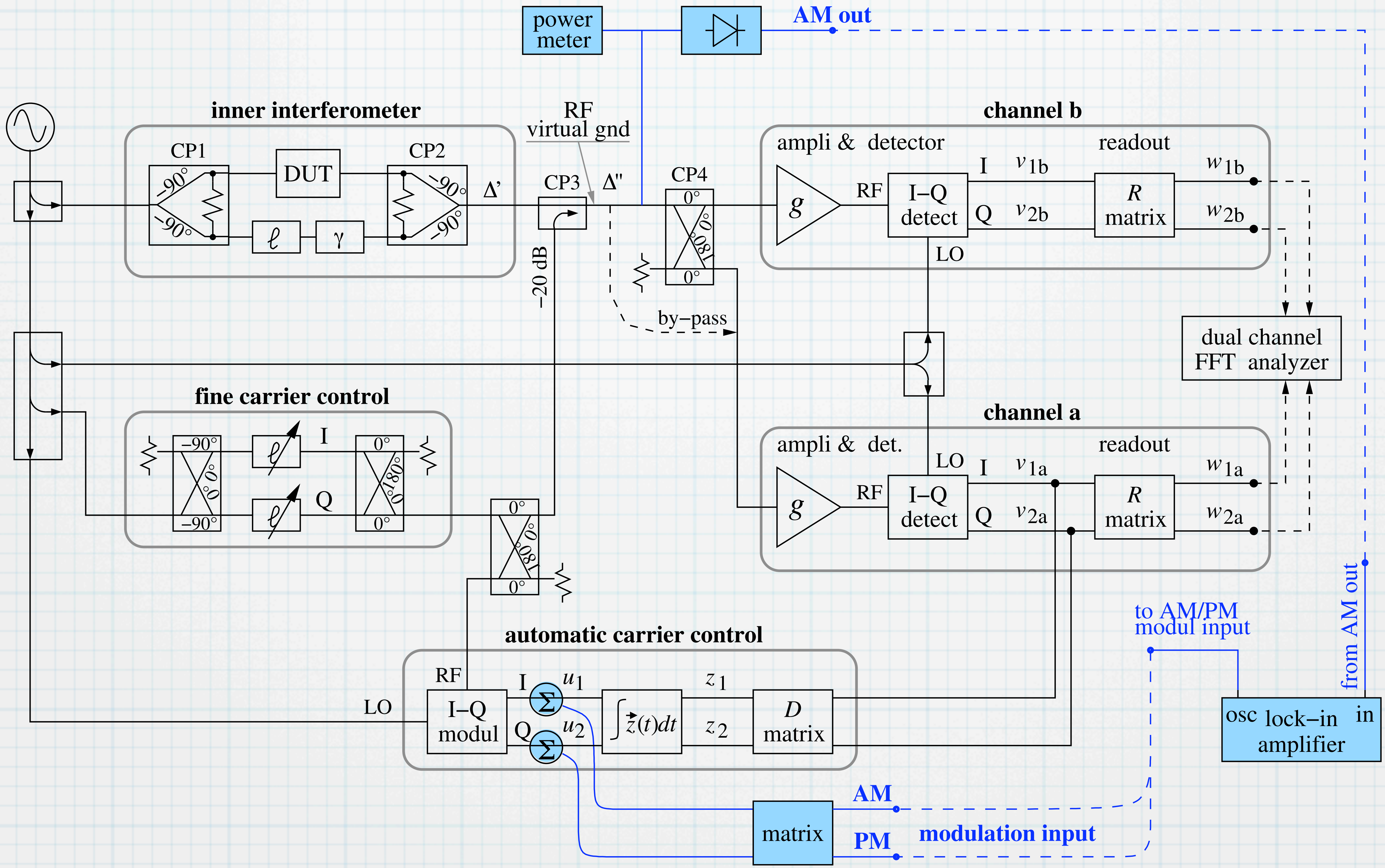
expected error, if non-linearity is ignored				
$\boldsymbol{i_{IF}}$	$\boldsymbol{\Delta v_{RF}/v_{RF}}$	v_{RF}	P_{RF}	
0.1	10^{-4}	3.91	0.305	−35.2
0.316	10^{-3}	12.4	3.05	−25.2
1	10^{-2}	39.1	30.5	−15.2
mA	(dimensionless)	mV_{rms}	μW	dBm

Error budget

parameter and conditions	value	
power ratio measurement (commercial power meter)	11.6×10^{-3}	(0.1 dB)
RF path (couplers, cables etc.)	23×10^{-3}	(0.2 dB)
reference 40 dB attenuator	5.8×10^{-3}	(0.05 dB)
mixer and detector linearity	1.0×10^{-3}	
null measurements (commercial lock-in, 10 bit)	1.0×10^{-3}	
signal-to-noise ratio	1.0×10^{-3}	
worst case total	43.6×10^{-3}	(0.37 dB)
rms total	26.5×10^{-3}	(0.23 dB)

Using off-the-shelf instruments and parts, an accuracy of 0.2-0.4 dB is feasible

Bridge (interferometric) instrument

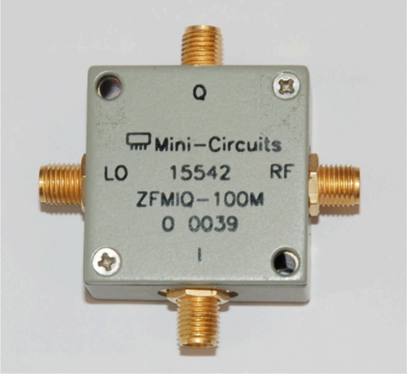


The dual-bridge contains almost all the blocks needed to calibrate the measurement

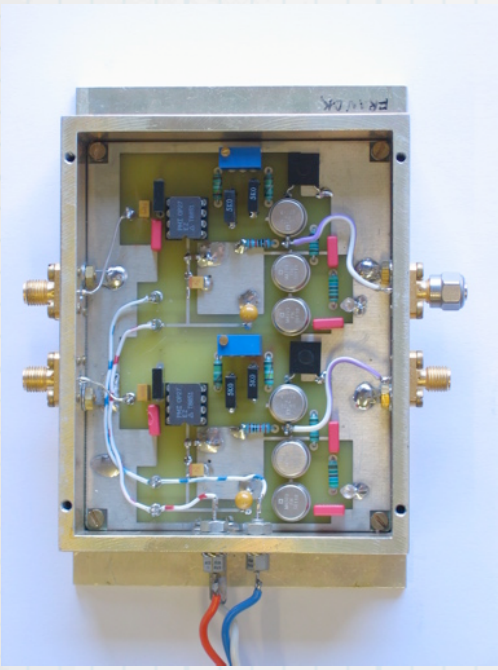
In light blue: the parts to be added (future work)

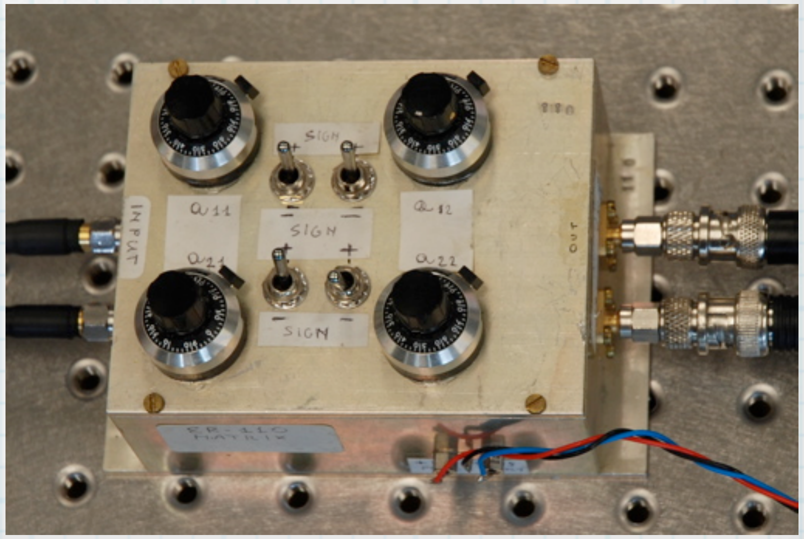
E. Rubiola, V. Giordano, Rev. Sci. Instrum **73** 6 p.2445–57, jun 2002. Also arXiv:physics/0503015

Conclusions



* The SI phase is a derived quantity, which can be obtained as $\varphi = \arctan(Y/X)$
* In principle, the application of primary-metrology methods to the AM-PM noise measurements is surprisingly simple
* FEMTO-ST has not primary-metrology facilities on site, which limits our possibility of a real test
* Using off-the-shelf instruments and parts, an accuracy of 0.2–0.4 dB is feasible
* The bridge (interferometric) instrument is suitable to the proposed method with a minimum added complexity





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