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ABSTRACT

Angle-resolved light scattering techniques are powerful tools to obtain structural and spectroscopic information on the investigated sample by means of the study of the pattern of the angular distribution of scattered light. In this paper, we show the details of a new electronic system conceived to automate a Raman coherent backscattering setup, in which it is crucial to acquire several spectra at different angles in a wide spectral acquisition range. In this frame, we used this electrical circuit to trigger the signal edges between the charged-coupled device and the motorized nanorotator stage in our setup, carrying out a considerable quantity of measurements only with an initial input given by the operator and minimizing the supervision of the experiment and, therefore, the time invested by the user in it. By means of this system that can be easily integrated in the setup, we can perform distinct type of measurements by using different configurations of the components that make up the experimental setup.

I. INTRODUCTION

Angle-resolved light scattering (ALS) allows the characterization of a sample by giving information about the angular distribution of scattered light and identifying important properties of the studied objects, including size, shape, and refractive index.[1] This technique is rapid, non-invasive, and easy to implement by using goniometer-based instruments where either the sample or the detector is mounted on a rotating arm.[2] In the last few decades, different types of ALS studies have been performed to improve the experimental setups and to investigate the properties of different systems of interest in a wide range of applications, ranging from medicine to photovoltaics.[3–9] Among the angle-resolved techniques, experiments of coherent backscattering (CBS) of light emerge as a valid procedure to obtain information about the structure factor in a random medium and its scattering strength as well as the light path length-distribution within the medium.[10–12] CBS of light is, indeed, a robust interference effect always occurring in random media in which the coherent superposition of counter-propagating multiply scattered light waves leads to an enhanced light intensity at small angles near the backward direction.[10,13–16] In the last few decades, CBS has been investigated in several systems,[16–21] and a considerable effort has been focused on the experimental setup improvements.[11,19,22,23] Recently, an experimental observation of a constructive interference effect in the inelastically backscattered Raman radiation was proposed.[10] In the case of Raman CBS (RCBS), the very low Raman cross section makes the signal difficult to detect without a long integration time being set; moreover, the experiments require a spectral analysis of the collected light, which then passes through a spectrometer before arriving to the Charge-Coupled Device (CCD). The user must manually carry out a considerable number of single measurements in a wide spectral acquisition range. Hence, it is clear that RCBS experiments are often very complex and time consuming. Hence, the opportunity to start the cycle of measurements automatically only by setting the software used for the desired type of experiment frees the user from the continuous supervision. In this article, we show an extremely precise and controlled way to automate the measurements in a RCBS experiment by using integrated circuits (ICs) and triggering the single signal edges of two important components of the RCBS experimental setup, i.e., the CCD and the motorized rotator stage.

Furthermore, the designed electronic system allows performing measurements with a different number of accumulations of the CCD. This value represents the number of individual acquisitions that will be averaged to obtain the final spectrum; the higher the accumulation amount, the better the signal-to-noise ratio. Specifically, we realized a circuit that allows using one or two accumulations working in Single Mode (SM) or Double Mode (DM) acquisition, respectively.

This paper is organized in the following way. After introducing the instrumentation used for the RCBS experiment, the realized circuit is presented in Sec. II. In Sec. III, the test methodology is illustrated with the distinct modes that can be used by means of our electronics. Finally, we report the concluding remarks in Sec. IV.

II. INSTRUMENTATION

In our RCBS experimental setup, we use a Coherent Verdi G5 SLM (532 nm, 5 W) laser focused onto a sample that it is located on a rotating mount to eliminate laser speckles. Light collection optics (e.g., fiber) are arranged on a rotating arm mounted on a NanoRotator 360° Stage (Thorlabs) that is controlled by using a One-Channel Benchtop Stepper Motor Controller (Thorlabs) to perform measurements for different backscattering angles in the range from −90° to 90°. The collected light goes into a monochromator, and spectra are acquired by means of a Syncerity CCD Deep Cooled Camera (Horiba). For details on experimental setups and possible configurations similar to the one considered in this paper, it is possible to refer to the articles by Fazio *et al.* and Muskens *et al.*[10,19]

The CCD camera and the stepper motor controller of the NanoRotator Stage are managed via proprietary software, Labspec 5 (Horiba) and Kinesis (Thorlabs), respectively. Labspec 5 has been designed for Raman measurements incorporating a very extensive range of data acquisition modes, such as the triggering mode. The software interface allows us to control the monochromator and the CCD by setting various typical parameters in spectroscopic measurements, such as the width of the input slit of the monochromator, the number of acquisitions of the CCD, and the acquisition time. Although replaced by the more recent software from the manufacturer, it is an excellent tool given its compatibility with both recent and old measurement and IT systems. Kinesis is a motion control software with a very simple interface through which it is possible to set several parameters such as the speed and the rotation angle, providing the option to activate or deactivate the instrument using the triggering function present in the Benchtop Stepper Motor Controller. Without going into further details, these software packages give the opportunity (i) to receive external Transistor–Transistor Logic (TTL) signals and subsequently (ii) to generate new signals. From now on, we will define (i) and (ii) as "TTL IN" and "TTL OUT," respectively. In this way, experiment synchronization can be achieved by means of edge triggering of the aforementioned components of our setup. Starting from this "initial condition," we have developed an electronic system, composed of ICs with combinational and sequential logic, to automate the measurements. The block diagram of the electronics is shown in Fig. 1, and the components used are schematized as follows:

(i) Start and debounce circuit: The "start" button provides the onset of electronics' functioning, and it is coupled to a "debounce circuit," which has the task of supplying the first signal edge to the CCD TTL IN useful at the start of the measurement cycle. This consists of a latch made with NOR gates compatible with TTL signals at 0 V–5 V. Note that the use of a debounce system inside the start-up electronics is imposed by the need to produce a single well-defined signal, instead of a series of spurious ones that could generate artifacts.

(ii) Monostables: Timers designed to furnish an output signal synchronized with the input by means of a very specific and constant time necessary to control the TTL IN signals of the setup components. In fact, when triggered by an input signal, a monostable multivibrator will swap to its unstable state, returning to its stable state after a certain period. This "delay" time is established by an RC time constant (τ) chosen to have a value neither too low (i.e., the signal is not interpreted by the electronics) nor too high (e.g., the value can be greater than the acquisition time, leading to errors on the edge reading—de-synchronization). Specifically, we use two monostables that interpret the output triggering signals coming from the CCD (Fig. 1, Monostable 1) and from the stepper motor controller (Fig. 1, Monostable 2).

(iii) Toggle flip-flop: The bistable multivibrator in which the output signal depends not only on the value of the input signal

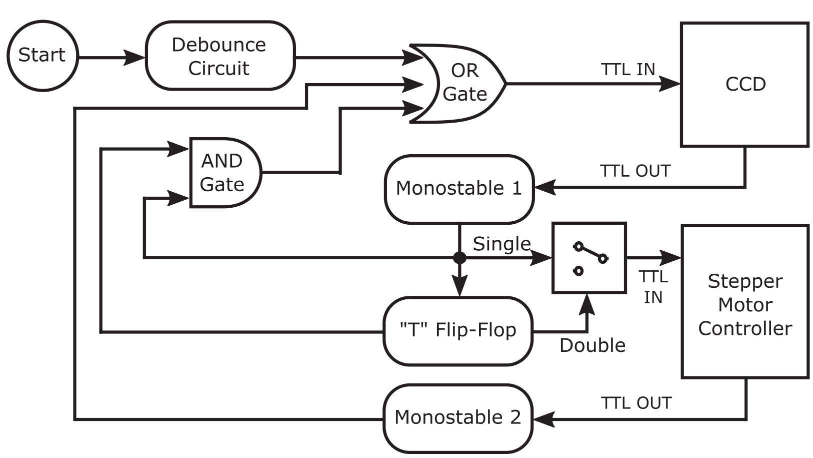

FIG. 1. Block diagram of the realized circuit composed of combinatorial and sequential electronics. Input and output TTL signals are indicated as "TTL IN" and "TTL OUT," respectively. The distinction in the circuit configuration between the SM and the DM is also reported. See the text for further details.

but also on the value that the output had before the event (clock). In our case, we take advantage of a "Toggle" flip-flop (T-type), which synchronizes the change of state of the output with the clock event, doubling the period of the signal applied to it. This timer is used only in DM acquisition with the purpose of activating the motor only every two consecutive acquisition cycles, while in SM, its use is not required since the number of CCD acquisition cycles must correspond exactly to the number of rotations of the NanoRotator Stage.

(iv) AND gate: It is a logic gate that implements logical conjunction, playing a very important role in DM configuration. In fact, it has the task of comparing the signal coming from the flip-flop with the one of the monostables, as shown in Fig. 1.

(v) OR gate. It is a logic gate that performs logical disjunction, interpreting the signals coming from the monostables and from the flip-flop furnishing commands to start the cyclic measurements. Successively, it selects between the start signal and the SM or DM signal based on the previously set mode.

(vi) Function mode switch: As shown in Fig. 1, we use a two-channel switch that allows the quick and unambiguous mechanical selection of the SM or DM acquisition.

III. TEST METHODOLOGY AND APPLICATIONS

In the development phase of the circuit, initially, we designed the circuit to perform acquisition of spectra in the SM, and then, we upgrade it with the DM acquisition configuration as well as the mechanical switching system from one acquisition mode to another in real time. For initial tests, we have arranged the circuit system on an experimental board, creating quick-fit connections, monitoring the ICs by means of a multitrack sampling Agilent DSO1024A oscilloscope, and using LEDs for quick feedback on the temporal execution of the commands.

The analysis of the functioning of the realized electronics was carried out linking the circuit to the CCD and the stepper motor controller (as reported in Fig. 1) and testing the synchronization of the edge-triggering between the input and output signals by analyzing the timeline map sampled by using the oscilloscope. In this way, we had the possibility not only to perform several measurements with different types of configuration changing the parameters within software but also to check for any loss of useful signals. The time maps of some SM and DM acquisition measurement cycles are shown below, in which we represent the TTL IN signals of the CCD and stepper motor controller (NanoRotator Stage) as "CCD TTL IN" and "Motor TTL IN," respectively, and the TTL OUT signals of the CCD and stepper motor controller as "CCD TTL OUT" and "Motor TTL OUT," respectively.

A. SM acquisition

Figure 2 reports two different measurement cycles in the SM with two distinct times and number of accumulations of the CCD, selected via Labspec 5 before the start of the experiment. In particular, we have chosen to perform five acquisition each lasting 5 s and eight acquisitions of 1 s each, as shown in Figs. 2(a) and 2(b), respectively, keeping the speed and the rotation angle of the NanoRotator Stage unchanged in both tests.

As discussed in Sec. II, the primary signal edge to the CCD TTL IN (black line, at about 2.5 s in Fig. 2) is furnished by the user via the start button, synchronizing its falling edge with the launch of the first measurement (red line, rising edge). In SM acquisition, the signal of the Motor TTL IN (blue line) is generated at the end of a single CCD acquisition (red line), instead the NanoRotator Stage starts to move (Motor TTL OUT, pink line) in conjunction with the rising edge of the Motor TTL IN. Once the desired angle is reached, the MOTOR TTL OUT falling edge generates a new acquisition signal from which the automatic measurement sequence will restart, in a completely automatic way, continuing until the desired number of measurements is reached. Therefore, in SM acquisition, it is clear that we obtain the complete automatism of our experimental setup, independently of the number and/or times of acquisition of the CCD and, as already said, eliminating the continuous supervision of the experiment by the user.

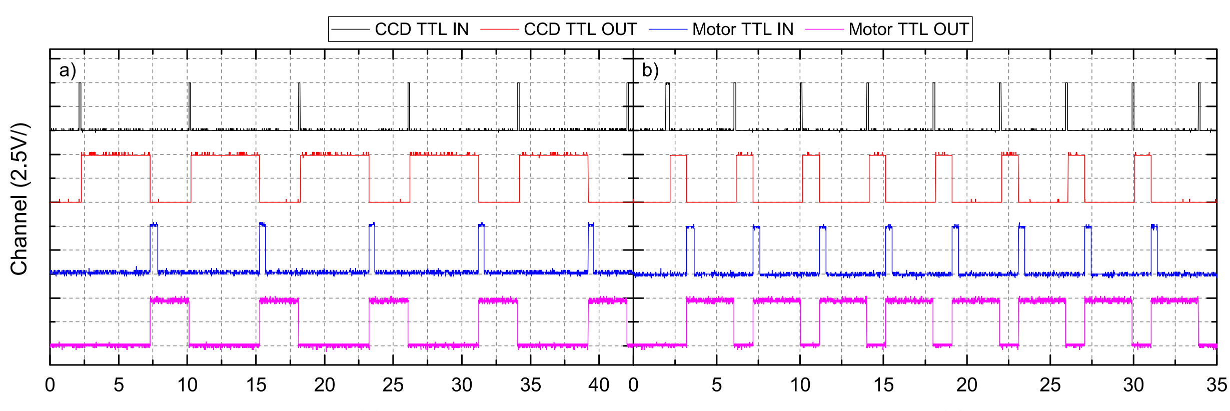

FIG. 2. Single mode tests with five CCD acquisition of 5 s each [panel (a)] and eight acquisition each lasting 1 s [panel (b)]. Black lines: CCD TTL IN; red lines: CCD TTL OUT; blue lines: Motor TTL IN; and pink lines: Motor TTL OUT. See the text for the detailed description of the signals' triggering to automate the experiment.

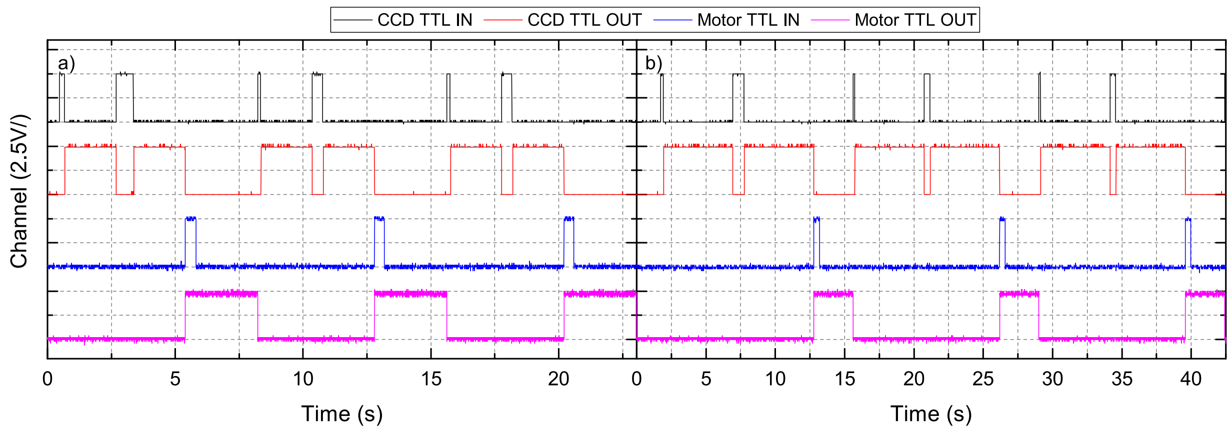

FIG. 3. Double mode measurements with three CCD acquisition of 2 s [panel (a)] and 5 s [panel (b)] each. Black lines: CCD TTL IN; red lines: CCD TTL OUT; blue lines: Motor TTL IN; and pink lines: Motor TTL OUT. See the text for the detailed description of edge-triggering to automate the experiment in this configuration.

B. DM acquisition

The DM acquisition tests are illustrated in Fig. 3 where, on the left [panel (a)], the time of each acquisition of the CCD is set at 2 s and, on the right [panel (b)], at 5 s for three rotations, keeping unchanged the parameters associated with the rotation (as before in SM).

In this configuration, electronics generate two starting signals (black line) each of which activate a CCD acquisition (red line), thus obtaining two accumulations that the software will average at the end of every measurement cycle. Furthermore, the use of the divider by the flip-flop toggle and the AND gate allows us to generate a single signal of the Motor TTL IN (blue line) every two acquisitions of the CCD (red line), as shown in the figure. Hence, for each rotation, it is possible to obtain not only an average of two acquisitions to obtain a cleaner signal but it is also easier to manage and use different measurement configurations that can be set via software. As seen for the other modality, with the completion of the rotation (pink line in Fig. 3) and, therefore, of the first cycle, the electronic system gives rise to a new triggering CCD TTL IN signal starting the experiment automation up to the completion of the pre-set desired measures.

C. Production and compatibility

The production of a master printed circuit could be achieved with the routing technique by means of computer numerical control (CNC) milling machinery. This technique is convenient to realize demo boards, passing from the CAD electronic design, directly, to the master board. In this way, we have created a complete circuit inserted in a metal housing for electronics, with all the connections (e.g., BNC, SMB, and DIN) and all the switches for controlling the equipment (e.g., ON/OFF), including warning LEDs for checking correct operation, as well as inhibit switch for circuit isolation from the equipment connected to it with the reset function. Thus, the LEDs, possibly coupled also with a simple acoustic device, allow a rapid control system of the correct operation of the device, which can be simply reset with the specific switch mentioned above in the event of measurement blocking, for example, due to the lack of a trigger impulse consequent to software or hardware problems.

This circuit is entirely compatible with other acquisition instrumentation (e.g., CCD) and the stepper motor controller, both with characteristics of edge-triggering mode functions, and can be easily implemented in other experimental setups. This makes it extremely versatile for use also with old software and instruments that can cause uncomfortable situations as they are no longer supported and/or in the absence of APIs not provided by the manufacturers.

IV. CONCLUSIONS AND REMARKS

The large number of acquisitions that must be carried out in a typical RCBS experiment demands creating a system that allows us to automate the measurements, resulting in a high time saving by the user who does not need to continuously supervise the experiment. Furthermore, this necessity also implies greater precision in the execution of the individual measures, guaranteeing the total correctness and excluding any error caused by human intervention. In this frame, after studying every single component of our RCBS configuration and analyzing the featuring of the software used, it was possible to design, build, and test a hardware circuitry composed of combinatorial (logic gates) and sequential (counters) electronics. The result is a complex electronic circuit, whose block diagram is shown in Fig. 1, characterized by extremely high-performance feedback and capable of acquiring a significant amount of spectra only with the command to start the measurement cycle, realizing the complete automation of the experiment.

The above has been possible through a complete treatment and interpretation of the Horiba Syncerity CCD and the stepper motor controller triggering signals, allowing therefore their total driving and synchronization during all steps of the measurement. Furthermore, the device was designed to provide also the possibility to carry out measurements with single or double accumulations of the CCD (SM or DM, respectively), setting up the software and the circuit by the hardware command, as shown in Figs. 2 and 3.

On the basis of what has been achieved, we have the opportunity to adapt this kind of edge-triggering management to other technologies likely compatible with those used in this work as well as to treat other devices with the digital (e.g., TTL) or analog (e.g., sinusoidal waves) signal. What has just been said is clearly an important reference for obtaining improvement both from the point of view of data acquisition times and for the minimization of user errors, and not only for the CBS technique but also for different techniques and instrumentation in which it is possible to implement electronics of this type. For example, a future use perspective is its coupling to another system that allows us to achieve an automatic alignment of the RCBS setup because it is very complex and time consuming to find the precise backscattering direction and, for instance, to get the focusing right. Therefore, the versatility of this device, which can be produced/reproduced at low cost and easily adaptable according to the needs of the experiment, makes it a valid support for improving the quality of research both by reducing the time invested by the operator in very long measurements and from the point of view of the experimental results.

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DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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