Wide-Band Spice Model of the High-Speed and High-Voltage Transformers for the CCD220

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Abstract

This poster presents the model parameters extraction of a high-speed transformer from real measured data which is a key component of the PID controller of the high-voltage clock generation for the CCD220. The extracted model includes the effect of the magnetic coupling between the transformer windings, the conductor losses and the interwinding parasitic capacitances, along with the stray capacitances of the PCB footprint and metal tracks. The model has been implemented, tested and validated in an outstanding way.

Introduction

The characterization of the high-speed transformer in the high-voltage clock circuit inside ESO's AO camera is crucial to understand the PID controller which stabilizes the high-voltage output that drives the amplification register of the CCD220. The extracted model presented here includes the effect of the magnetic coupling between the transformer windings, the conductor losses and the interwinding parasitic capacitances, along with the stray capacitances of the PCB footprints and metal tracks. The model has been implemented, tested and validated in an outstanding way. First, the raw wide-band and two-port network data was measured with a Vector Network Analyzer. Second, the parameter model was fitted through an easy-to-use and well established vector fitting technique. Lastly, the transformer's behaviour was accurately modeled as a linear circuit in the Laplace Domain by a network of controlled current and voltage sources.

Theoretical background

The success of the fitted model depends not only on how accurately its represents the physical properties (e.g., resonances, transient response, etc.), but, also how fast it can be simulated or whether it is stable at all. The methodology employed takes into account these considerations. A suitable set of parameters easy to measure, or, a well established fitting method that captures the properties of interest of the transformer can decide the quality of the design in which it will be used.

The Scattering Parameters

Theory of Scattering (or 'S') Parameters was developed in the early 60's (K.Kurokawa, 1965). The development of new multi-port network measurement instruments that directly extract the S-Matrix makes the art of radio frequency measurements really affordable. The S-Parameter measurements have the interesting property that it is not necessary to perform neither shorts nor opens on the network during the measurement process (unlike other kind of representations, say Z or Y parameters).

The physical meaning of S Parameters is similar to Z or Y: s_{11}, s_{22} represent how power is reflected in the system (input/output immittances or reflection coefficients), and s_{21}, s_{12} represent the forward/backward power-transference from/to source to/from load, respectively. In mathematical form:

$$b_1 = s_{11}a_1 + s_{12}a_2$$
$$b_2 = s_{21}a_1 + s_{22}a_2$$
$$[S] = \begin{bmatrix} s_{11} & s_{12} \\ s_{21} & s_{22} \end{bmatrix}$$

Where a_i, b_i represent the normalized incident/reflected wave into/from the i-th network port (i=1,2). These waves have the form:

$$a_i = \frac{V_i + I_i Z_0}{2\sqrt{\Re(Z_0)}}, b_i = \frac{V_i - I_i Z_0^*}{2\sqrt{\Re(Z_0)}} \quad \text{(eq.1)}$$

Where V_i, I_i represent respectively *rms* voltage and current flowing into the network, and Z_o is the reference impedance (it can be any, real or complex). The symbol '*' denotes complex conjugate.

Generic Two-Port linear network showing standard references for waves a_i, b_i; voltages V_i, and currents I_i, i=1,2. A transformer can be considered as a two port linear network in a first approximation.

The Vector-Fitting Method

In general, an analytical model of a measured transfer function is often desirable. In our case, we require a model for simulation purposes. Vector Fitting (VF) is a relatively simple procedure that lets the designer implement and test the model in an simple way. The result can be easily described in terms of simulation languages (scripting) or as in our case, in the form of a circuit that can be interpreted by any Spice-like time-domain simulator with behavioral simulation capabilities.

The starting point for modeling with the VF method is an analytical complex function, *i.e.*, a rational function expanded in partial fractions with residuals (the so called parallel form):

$$H(s) = \frac{r_0}{s-p_0} + \frac{r_1}{s-p_1} + \dots + \left[\frac{r_k}{s-p_k} + \frac{r_k^*}{s-p_k^*}\right]$$

Where p_k are the poles (real or complex conjugates), r_k are the residuals (real or complex conjugates), $s=\sigma+j\omega$ is the Laplace complex variable and ω, the angular frequency ($\omega=2\pi f$).

Vector Fitting (or pole fitting) aims to find all residuals r_k and poles p_k, plus two extra parameters d (a gain) and e (a pole at infinite) in the augmented model,

$$H(s) = \frac{r_0}{s-p_0} + \frac{r_1}{s-p_1} + \dots + \left[\frac{r_k}{s-p_k} + \frac{r_k^*}{s-p_k^*}\right] + \dots + d + s \cdot e$$

in order to minimize the (in general, weighted) least-square error from the set of measured data sampled at $s_n = j\omega_n$ (B. Gustavsen, 1999).

This is an iterative, but linear method that fits this augmented equation to the given data. To improve the result, data post-processing is recommended to assure stability (pole-reallocation). To reduce the order of the fitted model only the band-width of interest should be used.

In the case of a transformer or, in general, for any electrical network, a set of $H(s)$ (for instance, one for each of the s_{kl} of the transformer model) is achieved simultaneously. For the sake of simplification, all poles (but not residuals) are shared. This way the complexity of the VF method is highly reduced without noticeable loss of accuracy.

Spice Modelling

Considering the S-Matrix of a two-port network available and a analytic model expanded in parallel form constructed by using, for instance, the VF method, or any other suitable scheme, always it is possible to represent rational forms in terms of lumped elements such as Impedances and controlled sources (Stevens & Dhaene, 2008). Rearranging the expressions in eq.1:

$$V_i = Z_0 I_i + 2\sqrt{\Re(Z_0)}b_i$$

$$a_i = \frac{\sqrt{\Re(Z_0)}}{2}I_i + V_i / \left(2\sqrt{\Re(Z_0)}\right), i = 1,2$$

regarding a_i, b_i as normalized voltages and currents respectively, both expressions can be depicted in terms of circuit elements as follows (other configurations are possible, as well):
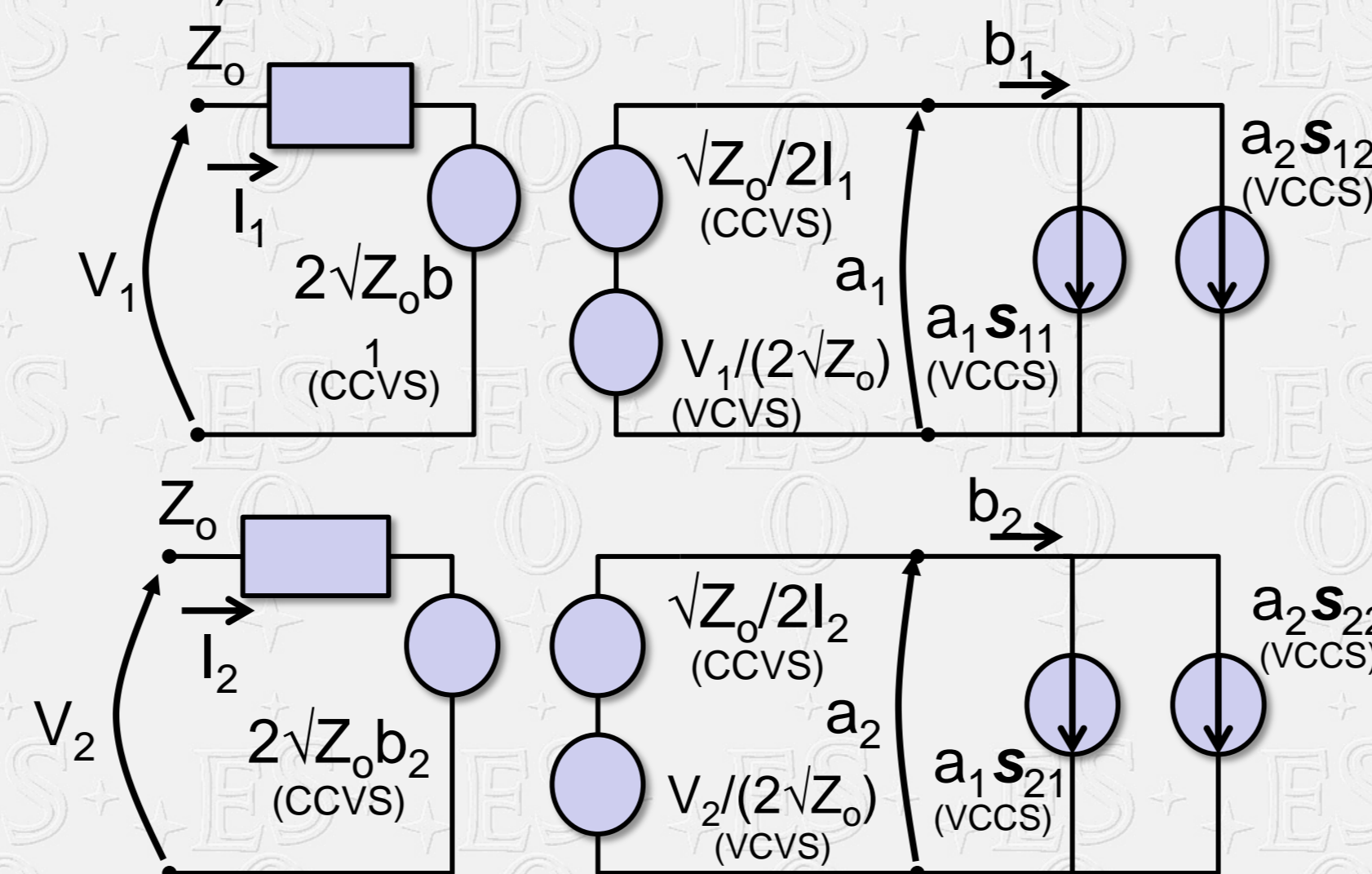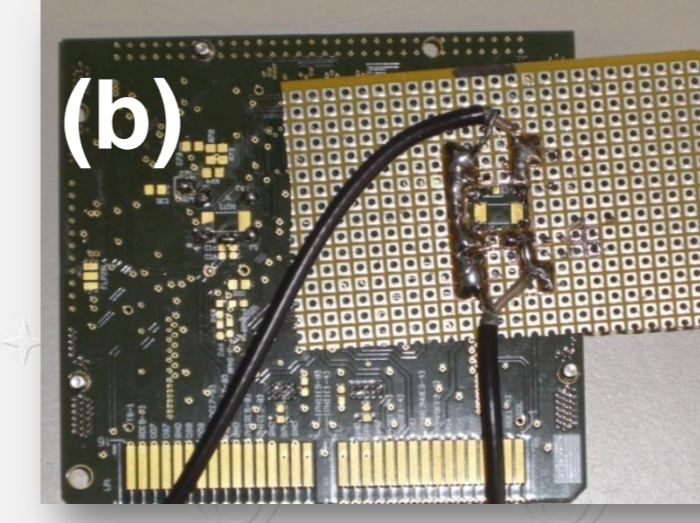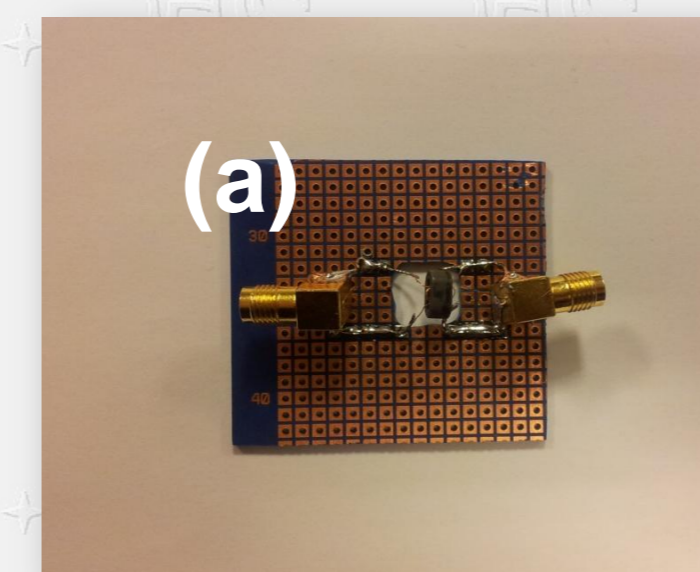

Generic Two-Port linear network described in terms of lumped elements: controlled sources and impedances. VCCS: Voltage-controlled current source. VCVS: Voltage-controlled voltage source. CCVS: Current-controlled voltage source.

Measurements, Simulations and Test Results

Test Bench Setup

The transformers used for high-voltage clocks of the CCD220 were two windings of copper wire wound on a pig-nose, wide-band balun ferrite core from Micrometals (www.micrometals.com); 2.5 turns on the primary and 5 turns on the secondary. The measurements were made using a Rohde & Schwarz ZVRE 9KHz-4GHz Vector Network Analyzer. The cables employed were RG-214/U 50Ω with SMA male connectors. For the test, the transformer was soldered directly to the SMA connectors.
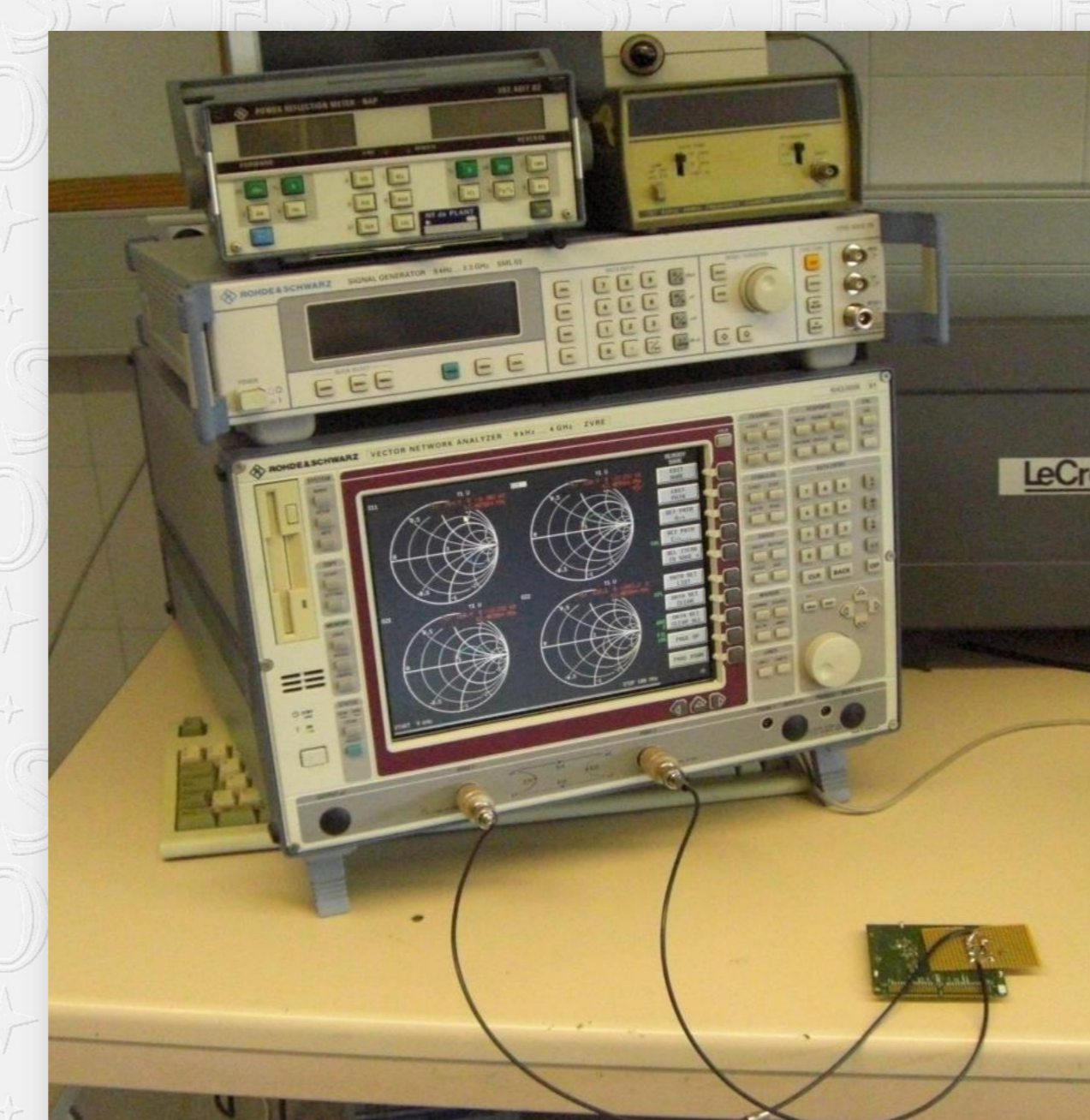
Data Processing

The data measured was processed with a free MatLab Toolbox developed by Gustavsen adapted especially for the transformer model calculations. The processing time is less than five seconds. The parasitic model was implemented by using a non-linear programming method in Matlab.
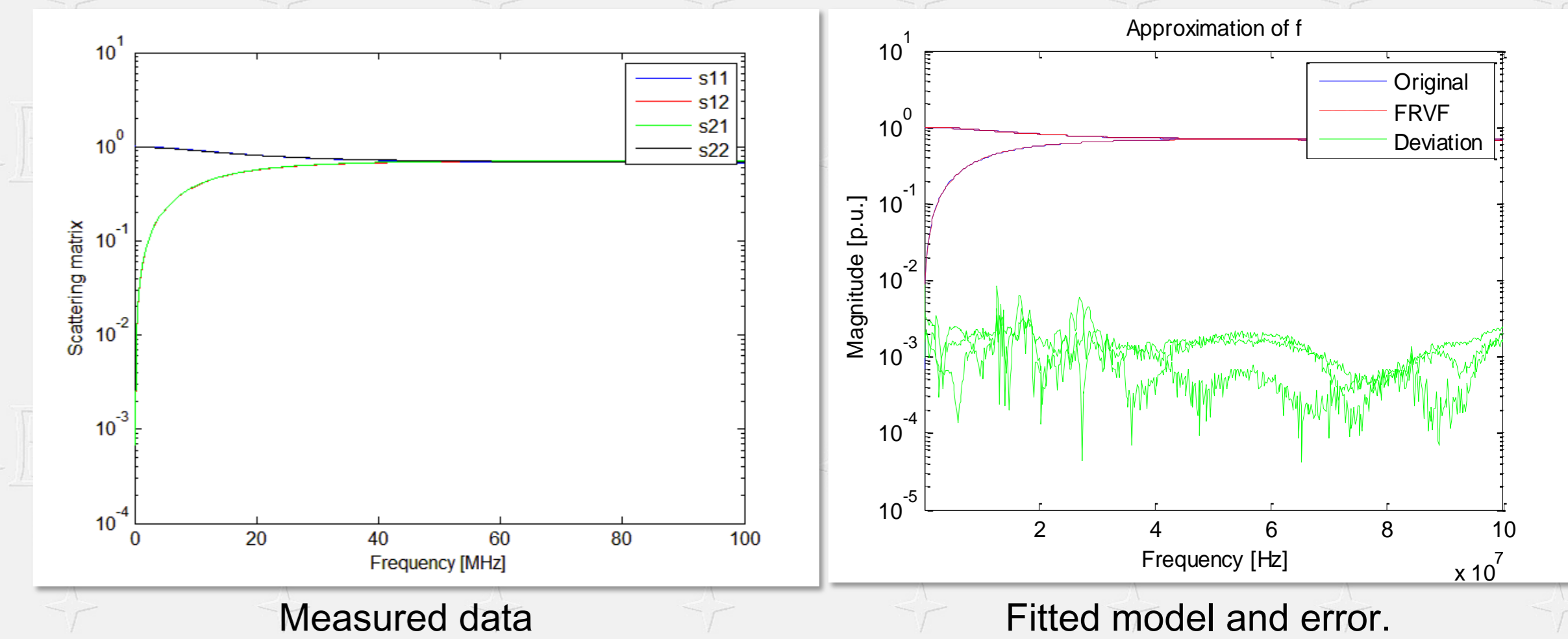
Measured data.   Fitted model and error.

Simulations

The simulator selected for model testing was SiMetrix, a fast time simulator with behavioral modeling capabilities (in Laplace domain). Like any Spice simulator, the schematic can be implemented by using the standard Spice lumped components.

Model of the PCB parasitics.

Model of the transformer.   Simulation Test-Bench.
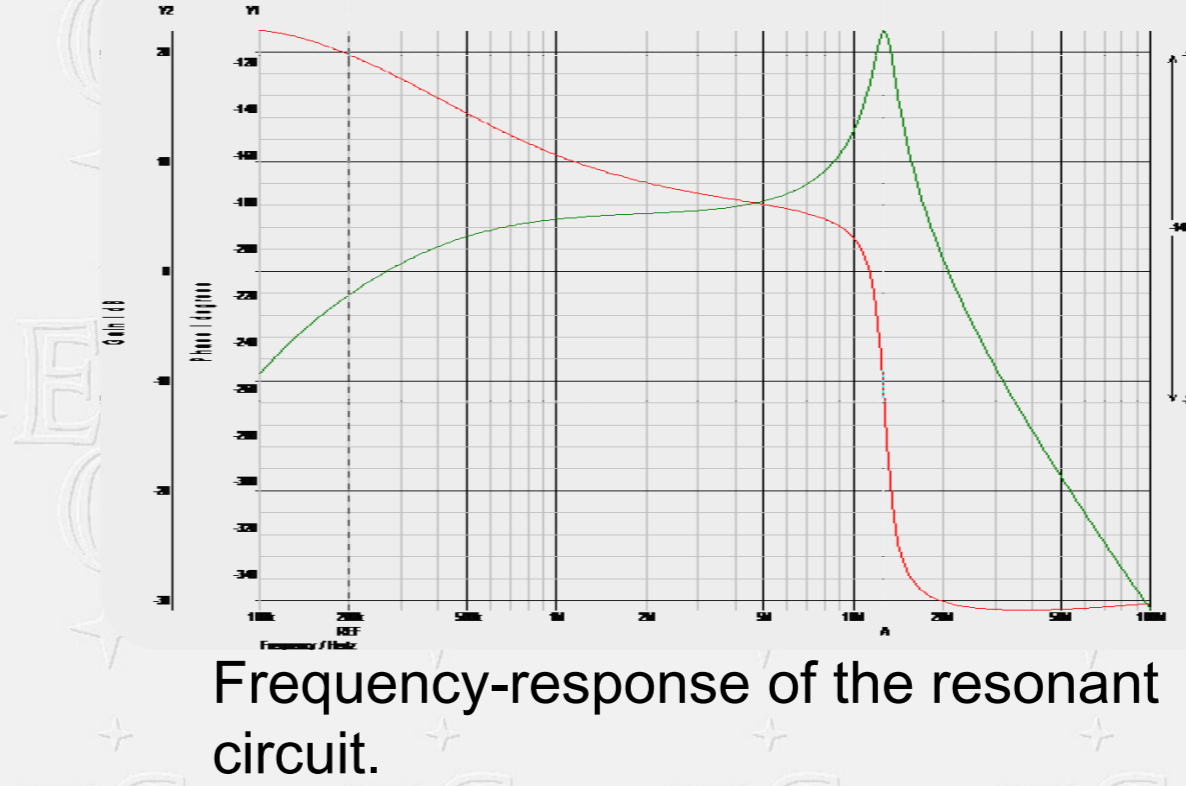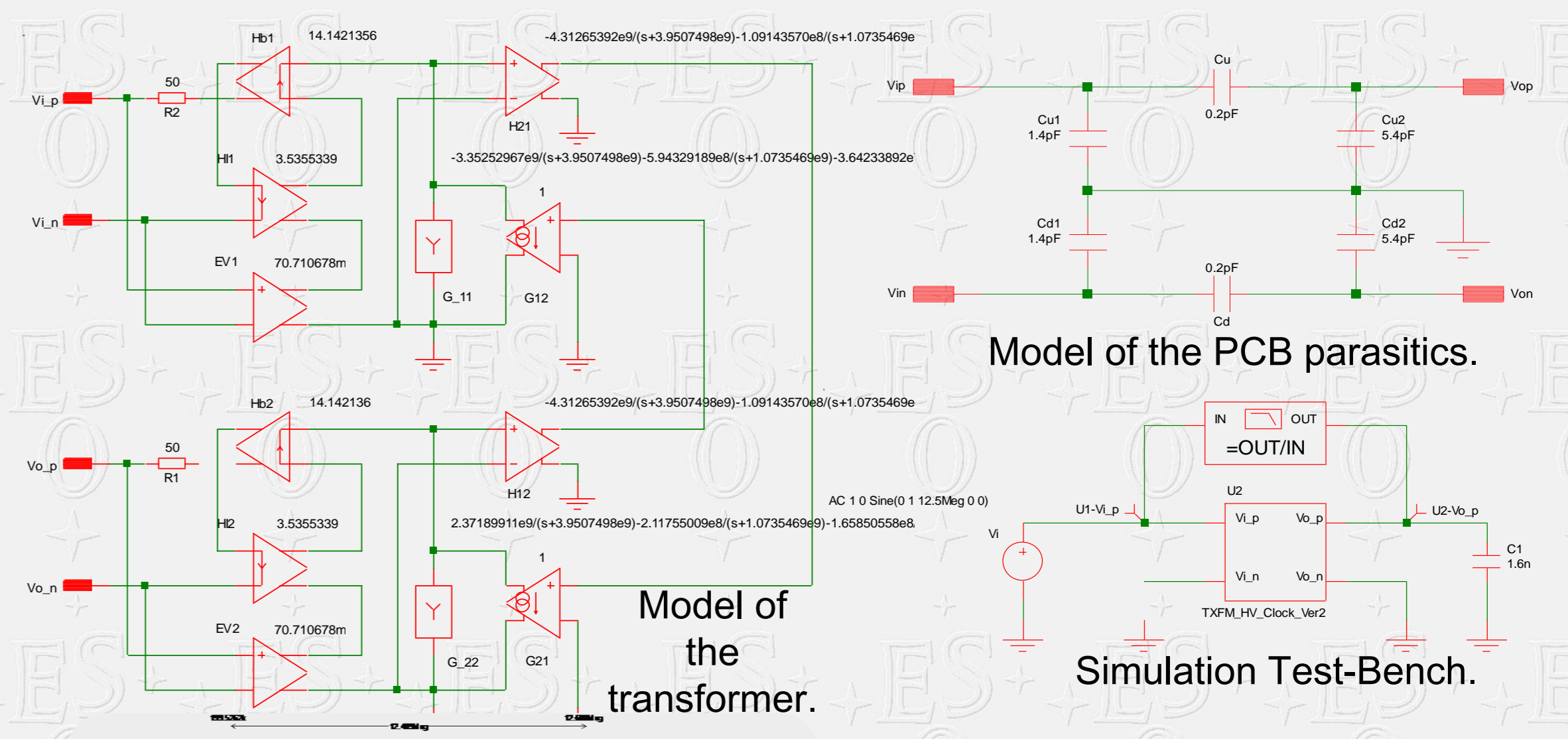
Frequency-response of the resonant circuit.   Time-domain simulation around the resonance frequency.

Experimental Results

The oscilloscope shows that the HV-clock of the CC220 varies during the frame readout and variation is proportional to illumination level. This sensitivity to disturbances can be minimized with the proper tuning of the PID controller. Thanks to the accurate model of the transformer the value of the components in the PID have been optimized by simulation to respond quickest to disturbances.

All the simulations have been confirmed by measurements and both agree extremely well. The excellent results speak by themselves.

Unoptimized HV-clock step response   Optimized HV-clock step response

RTD cut on the unoptimized CCD   RTD cut on the optimized CCD

ESO Adaptive Optics high-speed camera based on the e2v L3 Vision CCD220.

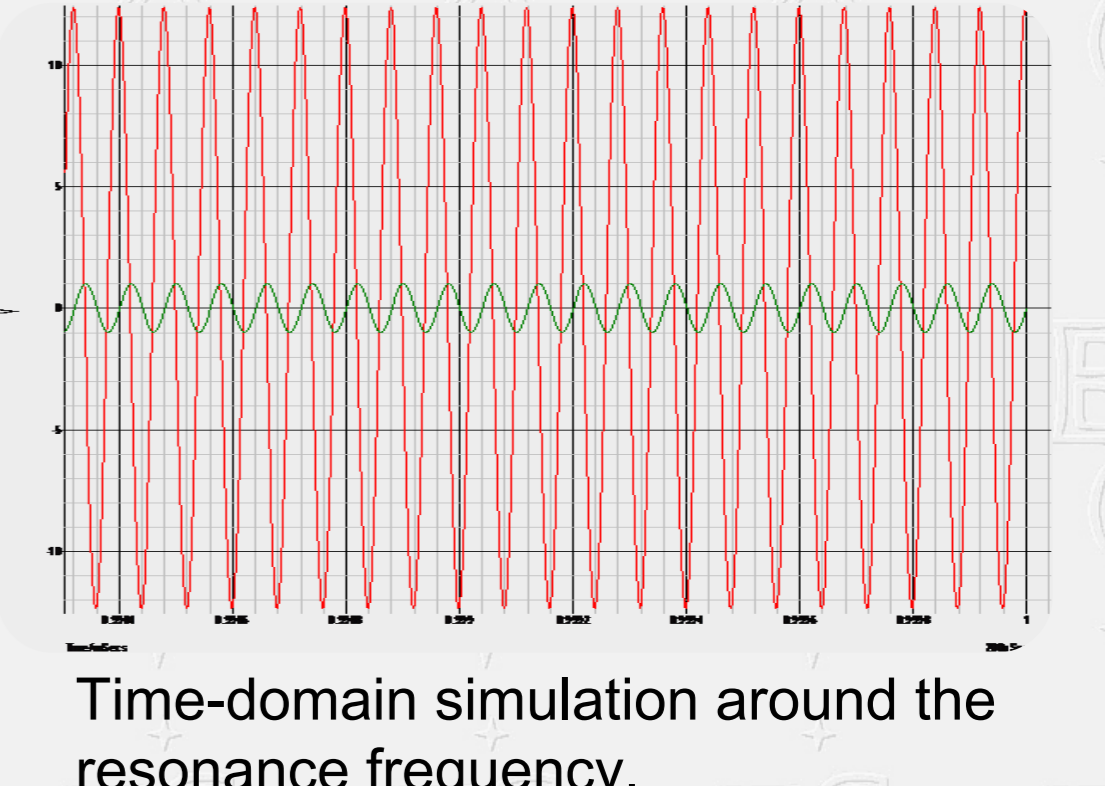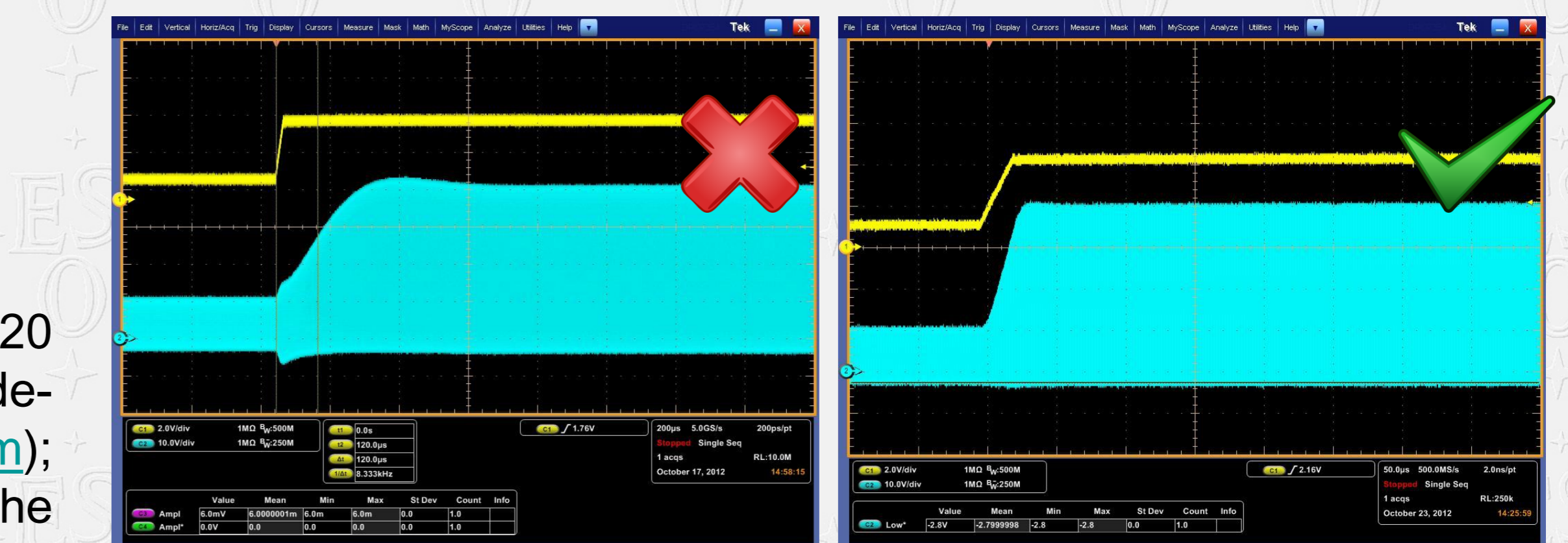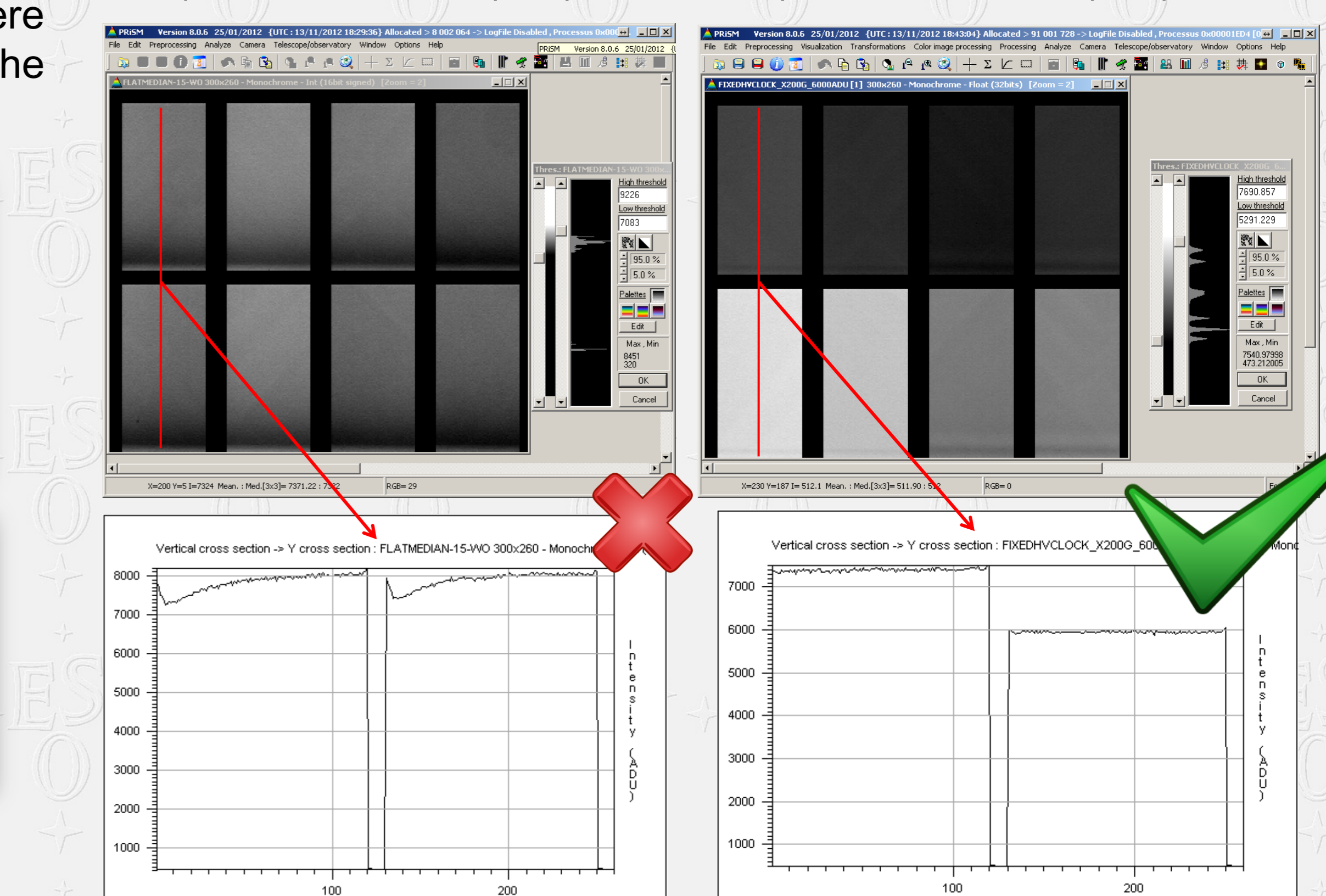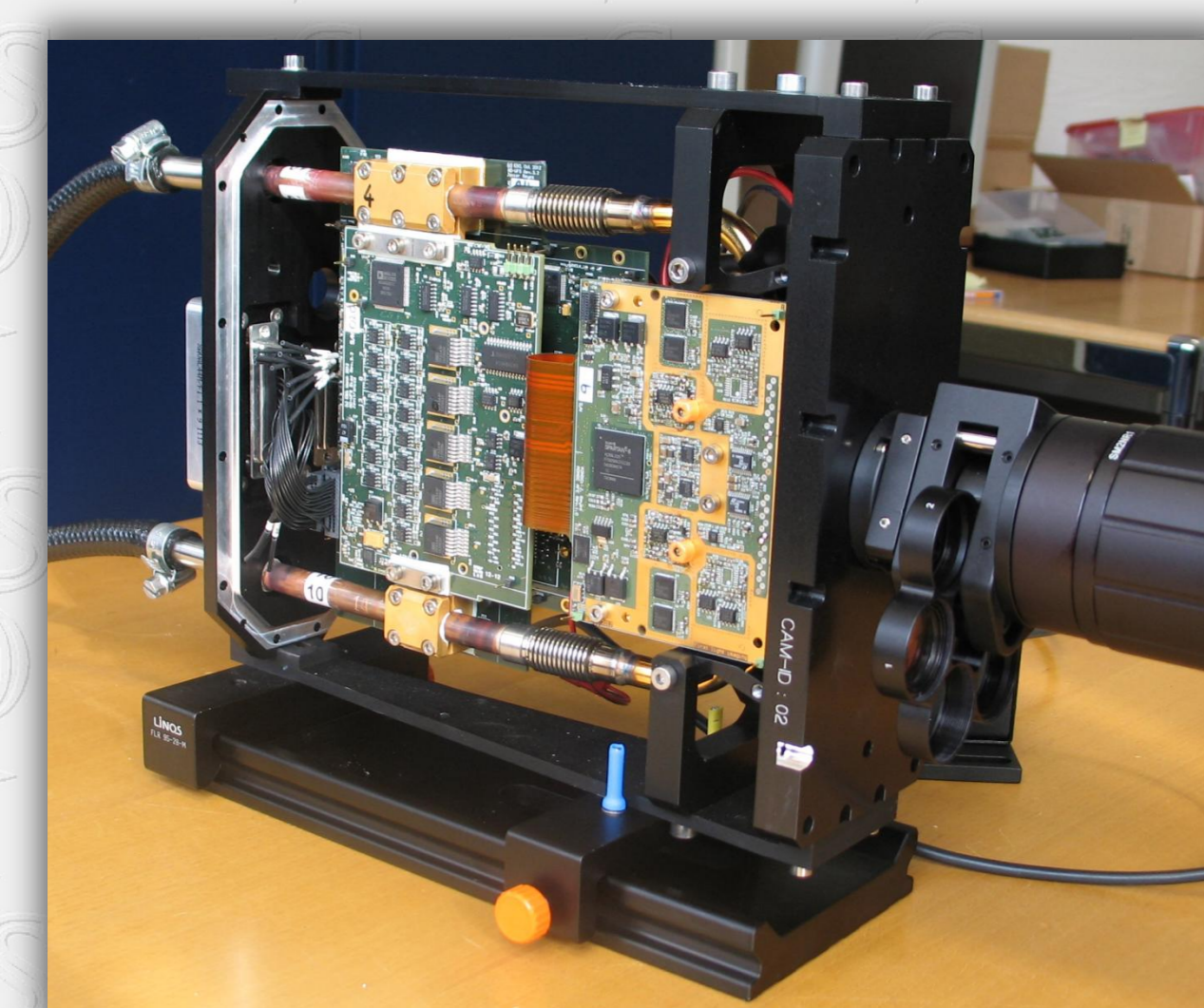| CCD Format	240x240, 8 ports
Pixel size	24 x 24 μm²
RON	< 0.1e-
Frame rate	1.5fps
Video ADCs	14-bit

Test-Bench with the ZVRE Network Analyzer and the cables-connector setup. The analyzer can measure all the parameters simultaneously as shown in the image.

(a)

(b)

a) SMA connector and the HV-clock transformer.

b) Setup for the PCB parasitic measurement.

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