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# Fully-digital low-frequency lock-in amplifier for photoluminescence measurements

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## Abstract

Lock-in amplifiers, used in several experimental physics applications, are instruments performing quadrature demodulation, which is useful when signals are affected by much noise. Generally, commercially-available lock-in amplifiers are very accurate, but expensive, especially if their operating range includes radiofrequencies. In many applications, high precision is not necessary for the measurements, but it is preferable to have low-cost, low-weight, compactness and a user-friendly graphical unit interface. In this paper, we describe a new fully-digital low-frequency lock-in amplifier developed at ENEA C.R. Frascati Laboratories for photoluminescence experiments based on an innovative low-cost architecture and processing algorithms. The hardware, firmware and software developed for the whole photoluminescence measurement set-up is presented. The present lock-in was first characterized with synthetic electrical sine wave signals and white noise. A dynamic reserve of 43 dB and a noise figure in the range of 25–44 dB were estimated. These results show compatibility with several measurement applications, such as photoluminescence, and the adequacy of the resolutions with respect to the hardware costs. Finally, preliminary results of photoluminescence measurements are presented.


**Keywords** Lock-in amplifier · Photoluminescence · Microcontroller · Digital signal processing

## 1 Introduction

Lock-in amplifiers demodulate a signal, with a proper carrier that can be in a very different frequency range, from an extremely noisy environment. At ENEA C.R. Frascati Laboratories, measurement instrumentation not available on the market, based on lock-in amplifier architecture in medium–high frequency range, was developed, such as interferometers [1], reflectometers [2], optical radars [3] and bolometers [4]. In high-frequency carrier applications, like optical radar demodulation, quadrature demodulation, based on a well-tested algorithm [3], Field Programmable Gate Array (FPGA) hardware was mandatory. On the contrary, in linear optical spectroscopy measurements, used in many applications and scientific investigations, the carrier frequency can be very low. In this case, considering the carrier frequency (i.e. ~ 200 Hz), the sampling frequency of 1ksps (1 k sample per second) is below the Nyquist Frequency.

In this paper, we describe a new family of fully-digital lock-in amplifiers, based on microcontrollers, developed for photoluminescence (PL) measurements at ENEA C.R. Frascati, with the aim of making instrumentation with the following characteristics: easy to use, cheap, reduced size and weight, accurate, reprogrammable and/or reconfigurable, with graphical user interface and digital data transmission to a Host PC without loss of precision. In order to check the validity of the present scheme and to enable comparison with other previous implementations, experimental tests were first carried out with synthetic electrical signals and white noise at different values of signal-to-noise ratio (SNR). This allowed us to carefully estimate the dynamic reserve and noise figure of our system. Then, the lock-in amplifier was applied to real electrical signals coming from photoluminescence measurements.

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## 2 System description

### 2.1 Lock-in hardware

The measurement system is based on a custom *DSP Box* containing a Microcontroller board and a simple. Signal conditioning mezzanine.

The microcontroller board is the low-cost Arduino Mega 2S60, based on the 8bit Atmel ATmega2S60 microcontroller, having 16 MHz crystal-oscillator, 16 analog inputs, and a USB port [5].

The conditioning board consists of two anti-aliasing low-pass filters for both CH1_R and CH2_S channels. Moreover, the CH2_S channel has a DC-block and a DC offset circuit, necessary to pull up the input in case of negative signals, such as in the case of PMT (Photomultiplier tube).

Figure 1 shows the DSP Box layout and the test-bench for its electrical characterization, as explained in par 3.1.

### 2.2 Microcontroller firmware

The firmware for the microcontroller board (see Figs. 2 and 3) has been developed in C language and performs several functions:

1. *Communication with Host PC*
2. *Oscilloscope feature*
3. *Lock-in feature and setup* see Fig. 2

Details on the functions listed above are given below:

1. *Communication with Host PC*
2. The microcontroller board communicates setup and starts oscilloscope and lock-in with the Host PC via USB port in serial protocol (19,200 baud). General-purpose serial monitor software or the custom software described in Sect. 2.3 must be installed on the Host PC.
3. *Oscilloscope feature*
4. The oscilloscope firmware acquires the CH1 and CH2 signals at 1ksps. Due to the low throughput of the USB port, it is necessary for the microcontroller to acquire and store the CH1 and CH2 signals in arrays. When the array is full, the microcontroller stops the acquisition and sends the data to the host PC.
5. *Lock-in feature and setup*
6. The microcontroller implements the quadrature demodulation in real-time with a fully digital signal processing,

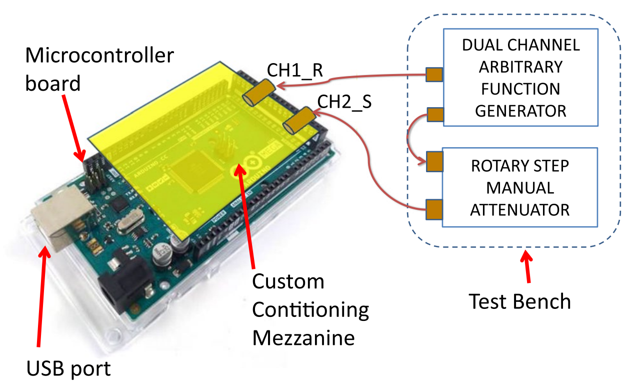



**Fig. 1** DSP box layout and electric characterization test bench

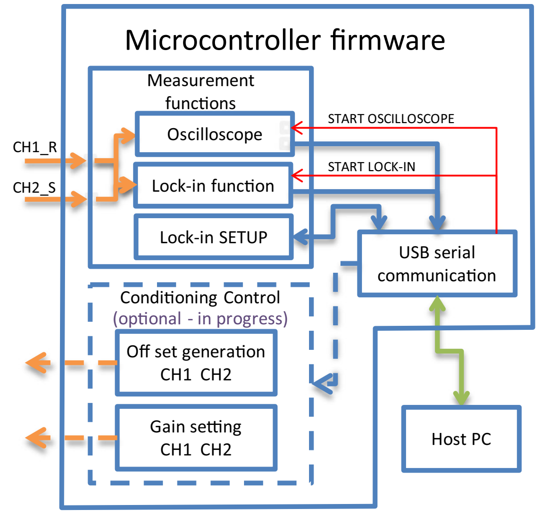



**Fig. 2** Microcontroller firmware function

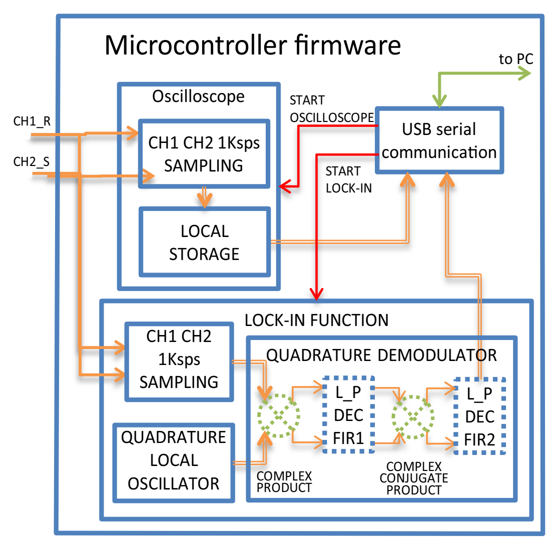



**Fig. 3** Firmware detail

sending the record containing the timestamp and the demodulated components to the Host PC.

Considering a sampling frequency of 1ksps, the chopper frequency (~ 200 Hz) is lower than the Nyquist Frequency, so it is possible to sample both channels (*CH1_R (reference)* and *CH2_S (signal)*) and perform quadrature demodulation with the digitalized signal using Digital Signal Processing.

The digital demodulation algorithm [3] needs a synthetized digital local oscillator, the Local Oscillator signals and the sampled signals are connected to a complex product generating low and high frequency components. The high frequency ones are removed by a first Low Pass Decimator FIR (Finite Response Filter). The complex low-frequency components, relative to Signal and Reference, are multiplied after a conjugation operation [3]. In such a way, even if the Local Oscillator is not perfectly synchronous to the Chopper frequency, the low-frequency components related to the sinusoidal and cosinusoidal part of the Photodetector Signal with respect to the Chopper Reference are obtained.

The time required for the dispatch of the records containing the lock-in measures up to 1sps, allows to process the signals CH1, CH2 without loss. If the chopper frequency is not known, it is possible to measure it by using the oscilloscope function (see. Figure 4); the position of the peaks in the FFT spectra provides the fundamental frequencies of the signals. We set the parameters of the two Decimation FIRs (decimation factor and FIR response) as a function of the desired output measurement frequency and the chopper jitter.

## 2.3 Host software and graphical user interface

The Host PC is connected to the microcontroller board via USB port in serial protocol (see Fig. 1 and Fig. 2). The microcontroller receives command strings such as *start_oscilloscope* and answers sending to the Host PC the oscilloscope data, the lock-in data or acknowledgement signal for the setup operations. The command strings can be sent to the Microcontroller in *command-line* interface mode, using generic software. For simplicity, an easy-to-use Graphical User Interface (GUI) has been developed in LabVIEW environment. Figure 4 and Fig. 5 show the Graphic User Interface for the Oscilloscope and Lock-In functions.

Figure 4 shows the acquisition of two sinusoidal signals having different amplitudes and frequencies (4 Vpp at 80 Hz and 0.4 Vpp at 180 Hz, red and blue signals, respectively).

Figure 5 shows the GUI for the lock-in function. The input signals are two sinusoidal signals slightly shifted in frequency (180.00 and 179.95 Hz). Signal at −20 dB

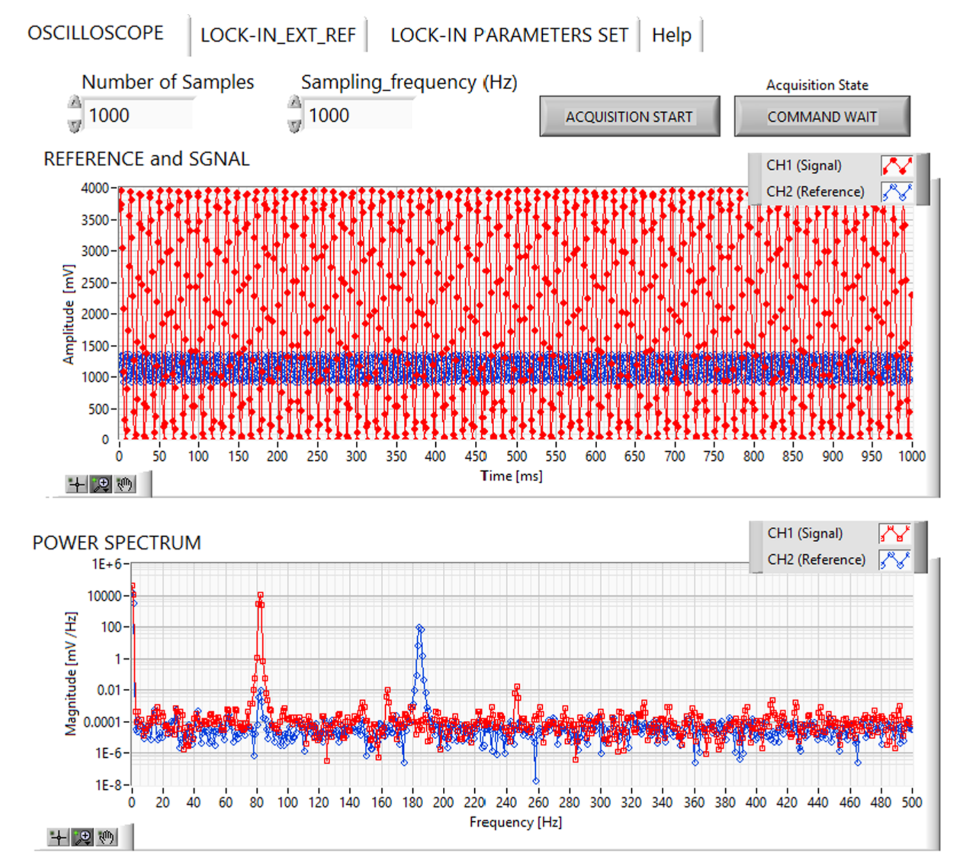



**Fig. 4** GUI: Tab for oscilloscope function

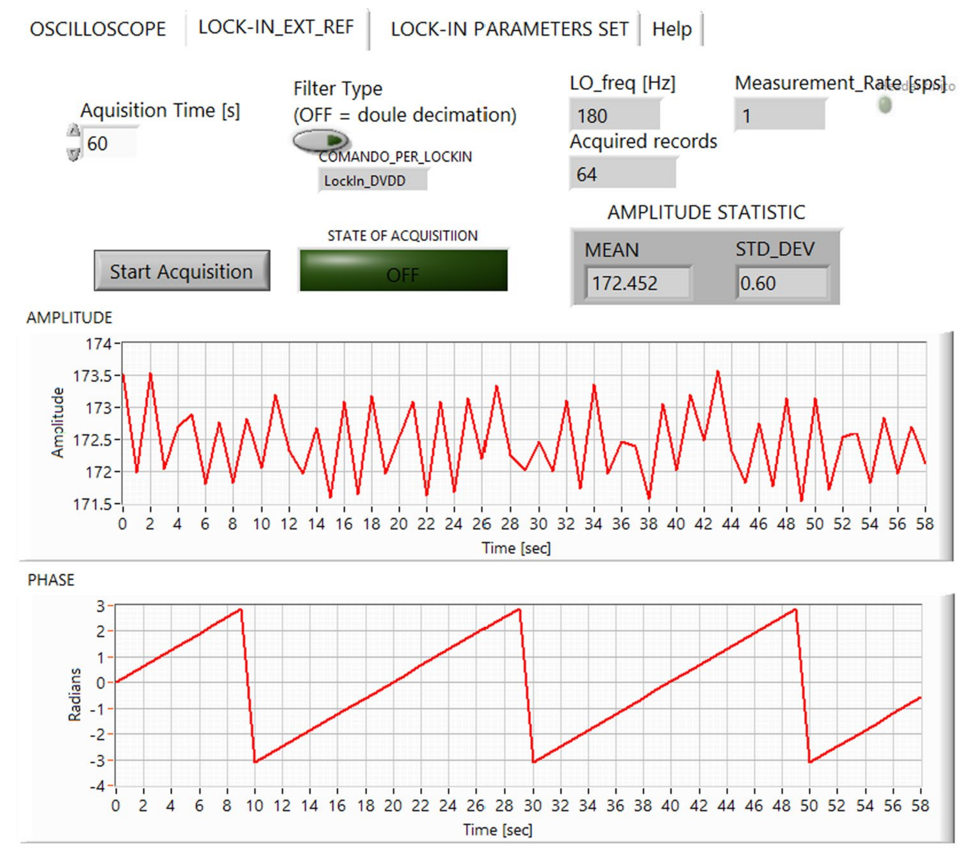



**Fig. 5** GUI: tab for lock in function

compared to the full range and reference at Low Level of 100–200 mV.

It is possible to appreciate the great phase linearity, and the small standard deviation of the amplitude (0.6 compared to the average 172.45 [a.u.]) even with an input level 20 dB below the maximum range.

## 3 System test

### 3.1 Lock-in electrical characterization

In order to characterize the lock-in, a test bench containing a dual channel synthetic generator (Tektronix AFG 3252) has been set up (see Fig. 1). The used generator can supply sinusoidal signals with very small frequency shifts; in this way, while the amplitude of the signals detected by the lock-in is fixed, the phase must have a sawtooth trend.

A manual rotary stepper attenuator allows to obtain signals at different amplitudes, while generator output sets were used to vary the amplitude of the reference. In Fig. 6 the *Measured_Amplitude* changes linearly with the reference amplitude, being proportional to *Reference_Amplitude* × *Signal_Amplitude*. If necessary, the components contained in

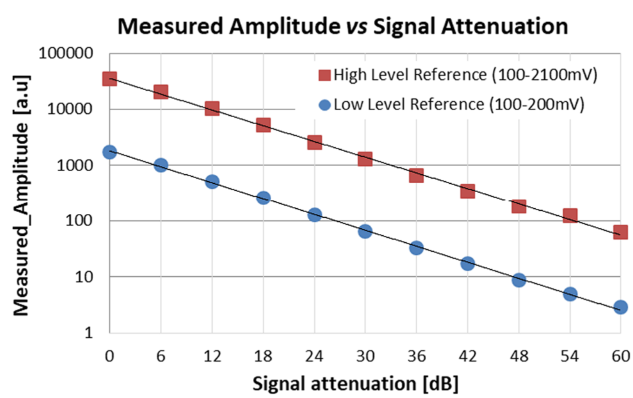



**Fig. 6** Measured_amplitude vs. signal attenuation with high and low reference input levels

the Lock-In amplifier record allow the evaluation of the *Reference_Amplitude* and the *Signal_Amplitude* separately.

Figure 6 shows the high linearity of the *Measured_Amplitude* and *Measured_Phase,* but also the presence of a cross-talk effect between the *CH1_R* and *CH2_S* channels, which makes it more convenient to use reference signals with not excessive levels.

All the results shown below were obtained with the following test setup:

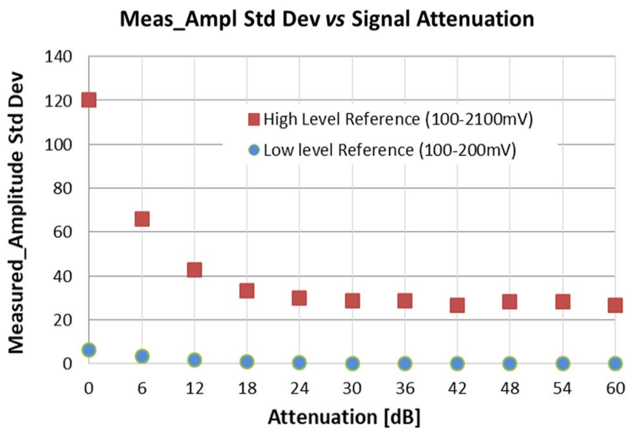



**Fig. 7** Standard deviation of the measured_amplitude vs the signal amplitude attenuation

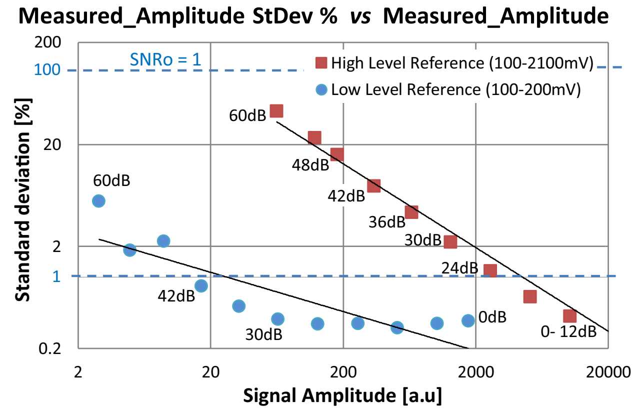



**Fig. 8** Percent standard deviation vs signal amplitude at two reference input levels

- Measurement rate 1sps;
- 2Vpp 179.9 Hz sinusoidal signal (100–2100 mV) attenuated at different levels with the rotary attenuator (0 – 60 dB);
- Sinusoidal reference at frequency 180 Hz with four different levels:
- High level (100–2100 mV)
- Medium levels I (100–1100 mV)
- Medium levels II (100–600 mV)
- Low level (100–200 mV).

Figure 6 shows that the *Measured_Amplitude* has high linearity as a function of the signal attenuation.

Figure 7 shows the *Measured_Amplitude* Standard Deviation for the high and low reference levels; it is possible to verify that, due to the cross-talk effect, the standard deviation cannot be lower than 30 (a.u.) in the case of High Reference Level, while in the case of Low Reference Level the standard deviation is less than 10 (a.u.) with a signal attenuation up to 60 dB.

The percent standard deviation of the *Measured_Amplitude* shows an almost linear dependence with the *Measured_Amplitude* in logarithmic scale, but in the case of High Level Reference (100–2100 mV), due to the presence of cross talk, the standard deviation is higher (see Fig. 8).

By using Low Level Reference (100–200 mV) the standard deviation is less than 1%, for signal attenuated up to 42 dB (see Fig. 8 and Fig. 9). This is a good result, considering the low cost of the instrumentation.

Figure 10 shows the time behaviour of the *Measured_Phase* in the case of input at two different frequencies (180.0 and 179.9 Hz) measured at three different reference levels and with the signal attenuated of 60 dB.

Being 1sps the measurement rate, the entire phase interval between $\pm\pi$ is linearly scanned in ten samples.

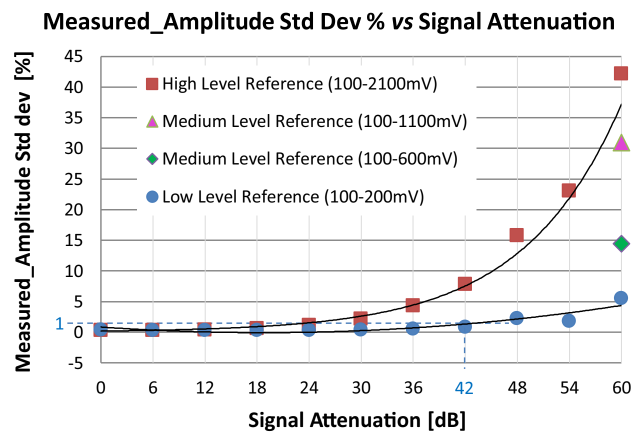



**Fig. 9** Standard deviation of the measured_amplitude calculated in percent vs signal attenuation at different reference input levels

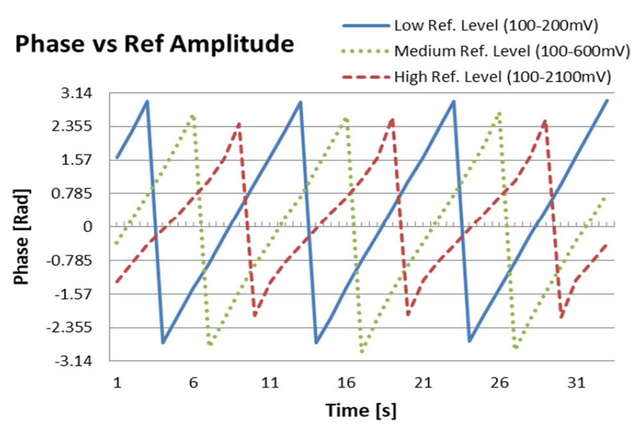



**Fig. 10** Measured_phase during the test with signal and reference at 180.0 Hz and 179.9 Hz, respectively at three different reference levels

We can observe the presence of non-linearity, if the reference has high level, due to the cross-talk between channels. Likewise, the amplitude is not constant over time for the same reason (see Fig. 11).

The cross-talk effect can be seen more easily by plotting the components of the quadrature demodulation in polar coordinates (see Fig. 12).

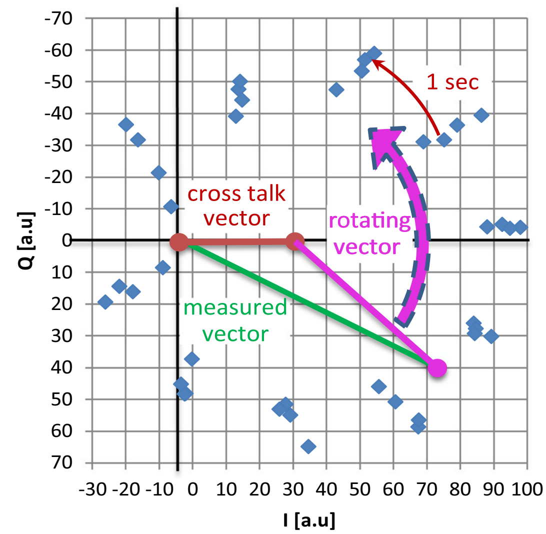



Fig. 12 Quadrature demodulation components vs. time

#### 3.1.1 Dynamic reserve and noise reduction performances

A figure of merit of the present implementation can be provided by the Dynamic Reserve, which is the ratio of the largest tolerable noise signal to the full-scale signal that is allowed before saturation occurs.

Conservatively, we have calculated the dynamic reserve using the maximum noise level obtained during all the measurements, and the signal measured before saturation, obtaining a value of 43 dB. This value, although lower than that of digital or analogic Commercial On The Shelf (COTS) lock-in amplifiers (typically 60–70 dB), is adequate for a wide range of applications.

In addition, the lock-in noise reduction efficiency has been tested by implementing a test setup including a dual channel synthetic generator (Siglent SDG6052X) and a noise generator (Agilent 33220A) (see Fig. 13). The Noise Figure (NF) was thus estimated as the ratio of the output SNR (SNRo) to the input SNR (SNRi) expressed in dB.

SNRi was simply evaluated as the ratio of signal power to the noise power on the CH2_S channel. On the other hand, since our lock-in directly provides a numerical output, SNRo was estimated as the square of the ratio of the mean of the *Measured_Amplitude* (recorded over a 60 s time period with a sampling rate of 1 measurement/s) to its standard deviation, thus considering the fluctuations of the digital output as the lock-in output noise.

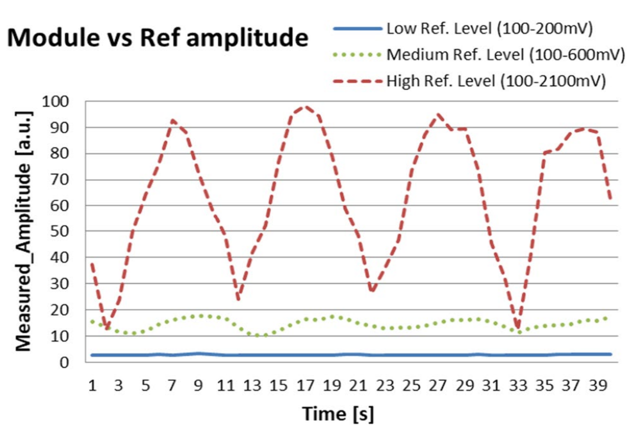



Fig. 11 Cross talk effect: measured_amplitude at different reference level in the case of low signal level 60 dB attenuation

Table 1 summarizes the NF obtained in the case of Reference at 200mVpp and signal frequency of 180 Hz, approximately.

The reason for the decrease of the NF with reducing noise lies in the presence of self-generated noise inside the lock-in amplifier, which becomes relevant as the external noise decreases.

#### 3.1.2 Lock-in amplifier performance comparison

Unfortunately, most of the literature [6–11] does not report the quantitative determination of the noise figures. In the Table 2, we compare the Dynamic Reserve and cost of some prototypes together with a typical COTS instrument.

It should be pointed out that the obtained Dynamic Reserve of the present system, although lower than that of COTS lock-in amplifiers, is adequate for a wide range

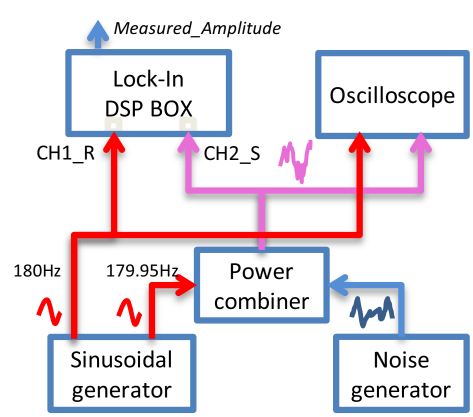



Fig. 13 Noise figure estimation layout

**Table 1** Noise figure recorded at different values of the input signal and added noise

| CH2_S | | | SNRi | SNRo | NF |
|---|---|---|---|---|---|
| Signal amplitude | Noise amplitude | | | | SNRi/SNRo |
| [mVpp] | [mVpp] | [mVrms] | | | [dB] |
| 100 | 4000 | 666.67 | 0.00281 | 67.70 | 43.82 |
| 200 | 1000 | 166.67 | 0.1799 | 4132.2 | 43.61 |
| 100 | 1000 | 166.67 | 0.0450 | 953.9 | 43.26 |
| 10 | 1000 | 166.67 | 0.00045 | 8.9 | 42.96 |
| 200 | 100 | 16.67 | 17.995 | 12,838 | 38.53 |
| 100 | 100 | 16.67 | 4.4986 | 32,225 | 38.55 |
| 10 | 100 | 16.67 | 0.04499 | 479.6 | 40.27 |
| 200 | 18 | 3.00 | 555.39 | 65,996.9 | 20.75 |
| 100 | 18 | 3.00 | 138.85 | 43,376 | 24.94 |

**Table 2** Comparison with other implementations and COTS instrument

| Prototype/instrument | Dynamic reserve | Approximate cost |
|---|---|---|
| ENEA DSP Box | 43 dB | < 50€ |
| S. Carrato [7] | 30–50 dB | Not applicable |
| J. Gaspar [8] | 76 dB | ≈200€ |
| Stanford research systems mod. SR810 | 100 dB | > 4000€ |

of applications and is achieved at very low cost (less than 50 €) which makes the DSP Box also suitable in disposable systems.

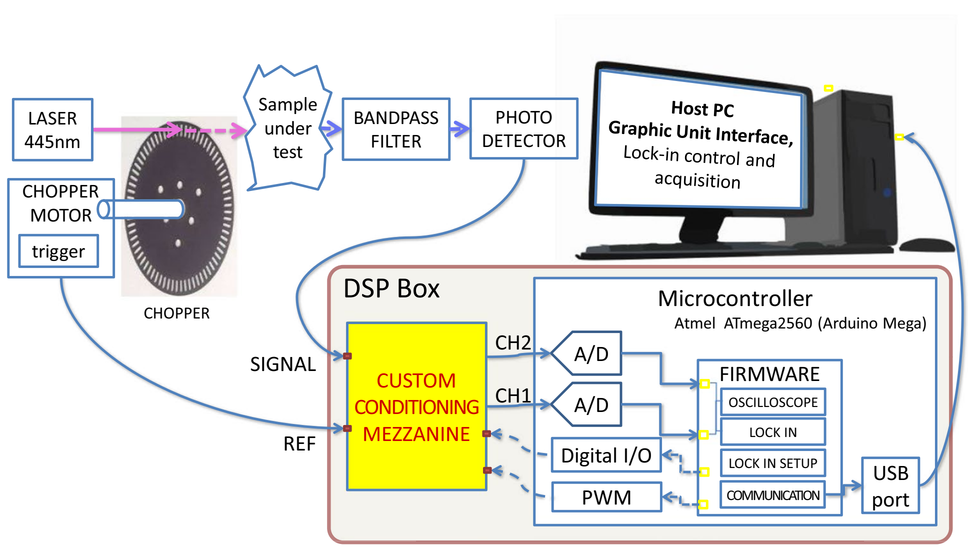
### 3.2 *Experimental test in photoluminescence measurements of $F_2$ color centers in lithium fluoride crystals*

As mentioned in Introduction, the present lock-in was especially designed for application to photoluminescence (PL) measurements, where low-cost and compactness can fit the needs of both portable systems and versatile laboratory setups [12]. As a specific example, here we report the experimental test of the lock-in amplifier within a compact system for measuring the PL of passive solid-state dosimeters based on the PL of $F_2$ color centers (CCs) in lithium fluoride (LiF) crystals.

Such CCs were created in LiF by irradiation with 26 MeV protons, produced by the TOP-IMPLART linear accelerator at ENEA Frascati, in the (0.5–48) Gy dose range [13]. When $F_2$ CCs are optically pumped with blue light, they absorb it and emit light in the red spectral range [14]. The PL intensity, due to the total amount of CCs created in the crystals by the ionizing radiation, is proportional to the deposited dose at constant blue light excitation intensity.

The PL measurement system (see Fig. 14) consisted of a 10 mW and 1.7 mm beam diameter continuous wave 445 nm Cobolt laser, modulated with a Thorlabs MC2000 chopper at 180 Hz. The emitted PL was focused by a convex lens into a phototube Hamamatsu H7422 with C7319 preamplifier unit, after an interference filter allowed PL to be transmitted only in a 50 nm-wide band centered at 670 nm, corresponding to the $F_2$ CCs maximum emission wavelength range. The acquired data, shown in Fig. 15, confirm that the 50 nm spectrally-integrated PL intensity response is linear with dose, as obtained in ref. [13] from the PL spectra of the same colored LiF crystals, measured with a more sophisticated system. Each plotted point is the average of a 60 s long signal acquisition.

**Fig. 14** Photoluminescence measurement layout



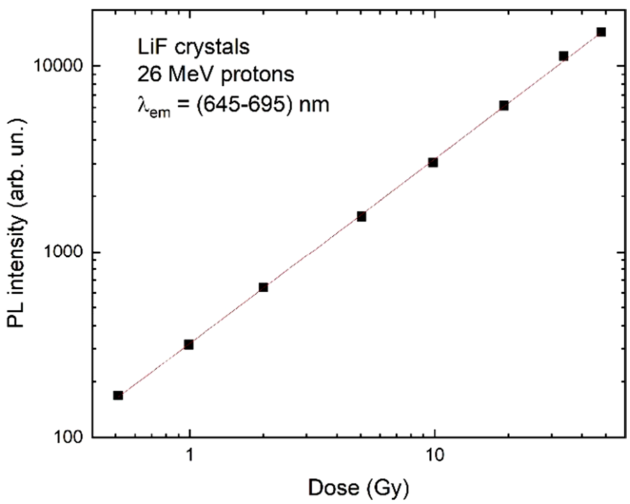



**Fig. 15** Linear dependence of F2 CCs PL with dose in LiF crystals

## 4 Conclusions

For low frequency application, a very low-cost lock-in has been developed in ENEA Frascati laboratories. The lock-in is based on a microcontroller board (Arduino Mega) and has been electrically characterized through experimental tests with synthetic electrical signals and white noise, which have demonstrated a dynamic reserve of 43 dB and a noise figure in the range 25–50 dB. These values, although lower than those of digital or analogic COTS lock-in amplifiers, are adequate for a wide range of applications. As an example of real application, our system was used in laboratory with good results for PL measurements.

Future activities include upgrading the lock-in with a more performing microcontroller board and its application to photoacoustic spectroscopy measurements [15].

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**Author Contributions** FP is the corresponding author; he developed and tested the electronic system and the relative firmware and software, writing the relative section of the manuscript. MP developed the experimental test in photoluminescence for measurements of $F_2$ color centers in lithium fluoride crystals (see par 3.2.), carrying out the test of the electronic system developed for this application. He wrote the related section of the manuscript. RP proposed the development of a low-frequency low-cost lock-in amplifier for fluorescence measurements; the updating of this system and its application for radiometric dosimetry measurements is the main topic of the article. RMM and AP are respectively the responsible of the ENEA FSN-TECFIS-MNF and FSN-TECFIS-DIM laboratories. RMM is the responsible of the project TecHea (Technologies for Health). All authors reviewed the manuscript, conducting a critical analysis and updating it.

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**Data availability** The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

## Declarations

**Conflict of interest** All authors declare that they have no conflict of interest.



## References

1. Neri, C., Pollastrone, F., Tudisco, O. (2009). Fully Digital implementation of a high dynamic fast Vector Voltmeter, In *2009 23rd IEEE/NPSS Symposium on Fusion Engineering, San Diego, CA*, (pp. 1–4), https://doi.org/10.1109/FUSION.2009.5226464.
2. Tudisco, O., Lucca Fabris, A., Falcetta, C., Accatino, L., De Angelis, R., Manente, M., Ferri, F., Florean, M., Neri, C., Mazzotta, C., Pavarin, D., Pollastrone, F., Rocchi, G., Selmo, A., Tasinato, L., Trezzolani, F., & Tuccillo, A. A. (2013). A microwave interferometer for small and tenuous plasma density measurements. *Review of Scientific Instruments, 84*(3), 033505. https://doi.org/10.1063/1.4797470
3. Neri, C., Bartolini, L., Coletti, A., De Collibus, M. F., Fornetti, G., Lupini, S., Pollastrone, F., Semeraro, L., & Talarico, C. (2002). Advanced digital processing for amplitude and range determination in optical RADAR systems [fusion reactor inspection]. *IEEE Transactions on Nuclear Science, 49*(2), 417–422. https://doi.org/10.1109/TNS.2002.1003764
4. Pollastrone, F., Neri, C., Florean, M., & Ciccone, G. (2013). FTU bolometer electronic system upgrade. *Fusion Engineering and Design, 88*(6–8), 1441–1444. https://doi.org/10.1016/j.fusengdes.2013.02.068
5. Arduino project web site https://www.arduino.cc/
6. Xicheng, Xu., & Yoshinori, S. (2020). Dhirani Al-amin (2020) low-cost, high-performance lock-in amplifier for pedagogical and practical applications. *Journal of Chemical Education, 97*(4), 1167–1171. https://doi.org/10.1021/acs.jchemed.9b00859
7. Carrato, S., et al. (1989). Versatile low-cost digital lock-in amplifier suitable for multichannel phase-sensitive detection. *Review of Scientific Instruments, 60*, 2257–2259. https://doi.org/10.1063/1.1140787
8. Gaspar, J., Chen, S. F., Gordillo, A., Hepp, M., Ferreyra, P., & Marqués, C. (2004). Digital lock in amplifier: study, design and development with a digital signal processor. *Microprocessors and*

*Microsystems, 28*(4), 157–162. https://doi.org/10.1016/j.micpro.2003.12.002

9. Das, A., Yaswanth, T., (2015). A low-cost, portable alternative for a digital Lock-In Amplifier using TMS320C5535 DSP, 2015 Annual IEEE India Conference (INDICON), 2015, (pp. 1–4). https://doi.org/10.1109/INDICON.2015.7443743
10. Bhattacharyya, S., Ahmed, R. N., Purkayastha, B. B., & Bhattacharyya, K. (2016). Implementation of Digital Lock-in Amplifier. *Journal of Physics: Conference Series* (Vol. 759, pp.012096). https://doi.org/10.1016/j.micpro.2003.12.002
11. Kar, A., Chandra, M., Goel, P., Gupta, V. K., (2014). A low-cost, portable alternative for a digital Lock-In Amplifier using TMS320C5535 DSP, TENCON 2014–2014 IEEE Region 10 Conference, 2014 (pp. 1–5). https://doi.org/10.1109/TENCON.2014.7022482.
12. Kaciulis, S., Mezzi, A., Soltani, P., Pizzoferrato, R., Ciotta, E., & Prosposito, P. (2019). Graphene quantum dots obtained by unfolding fullerene. *Thin Solid Films, 673*, 19–25. https://doi.org/10.1016/j.tsf.2019.01.030
13. Piccinini, M., Nichelatti, E., Ampollini, A., Bazzano, G., De Angelis, C., Della Monaca, S., Nenzi, P., Picardi, L., Ronsivalle, C., Surrenti, V., Trinca, E., Vadrucci, M., Vincenti, M. A., & Montereali, R. M. (2020). Dose response and Bragg curve reconstruction by radiophotoluminescence of color centers in lithium fluoride crystals irradiated with 35 MeV proton beams from 0.5 to 50 Gy. *Radiation Measurements*, *133*, 106275. https://doi.org/10.1016/j.radmeas.2020.106275
14. Baldacchini, G., De Nicola, E., Montereali, R. M., Scacco, A., & Kalinov, V. (2000). Optical bands of $F_2$ and $F_{3+}$ centers in LiF. *Journal of Physics and Chemistry of Solids, 61*, 21. https://doi.org/10.1016/S0022-3697(99)00236-X
15. Fiorani, L., Pollastrone, F., Puiu, A., Nuvoli, M., & Menicucci, I. (2021). Patent "Un Apparato e un Metodo Fotoacustico per Rilevare un Analita in un Campione di un Materiale da Ispezionare" 22/12/2021, Patent Number. D.N. 102021000032276, nro ENEA 923, Ufficio Italiano Brevetti e Marchi (UIBM), country of registration: Italy.



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**Massimo Piccinini** Physicist with experience in the investigation of condensed matter by fluorescence microscopy and optical spectroscopy, FTIR spectroscopy and imaging in the near, medium and far infrared with conventional sources and synchrotron radiation, Raman spectroscopy and imaging, in the characterization and dosimetry of ionizing radiation beams and development of optical read-out dosimeters based on color centers in lithium fluoride.

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**Rosa Maria Montereali** Senior research physicist, head of the Photonics Micro and Nanostructures Laboratory at ENEA, has more than 30 years of experience in the experimental field of optical properties of point defects in insulating materials and R&D of organic and inorganic thin films for light-emitting devices and novel radiation sensors for imaging and dosimetry, applied to scientific, bio-medical and nuclear fields. Coordinator of several projects and co-inventor of patents, she published more than 200 peer-reviewed papers and is member of organising and Advisory Committees of prestigious national and international conferences.