Journal of ELECTRICAL ENGINEERING, VOL. 60, NO. 4, 2009, 215–218

COMMUNICATIONS

CUSTOM PHOTON COUNTING OTDR FOR OPTICAL C–BAND

Marek Hlaváč * — Jozef Jasenek ** — Jozefa Červeňová **

The design of an experimental device for photon counting OTDR is presented. The device features high degrees of freedom in the choice of measurement strategy, which is commonly not possible with the commercial OTDRs. This allows investigations of different methods of data acquisition from the selected portion of the fiber. The device also provides a set of features for studying single photon detection using gated Peltier cooled avalanche photodiodes.

K e y w o r d s: distributed fiber optic sensing, photon counting, OTDR, single photon avalanche diode, active quenching circuit

1 INTRODUCTION

Optical time domain reflectometry (OTDR) [1] is a well established method dedicated for measurements in fiber optics. It can be used as a core technology for distributed fiber optic sensors (DFOS) [2]. There is a well known trade-off between the spatial resolution and dynamical range of the OTDR. A better spatial resolution can be achieved at the expense of a lower level of the optical signal.

If very good timing resolution is required, the very low level of the detected optical power is often the most restrictive constrain for the designer of the OTDR. It is essential for detection circuitry to achieve a very high gain. Detection of such a low level optical signal by conventional analogue detection schemes involves plenty of problems including drifts or nonlinearities of analogue amplifiers.

Photon counting OTDR (PC-OTDR) is a variant where the measurement of the backscattered optical signal is done by a sequence of time correlated photon counting (TCPC) experiments. The very low level of the optical signal that is the main drawback for conventional OTDR becomes an advantage for PC-OTDR. In this case the process of signal detection has a discrete nature and PC-OTDR does not suffer too much from problems with analogue electronics.

We present a design of the PC-OTDR device where each TCPC experiment is controlled by three digital values: requested number of experiments, position and width of the region of interest along the measured optical fiber. Our device allows adaptive setting of these values even during the ongoing sequence of experiments. Such a feature is especially attractive for DFOS allowing to focus interest on the specific region of the sensing optical fiber.

2 PRINCIPLE OF PHOTON COUNTING OTDR

The basis for the OTDR method is the measurement of the time evolution of the optical power that is back scattered from the optical fiber after excitation by a short optical pulse. This optical power can be described by the following formula

$$P_{BS} = \frac{v_g}{2} ES\alpha e^{-\alpha v_g t}\,, \tag{1}$$

where v_g is the group velocity of optical signal propagation within the fiber, back-scattering coefficient S denotes the part of scattered energy that is caught by the fiber and guided backward and α is the attenuation coefficient of the fiber. Taking into account the properties of a typical single mode optical fiber for conventional band (*eg* SMF-28) and a rectangular excitation pulse with a duration of 1 ns, one can calculate that the power backscattered from the initial areas of the fiber can reach 90 dB under the level of the excitation pulse.

The essence of any photon counting method is the fact that the backscattered power (1) can be expressed as a sequence of emissions of discrete photons (photonic flux)

$$P(t) = hvI(t)\,. \tag{2}$$

The product $h?$ represents the energy of single photon and function $I(t)$ is known as the illumination function. The total count of photons emitted by the source within the interval Δt is given by equation (3).

$$E_{\Delta t} = \int_{\Delta t} I(t)\mathrm{d}t\,. \tag{3}$$

In PC-OTDR the measured process is many times repeated and measured with the quantum efficiency η. From the sequence of trials the quantity

$$G = \eta R_{\Delta t} \tag{4}$$

* Cross National Solutions s.r.o., Bernolákova 1A, 901 01 Malacky, Slovakia, hlavac@cn-s.eu,
** KTEE FEI STU Bratislava, Ilkovičova 3, 812 19 Bratislava, Slovakia

ISSN 1335-3632

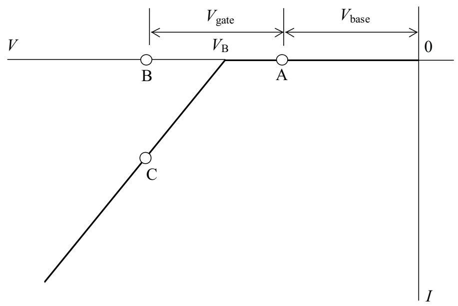

Fig. 1. Typical operation of single photon avalanche photodiode.

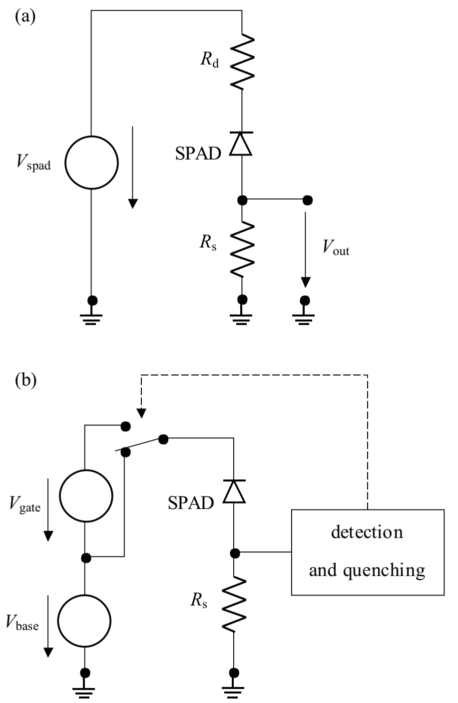

Fig. 2. Principle of the avalanche quenching circuits: passive quenching circuit (a), active quenching circuit (b).

is determined that represents the total count of photons detected within the given time interval. The method is based on the fact that the measured optical power is of such a low level that the probability of detection of one photon within a certain time interval is less than one. It means that if one performs M trials to detect the photon, he detects just $G < M$ photons. If the quantum efficiency is known, using relations (2–4) it is possible to determine the desired time evolution of the backscattered optical power.

Different methods of PC-OTDR signal acquisition and processing (measurement strategies) are possible. The conventional approach often used in quantum cryptography is to enable the detector for a very short time interval (time slot) delayed by the specific amount of time from the impulse launch (shift). This process is repeated many times for different shifts. Every measurement retrieves the information if any photon was detected or no photons were detected in the given time slot. In another approach the detector is enabled for a sequence of time slots and the time is measured from the beginning of this sequence to the detection of the first photon of the backscattered energy.

Different measurement strategies have different mathematical models and their suitability depends on exact values of the measured power. For experimental research of these measurement strategies it is necessary to have a device that is able to flexibly manipulate the position of the time interval during which the detector is enabled and ready to detect the single photon. We present a design and features of such a device in the following chapters.

3 DETECTION OF SINGLE PHOTONS USING THE SEMICONDUCTOR DIODE

Detection of single photons can be conventionally performed by the means of a vacuum photomultiplier where the photocurrent from a photon impinging on a photocathode is multiplied by a system of dynodes [3]. Fragility of photomultipliers, relatively spacious dimensions and difficulty for integration are the main drawbacks of these devices.

Though, it is also possible to use special semiconductor avalanche photodiodes (APD) that are very versatile devices. These specially designed APD are known as single photon avalanche diodes (SPAD). Unlike standard APD, SPAD are specially designed to operate in the so-called geiger mode where the voltage temporarily exceeds the breakdown voltage of the diode.

Typical operation of SPAD is depicted in Figure 1. The thick line denotes the quasistatic voltage-current characteristics of the reverse biased diode. Initially the diode is held on voltage V_{base} (A-point). To enable detection, voltage is temporarily raised by the amount of V_{gate}. Now the voltage across the diode reaches $V = V_B + V_{ex}$, where $V_{ex} = V_{\text{base}} + V_{\text{gate}} - V_B$ is the excess voltage over the diode breakdown. Albeit the actual voltage is over the breakdown, the current does not rise immediately. Instead, the operation point resides in the B-point. Now any single photon impinging on the active area of the SPAD causes the development of the avalanche current that can be detected by the discriminator electronics.

Unfortunately not only photon detection but also thermally generated carriers can initiate avalanche process. This is the cause of the so called dark noise that limits the signal to noise ration (SNR) of the detection process.

After the avalanche occurs it is necessary to move the operation point back to the initial state (A-point) as soon as possible to quench the avalanche. Two methods are used for this purpose: passive quenching and active quenching (Fig. 2). Passive quenching circuits exploit a serial connection of SPAD and a dumping resistor with rather high resistance. The avalanche current flowing through the dumping resistor generates the corresponding voltage over it which effectively decreases the voltage over the diode. In an active quenching circuit the voltage

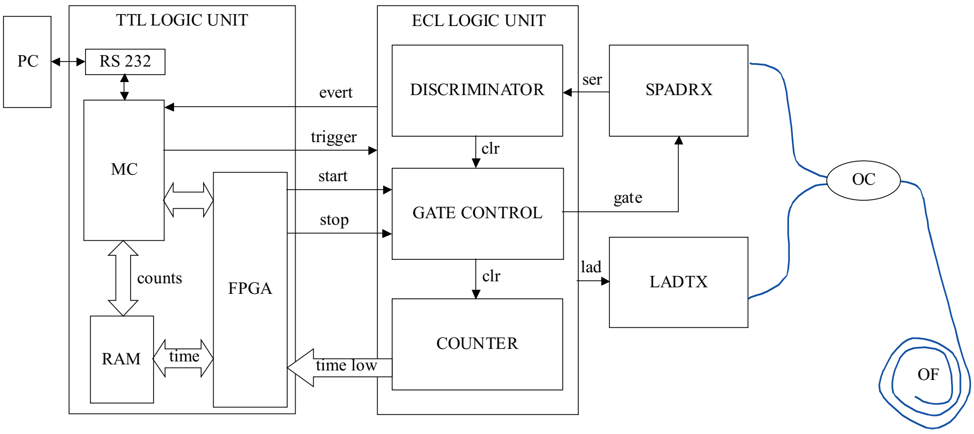

Fig. 3. Design of the custom PC-OTDR reflectometer. PC – personal computer, MC – microcontroller, RAM – random access memory, FPGA – field programmable gate array, RX – receiver, TX – transmitter, OC – optical coupler, OF – optical fiber.

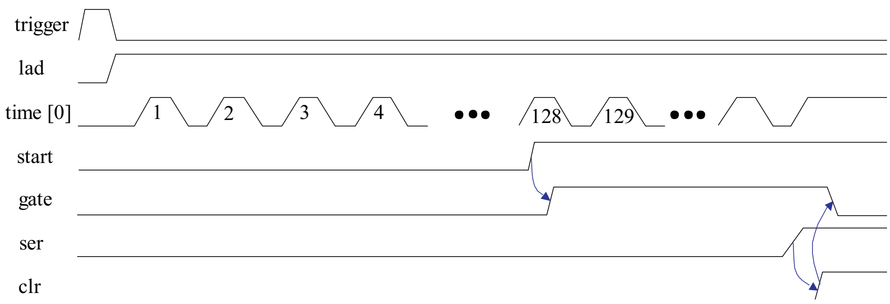

Fig. 4. Operation of the custom PC-OTDR reflectometer. The situation is displayed where the photon detection occurs within the active gate signal. If no photon is detected the actual gate is cancelled by the mean of another signal stop that is not displayed in this figure.

over the diode is actively set to the base point after the detection.

One of the advantages of the active quenching is the possibility to adjust the time during which SPAD detector is inactive. This is important in order to control the noise contribution of the so-called afterpulses. If the time of inactivity is too short and the diode is reenabled for the next detection, some carriers trapped in the deep defects of the semiconductor crystal lattice during the previous avalanche can cause false detection. To suppress this afterpulse effect it is also essential to quench the avalanche very quickly, which puts hard requirements on the reaction time of the quenching circuit.

Nowadays the technology of silicon SPAD is well matured. However, silicon devices are not suitable for operation in the long wavelength range which provides the smallest attenuation and is preferred by the contemporary optical fiber systems. For photon counting in long wavelength band one can use well selected APD based on Ge, InGaAs or InGaAs/InP. Due to the high dark noise rates provided by these long wavelength APDs under room temperature it is necessary to cool these devices intensely. The common method is to immerse APD in liquid nitrogen and control its temperature by means of an attached heater. Such a cooling method is good for laboratory use but is unsuitable for the field conditions. Fortunately there are now commercially available APDs that can operate as SPADs in temperatures achievable by thermoelectric cooling, which is much more convenient for field conditions. We adopted the concept of thermoelectrically cooled commercially available APD for our PC-OTDR.

4 IMPLEMENTATION OF THE SYSTEM

To support our research on DFOS we decided to design and develop a custom PC-OTDR reflectometer. We require a spatial range of about 10 km with resolution better than 0.5 m. We also require the possibility to focus the measurement on the specified region of interest within the fiber, that is not to measure the whole fiber but for every OTDR launch to specify the measured area. To do so we have adopted the following principle. There is a high speed digital counter driven by a clock generator at the core of the system. For every impulse launch it is possible to set the two digital values representing the start position and stop position of the region of interest. During operation the actual value of the counter is compared against these values producing an electronic gate enabling the optical receiver for the required time interval.

The PC-OTDR reflectometer consists of four main parts (Fig. 3):

- optical impulse source launching the test impulse into the measured optical fiber,
- SPAD receiver providing information about photon detection timing,
- high speed logical unit populated by emitter-coupled logic (ECL) devices designated for SPAD active quenching and for time measurement,
- logic unit with microcontroller (MC) and field programmable gate array (FPGA) device that communicates with personal computer and conducts the measurement process.

The operation of the device is depicted in Fig. 4. Initially the user (or a server software on PC) sets the position of the gate and the requested count of repetitions. The microcontroller registers these values and pulses the *trigger*. Immediately after trigger the laser launches impulse into the fiber and ECL counter starts counting.

There is another counter implemented in FPGA that is cascaded after the ECL counter. Both counters together provide the low and high parts of the digital time signal that is connected to the address bus of the RAM. The registered values of the start and stop of the gate are in FPGA compared with the actual value of the high counter. When the digital time reaches the desired values, signals start and stop produce the gate enabling SPAD detector for the desired time interval. The first photon detected within the gate quickly forces stop of the gate (signals *ser* and *clr*). Simultaneously the counter is stopped and event is activated that is mapped to the interrupt vector of the MC. Now signal time that addresses RAM contains the actual digital time between launch of the optical impulse and detection of the first photon. MC reads the data from RAM, increments its value and writes it back. Repeating of this process required number of counts creates in RAM the desired PC-OTDR histogram. Finally measured data is transferred to the personal computer where it is further processed and displayed.

This gives us the high level of freedom in the choice of measurement strategy which is not possible with the commercial OTDRs. Device is also suitable for investigations of operation of the single photon detection circuits and SPADs, because our receiver features set of adjustable parameters. It is possible to adjust temperature of SPAD and both operation voltages V_{base}, V_{gate} (Fig. 1).

5 CONCLUSION

In this paper we present the design of the custom PC-OTDR reflectometer. We explain basics of PC-OTDR method and specific features of the time correlated single photon counting at the C-band optical wavelengths. The presented device is especially designed to support our research in the area of DFOS based on single photon counting metod. The device features high flexibility in setting of the position and length of the gate signal that controls the SPAD detector. This allows for research of adaptive strategies of data acquisition from the sensing optical fiber. Photon counting receiver is designed so that the parameters of the detection process are adjustable to allow for research of different operation regimes.

Acknowledgments

This work was supported by the scientific grant agency MŠ SR and SAV under the project contracts VEGA 1/3097/06 and VEGA 1/0617/09.

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Received 9 December 2008

Marek Hlaváč (Ing) was born in Malacky, Slovakia on January 1, 1979. He received his MSc degree in electronics from the Slovak University of Technology, Bratislava, in 2005. His research activity is focused on the fiber optic sensors, photon counting technologies and polarization sensitive measurements in the fiber optics. Currently he is working on completion of his PhD studies.

Jozef Jasenek (Prof, Ing, PhD), born in 1947, in Bobrov (Slovakia), graduated from the Faculty of Electrical Engineering and Information Technology of the Slovak University of Technology Bratislava in 1971, in solid state physics. Since 2004 he is a Full Professor in electromagnetic theory. Currently his professional interests concern mainly the theory of linear and nonlinear optical waveguides and the development of experimental methods for testing of optical waveguides and optical fibre components. Especially he is involved in analysis and implementation of optical reflectometric methods (OTDR an its modifications). He has lead several scientific projects and published more than 40 scientific papers and two monographs.

Jozefa Červeňová(Ing, PhD), born in 1958 in Bratislava, graduated from the Faculty of Electrical Engineering and Information Technology of the Slovak University of Technology in Bratislava in 1971 in the study field Electronics. She completed her PhD studies in 1993 in the field of Electromagnetic Theory. She took part in the solution of several VEGA scientific research projects oriented to optical fiber technology. Her current research interests concern mainly the testing methods of optical fiber systems and components.