A Specific Multi-channel Photon-Counting Unit for Air-Pollution Measurement

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ABSTRACT

A photon-counting system based on an appropriate microcontroller has been developed. This system controls, acquires, processes and stores the data from a high-resolution multi-channel gas analyzer and provides accurate photon-counting measurements using suitable Photomultiplier Tubes (PMTs) as detectors of the Raman scattering signals. The implemented system ensures low power consumption (90 W for the overall system), low cost, increased reliability and high sensitivity. Also the entire unit allows auto-calibration and drift compensation. Finally, the present photon-counting system can be used in a broad field of applications, in medical electronics (e.g. confocal microscopy), air pollution optical measurements, laser sounding of the atmosphere, and electrooptical systems, provided that PMTs are used in the pulse-counting mode.

1. INTRODUCTION

Raman spectroscopy of gases has been extensively used in research laboratory, [1],[2] especially since the development of appropriate laser light sources. The corresponding development of portable multichannel Raman spectroscopes has been extremely difficult due mainly to the size of the laser light source. This situation has changed during the last years with the development of diode-pumped solid state micro-lasers in the green and blue regions of spectrum, opening the way for the development of portable multichannel systems using the Raman scattering technique.

The described apparatus realizes a multi-channel photon-counting system for the in situ quantitative monitoring of up to five air pollutants simultaneously and one calibration channel (nitrogen). The electronics of the system comprises six photon-counting modules, one for each channel, and a microcontroller unit. In the literature, detailed electronic schematics are seldom provided for the realization of a photon-counting system [4]-[6], and for this reason a detailed description of the electronics used for the realization of the photon-counting modules will be given.

2. SHORT DESCRIPTION OF THE ENTIRE MULTICHANNEL RAMAN GAS SENSOR

The multichannel photon-counting system under presentation is the electronic and signal handling part of a complete multichannel Raman gas sensor (MRGS) developed within the framework of a project of European Commission concerning air pollution monitoring. The optical part of this set-up consists of a laser source that excites the mixture of gases under test housed in an appropriate multipass optical resonator, which has the form of a mirror-faced cylinder (cuvette). In Fig. 1 we present a block diagram of the whole system.

The laser sources used were a green (532 nm) and a blue laser (457 nm), both solid state with output power of 100 mW manufactured from Laser Power Co. The laser light excites the Raman effect in the (up to six) gases within the cuvette and the corresponding Raman scattered light is partitioned, by means of appropriate interference filters, into six spectral channels. The scattered light is detected by six Photomultiplier Tubes (PMTs) arranged in the equatorial plane of the cuvette. Typically, the six gases measured simultaneously by the MRGS set-up were SO_2, NO_2, CO, CO_2, O_3, and N_2. The latter was used as an internal standard of the system, with the concentration of the N_2 gas in the ambient air being taken as the basis for normalization of results obtained from the other channels.

The electric signals appearing at the outputs of the foregoing PMTs are collected by the six corresponding photon-counting modules/units of the multichannel photon-counting system. Each photon-counting module amplifies the corresponding PMT signal, discriminates it from the noise, and then –after appropriate pulse shaping- the number of pulses is counted electronically. A microcontroller unit controls and coordinates the combined operation of the entire MRGS set-up. Also, a practical gas sampling system is integrated in the set-up and, in addition, important variables such as temperature, pressure, relative humidity and laser power are continuously measured, to make a conversion of the number of counts into concentrations.

3. THE MULTICHANNEL PHOTON-COUNTING SYSTEM

The multichannel photon-counting (MPC) system under presentation comprises six similar photon-counting modules, each of which is inserted in the housing of the corresponding PMT, and one microcontroller unit combined with the appropriate sensors. Each photon-counting module consists of the following four circuit stages: The preamplifier stage, the Upper Level Discriminator (ULD), the Lower Level Discriminator (LLD), and the counter module. These stages, which in practice are realized by means of appropriate circuit boards, are depicted in the block diagram of the MPC system shown in Fig. 2.

The preamplifier stage performs voltage amplification, from the voltage created by the photocurrent of the PMT. As to the role of the discriminators, it has to do with the fact that not all of the output pulses from each PMT are due to photons created from Raman scattering in the gas sample. Indeed, there are output pulses which are generated from internal noise in the load resistor and preamplifier circuit, from noise in the PMT itself and from environmental radiation, cosmic rays included. As a result of that, the amplitude U of the useful pulses (i.e. of pulses due to photons from Raman scattering) should be discriminated from the amplitudes of pulses due to internal and PMT noise, (the PMT pulses are negative referenced to ground) that their absolute values are on the average noticeably smaller than a lower-level value U_{min}, and the amplitudes of pulses due to environmental radiation, that their absolute values are on the average higher than an upper-level value U_{max} ([4],[5]). That is $U_{max} < U < U_{min} < 0$.

In accordance with the above, for cutting off the electronic noise contamination, a LLD has been introduced into the system, immediately after the preamplifier, and has been designed and adjusted so as to count all pulses with absolute amplitude greater than the lower-level threshold U_{min}, which is empirically determined. Similarly, for removing the effect of electromagnetic radiation, particularly of cosmic rays, an ULD has been inserted in parallel with the LLD, as shown in Fig. 2, and has been arranged so as to count all pulses with absolute amplitude greater than the upper-level threshold U_{max}, which is also empirically determined. Inversely, a gain control in the preamplifier stage allows to amplify adequately the amplitude of the PMT output pulses in correspondence with given settings and thresholds of the LLD and ULD discriminators.

In our system, the detection of the Raman scattered light and the measurement of its optical intensity is made by counting the number of PMT output pulses, appearing in a given time interval, with amplitudes lying within the pulse window defined above. Consequently, after the LLD and ULD discriminators, a counter module is necessary for counting the digital pulses coming out from this pair of discriminators. This counter module has been implemented by means of a Complex Programmable Logic Device (CPLD). The number of pulses with amplitudes within the specified pulse window is given from the difference between the counts measured by the above two counter circuits, over a given time interval, and is proportional to the individual concentration of the gas corresponding to the channel under consideration. In this type of measurements, the PMTs must be operating in the photon-counting mode.

3.1 Detailed description of the preamplifier and discriminators stages

The preamplifier stage has been realized in the form of a small-size board on the basis of the Burr-Brown OPA623 operational amplifier which exhibits a useful bandwidth of 200 MHz with a power consumption less than 50 mW. The LLD and ULD discriminators have been implemented as two identical boards. Each one of these boards consists of a high-bandwidth comparator, a pulse shaper, and a prescaler circuit. The schematic diagram of the so-realized discriminators is depicted in part of Fig. 3 (where only the ULD is shown).

In the practical system we have made use of the MAX9690C comparator of Maxim Co, that exhibits a bandwidth of about 600 MHz. The threshold level of the discriminators was arranged by adjusting, via the RV2 multi-turn potentiometer/trimmer, the buffered voltage reference at the inverting input of the comparator (Fig. 3). This voltage reference is generated, with a value of 2.5 V, from the U2 chip in conjunction with the opamp U3, which acts as a buffer. Also, the comparator under consideration is operated in the Schmitt trigger configuration with positive feedback put on via the resistor R7. This arrangement provides an additional noise immunity that affords a useful positive hysteresis to the comparator ([4]). In our case, this positive hysteresis has been set at 16 mV referenced to the input of the comparator.

After the comparator, its output (being at ECL levels) is pulse shaped by the 1/2 U4 circuit, which is used as a monostable multivibrator. The output of this pulse shaper is a series of pulses with amplitudes at ECL levels and with constant time width of approximately 2 ns. The second half of the U4 chip provides a prescaling by 2 on the pulse- shaped signal and is conveyed for counting to the counting module. The foregoing pulse shaper and prescaler stage has been implemented by means of the MC10H131 dual ECL flip-flop of Motorola Co. The required control signal is hardware generated from the memory chip of the microcontroller board, where a stabilizing crystal is used as a reference resulting in high stability and precision for the counting period, which is software programmed in 5 ms steps.

On the other hand, the transistors Q1 and Q2 have been used, in conjunction with the DZ1 and DZ2 zener diodes, to provide translation of the two reset and start/stop control signals from TTL to ECL levels. As to the U10 and U11 chips, they are voltage regulators for the power supplies of the various integrated circuits of the implemented board.

One of the most important aims considered during the design of the photon-counting system was the reduction of the noise that can be coupled to the system (from electric and/or magnetic fields) and could interfere with the measurements. The circuit layout and shielding are playing a critical role in the performance of the system. The ground of the low voltage, high-bandwidth, signals at the preamplifier section is made separate from the ground of the digital sections and a star topology was followed for the common ground [7], [8]. Special attention has been given to the grounding points of the different sections with a view to avoiding ground loop effects that can deteriorate the system performance.

3.2 The counter module

The counter module, implemented by means of six counter boards (one for each PMT output), includes the level translation circuits and a CPLD device, which realizes the individual counters and also supports a multidrop byte-wide bus for the interface effected with the microcontroller board. Each of the six so-supported counter boards is identified by a specific address and the communication with the microcontroller takes place in a serial access sequence, during which the microcontroller interrogates successively –one after another- all of the counter boards.

The ECL outputs from the two discriminators are level translated to TTL logic via a MC10H125 IC of Motorola Co and then the so-resulting pulse train is directed for counting to the CPLD device. In our system, this device was an EPM7064LC44-6 chip of Altera Co. The CPLD device under consideration provides two synchronous counters, which are used for counting the pulses after the upper and lower level discrimination, respectively. Typically, the ULD counter has a width of 16-bits while the LLD counter has a width of 28-bits.

One part of the schematic diagram of the as above CPLD-based counter is presented in Fig. 3 for the ULD counter. In this unit, the concept of Count-Enable Trickle/Count-Enable Parallel design, has been used for the realization of a fast non-loadable synchronous binary counter of arbitrary width. In the system, the Terminal Count of the least significant 74161 was used as a parallel clock enable for the other remaining counters. This scheme has effectively reduced the clock rate for these counters by a factor of 16, thus allowing their ripple-enable path 16 times longer to settle. The corresponding maximum clock frequency allowed a maximum counting frequency of 150 MHz and, with the ECL prescaler (having a factor of two), this frequency mounted up to approximately 300 MHz. Hence, as the preamplifier used has a bandwidth of approximately 200 MHz, this is the maximum counting frequency imposed on the entire MPC photon-counting system.

3.3 The microcontroller unit

An 87C196KC microcontroller of Intel Co constitutes the basis of a single board microcomputer which supports the data acquisition and control functions in the present MRGS. This microcontroller unit is combined with an NVRAM (Non-Volatile RAM) memory, which is the type of memory that we have adopted in the design of the control unit for the storage of software and data because it meets the need for software upgrade that is becoming increasingly important in embedded systems. A small software library is stored into the microcontroller OTP memory, which supports mainly an asynchronous RS-232C communication with a host computer and a command parser for the remote control of the unit.

The data acquired from the counter module are stored in the NVRAM of the control unit. The serial communication of this system with a host computer based on a portable PC allows the mass storage of data along with further processing and versatile presentation of the acquired data. On the other hand, the NVRAM memory has been implemented with the DS1386-32 chip of Dallas Semiconductors. This chip comprises -in one package- a Static RAM of 32 Kbytes, a real-time clock, and a watchdog programmable Timer, along with a lithium battery and all the circuitry that is needed for the operation of the real-time clock and the retention of data in the RAM memory. The watch-dog operation serves to reset the whole system in case of a software fault.

Finally, the software for the entire control system supports the concurrent execution of three tasks: a) collection of data, b) preprocessing and storage of collected data and c) remote control of asynchronous communication.

4. PERFORMANCE MEASUREMENTS

A number of experiments have been conducted in order to define the performance of the developed Photon-Counting System. First of all, we have made extensive tests regarding the noise level at the analog parts of the discriminator sections, because these are the most important points for the proper operation of the photon-counting system. The noise of the system at the comparator input was measured to 2 mV peak-to-peak and the Full-Width-at-Half-Maximum(FWHM) value, which can be taken as a measure of the time resolution, was measured to 3 ns. In Fig. 4 the input at the LLD comparator for one of the six photon-counting modules is shown. This measurement has been accomplished with the LeCroy 9361 Digital storage oscilloscope, with a sampling rate of 2.5 Gsamples/sec and the integration time shown in this figure is 20 sec.

Tests were conducted using signal generators up to 200 MHz and a commercial photon-counting unit (SR400 type from Stanford Research Systems Co.) as reference. These experiments were performed using identical discriminator level settings between the two systems. As signal source, a DS345-type synthesized function generator was used for frequencies up to 30

MHz. For higher frequencies, up to 220 MHz, the Schomandle SG1000 RF generator was used. In Fig. 5 the intercomparison between these two systems is depicted. The absolute maximum error was less than 10 ppm in this frequency range. The main source of error for absolute counting measurements is the crystal oscillator, that is used for the determination of the counting time interval, along with the electronics used for translation from TTL to ECL. Due to the ratiometric nature of our system (the measurement for each channel is normalized with respect to the measurement obtained from the N_2 channel) it was not necessary to develop a high accuracy oscillator circuit or to use special electronics for the generation of the control signal of the counting time interval.

We have estimated the detection limits for specific gases involved in air pollution using test gases with known concentrations. Table 1 summarizes these estimations using as excitation green and blue solid-state laser sources. We underline that our system possesses the advantages of portability, reduced volume, no need for cumbersome power supplies and the possibility of simultaneous measurement concentrations of five different gases. These advantages represent a good tradeoff for the fact that our system (although having good sensitivities) has not the best performance of all the systems of pollution monitoring existing in the laboratory and industrial field.

5. CONCLUSIONS

Apart from its simplicity, low power consumption, portability and low cost, the photon-counting system described in this work presents a number of advantages, mainly: a)The preamplifier-discriminator stages exhibit a bandwidth of 200 MHz, b)good thermal stability in the amplifier and discriminator sections and c) satisfactory low noise level .

The described photon-counting system represent an economical exploitation of multichannel Raman scattering effect targeting to commercial applications. Compared to a system based on a single channel Raman scattering the present one offers satisfactory insensitivity to variations in excitation intensity and to changes in sample properties or errors in the optics, thus resulting in stable quantitative measurements.

ACKNOWLEDGMENTS

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6. REFERENCES

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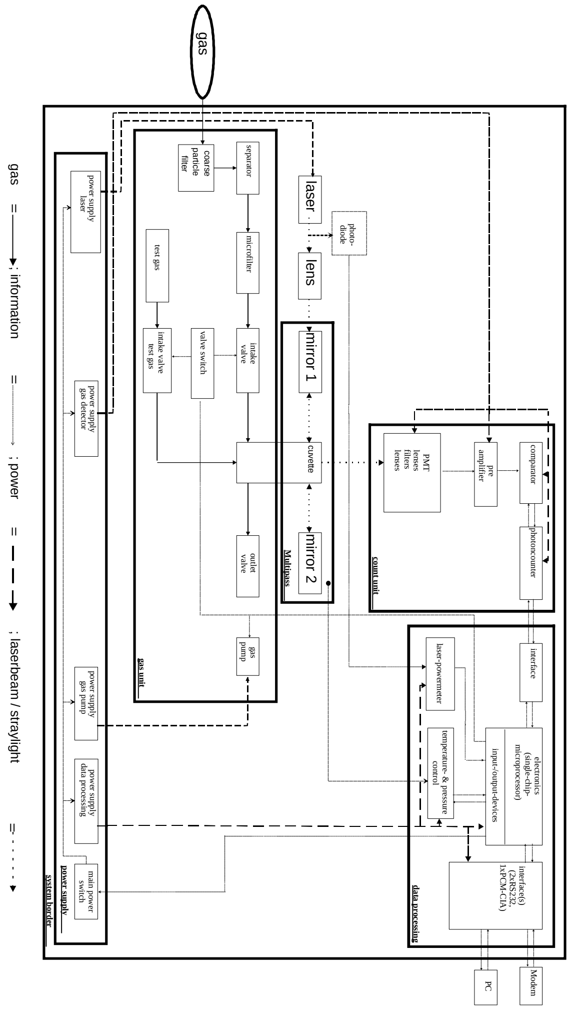

Fig. 1: Block diagram of the system

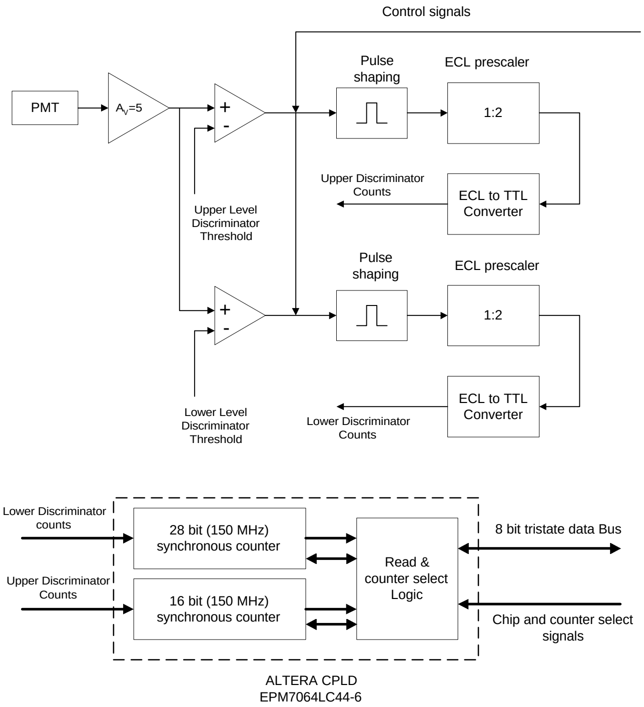

Fig. 2: Block diagram of the photon counting module.

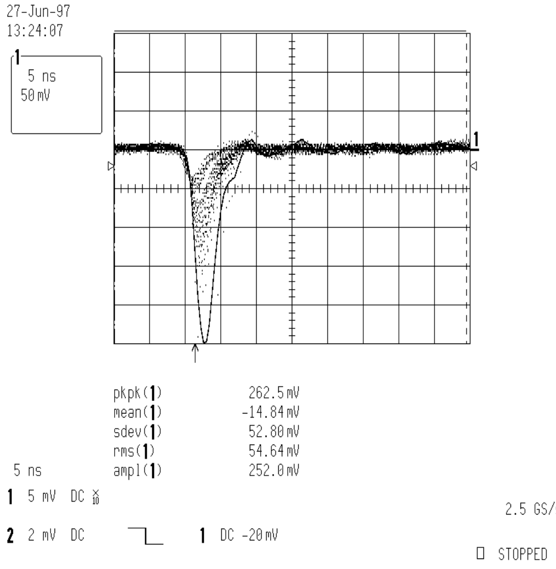

Fig. 4: Oscilloscope measurement at the comparator input for integration time period of 20 sec and sampling rate of 2.5 Gsamples/sec.

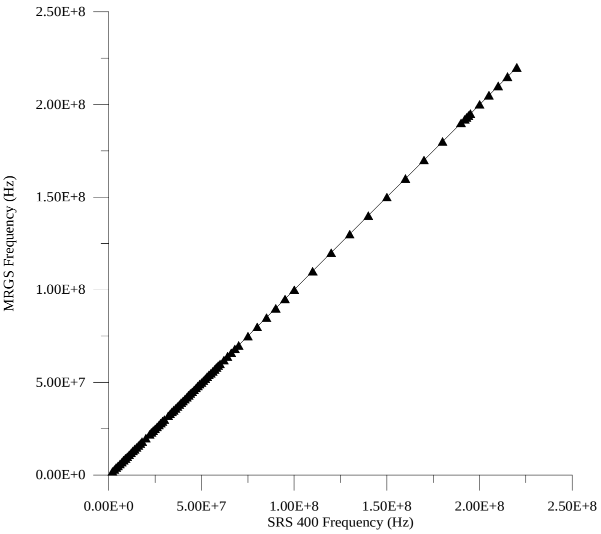

Fig. 5: Comparison of frequency measurement between the MRGS and the SRS400 photon-counting systems.

Gas	Green Laser	Blue Laser
	Sensitivity	**Sensitivity**
N_2	< 0.5 %	< 0.5 %
SO_2	< 50 ppm	< 100 ppb
CO_2	< 15 ppm	60 ppb
NO_2	< 0.5 ppm	60 ppb
C_6H_6	< 50 ppm	< 0.50 ppm
CO	300 ppm	< 0.50 ppm

Table 1: Sensitivities for the measurement of concentrations with green and blue laser

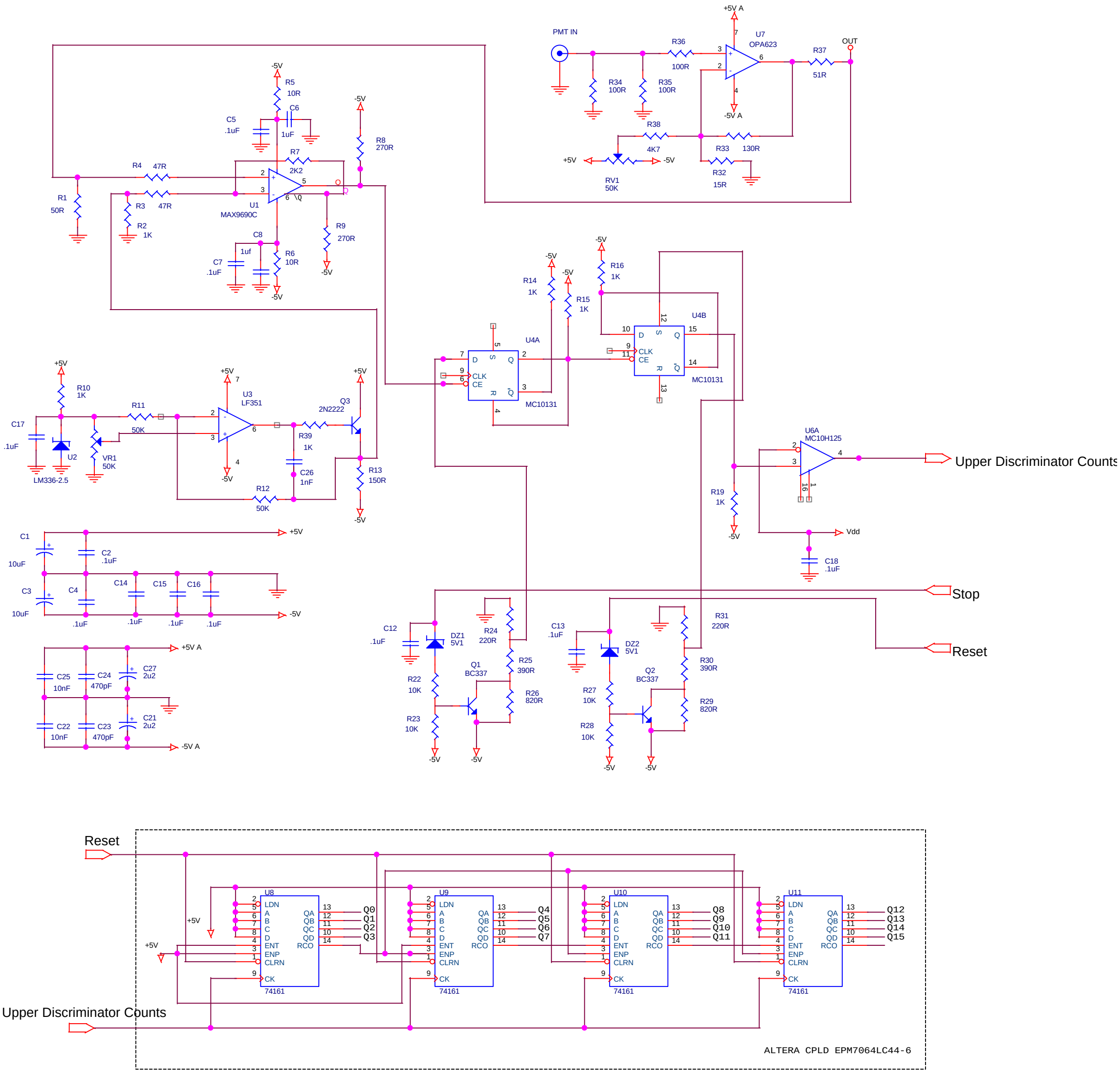

Fig. 3: Schematic diagram of the preamplifier, discriminator and CPLD counter modules for the ULD.