EXCITATION OF SEMICONDUCTOR LASER FOR OTDR BASED ON PHOTON COUNTING

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ABSTRACT

The main goal of the paper is to explain the design of the excitation circuit for the semiconductor laser diode used in OTDR reflectometer based on photon counting. The main criterion was to achieve a rather high space resolution of the device and simultaneously to maintain the maximum possible simplicity of the circuit. The key parts of the designed system are based on technology compatible with emitter coupled logic. The numerical simulation of our hierarchical model has proved that the excitation optical impulse with the minimal width of 300ps can be achieved. That kind of circuit makes possible to construct OTDR reflectometer with rather high space resolution approaching 3cm.

Keywords: *OTDR, photon - counting OTDR method, excitation circuit, emitter coupled logic (ECL)*

1. INTRODUCTION

Nowadays in many areas of optical fiber technology the optical reflectometry in time domain is used (Optical Time-Domain Reflectometry, OTDR). OTDR is a method used not only for testing the integrity of optical fiber systems but also as a method used in design of optical fiber sensors with distributed parameters (distributed optical fiber sensors, DOFS). One of the main advantages of this method is its non-destructive character and also the fact that it requires the access to only one end of the fiber.

The architecture and mechanical features of optical fiber allow this fiber to be built for example into the building structures on purpose of measuring numerous physical magnitudes. Through the creation of intelligent structures with implemented optical fibers so we can get multi-dimensional view on measured physical magnitudes. In such a way for example we can measure the pressure fields in constructions of roadways. DOFS of this type can be also used as a system for monitoring the road traffic in real time.

The main advantage of the DOFS conception consists in the use of a single optical fiber that makes possible to monitor a segment of the road with a length of tenths of kilometres with a very high space resolution. Our approach to the problem solution provides more performance parameters of the road monitored as compared with the application of contemporary commercially available sensors, which are financially more demanding and are much more complicated.

2. PHOTON-COUNTING BASED OTDR

Traditional OTDR method is based on launching a very narrow testing optical impulse into optical fiber through a 3dB optical coupler. The impulse is spreading along the fiber as a “light region” with the length of

$$\Delta l = \frac{t_W \cdot v_G}{2} \qquad (1)$$

where v_G is the velocity of light impulse with duration t_W. Part of the impulse energy is scattered on microscopical fluctuations of refractive index (Rayleigh scattering) and the other part is reflected on rather strong inhomogeneities in optical fiber (Fresnel reflection). Backscattered and reflected energy is guided with the fiber waveguide structure back through coupler on a photo detector.

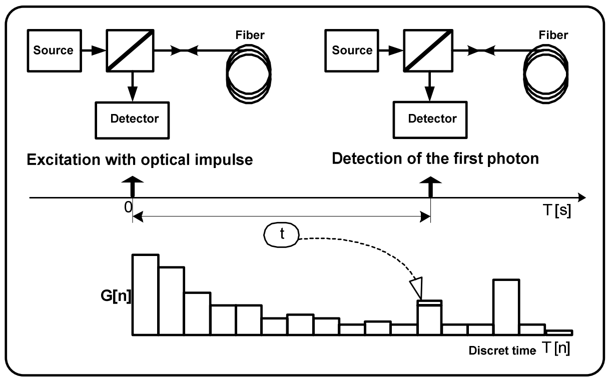

Fig. 1 The principle of PC-OTDR histogram forming [1]

One of the unconventional approaches to OTDR is based on the application of the photon counting (Photon Counting OTDR, PC-OTDR) method [1]. PC-OTDR utilises the Poisson statistics of backscattered optical power with ultra low level. The simplified diagram of the signal processing in PC – OTDR is shown on Fig. 1. In contrast with classic OTDR it dominantly uses the digital signal processing.

The optical source generates a test impulse which is launched through 3dB optical coupler into optical fiber. Backscattered photons from the fiber are detected by a very sensitive detector based on single photon avalanche diode (SPAD). The result of measurement is a PC-OTDR histogram. As it implies from the Poissons statistics the measured values accumulated in the histogram are directly proportional to backscattered power that can be also measured by classical OTDR [2].

Let us consider that the initial point of the time axis is the moment of launching the impulse. The creation of the histogram is then based on the repeated measurement of the time interval from launching to detecting of the first back scattered photon. The required signal noise ratio (SNR) is then achieved by sufficient number of repetitive measurements. This phenomenon is common for all modified OTDR methods.

Data extracted from PC–OTDR histogram are necessary for the next signal processing. From the analysis of measured data two basic results can be extracted: localization of inhomogeneities and the characteristic curve of attenuation. Signals with information about localization of strong inhomogeneities come from Fresnels reflections. The reflections are caused by sharp differences of refractive index in optical fiber. The discontinuity in refractive index act like mirror for optical signal. The refracted signal is then in strong correlation with the input signal of optical excitation. The localization of local extremes in PC–OTDR histogram is a direct localization of refractive index inhomogeneity. One can also use the correlation analysis to do that. The application of DOFS often requires the extraction of the characteristic curve describing the attenuation. It requires removing all graphical elements caused by Fresnel reflections. This task can be realized by deconvolution of the signal components.

The contribution of PC–OTDR in comparison with the classic OTDR consists in simplicity of circuit realization. The demands for the band - width, signal noise ratio and linearity are less strict in this method. Digital signal processing in PC–OTDR is more economical, not so demanding and in such a way one can achieve a better space resolution and cost effectivity of the device.

Another important performance parameter of an OTDR reflectometer is also its space resolution Δl, which is linearly dependent on the testing impulse width t_w as it results from the equation (1).

3. EXCITATION CIRCUITS SPECIFICATION

In this paragraph the specification of exciter circuits is discussed. We will focus at the key parts of the whole system only.

The analysis of electric circuit specification includes tree substantial factors: characteristics of laser diode, parameters of excitation circuits and the type of connection between them.

Functioning of excitation circuit for laser diode with distributed feedback (distributed feedback laser, DFB) is schematically described in Fig. 2. One of the main constraints for the circuit realization is the compatibility with the positive emitter coupled logic (PECL). The block of PECL logic, using the leading edge of the testing impulse, defines the moment of the fiber excitation. The solution of laser exciter design includes elements for modulation setting (I_{MOD}) and bias (I_{BIAS}) current. To be able to control the space resolution it is necessary to have the possibility to set the pulse width (T_W) smoothly or discreetly at least.

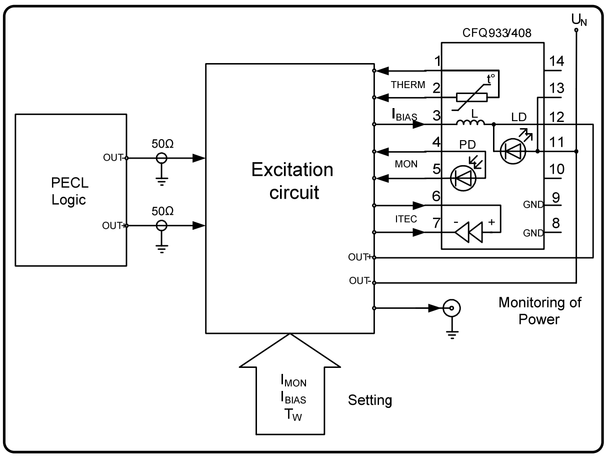

Fig. 2 The excitation circuit scheme

The output for power monitoring is obtained by generating electrical signal which is linearly dependent on the optical power impulse shape. The parameters of the testing impulse should be independent on temperature and working time. That's the reason why one has to implement the temperature stabilization of the excitation circuit.

3.1. Modulation of laser diode

Optical signal from the laser diode (LAD) can be modulated directly or indirectly. In the case of direct modulation, the optical output depends on modulation current through the LAD. The advantage of direct modulation consists in rather simple realization. In the case of indirect modulation an external modulator is used and the light generated by the laser diode is continuous. The advantage of indirect modulation is very high speed and the possibility to do it with high optical power outputs. However the significant disadvantage is more complicated circuit realization. Other disadvantage is that during the "turn off" state there could be still a leakage light. For PC–OTDR it is totally important not allow to input any light into fiber except the test impulse. It is so important due to the extreme sensitivity. That is the reason why it is better the use of direct modulation which satisfies the conditions for PC–OTDR optical source. Paper text

3.2. Bias current

In optical communication systems the excitation of DFB lasers is mostly realized by a combination of modulation current I_{MOD} with bias current I_{BIAS}. This approach is illustrated in the Fig. 3, a. The bias current determines the time response of the modulation impulse current I_{MOD} above the threshold current I_{th} as shown on LI characteristics.

In the PC-OTDR reflectometry the backscattered power of ultra low level is detected (less than 10^{-12} W) and consequently the setting of a non-zero bias current could cause the emission of non-coherent photons. This effect is unacceptable. That is the reason why it is necessary to set the bias current to zero $I_{BIAS} = 0$. This situation is illustrated in Fig. 3, b.

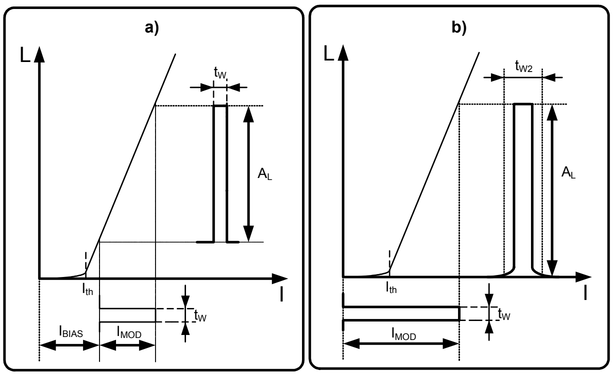

Fig. 3 a/b Types of modulation in PC-OTDR

3.3. Fast emitter coupled logic

The emitter coupled logic (ECL) is one of the fastest technologies for logical circuits. The price for top speeds is paid by higher demands for the electrical design solution. One of the complications is the necessity of the negative source voltage [3]. That could be a problem of compatibility with CMOS and TTL logic. PECL or positive ECL is nothing else as ECL logic with a positive voltage source. Every kind of ECL circuit could be also a PECL. However it is important to know that positive voltage line gives better results like stability, filtration and SNR. PECL makes possible to construct hybrid systems with fast PECL part and slower circuits with standard logic [4]. In PECL logic the transistors work in a non saturated regime, which eliminates the delay caused by over saturation of transistors. The input is realized by differential current switch and output with emitter followers. To achieve very high switch frequencies it is necessary to have small voltage difference between logical levels. Small output and high input impedance enables high logic gain and direct line coupling with low impedance.

4. EXCITATION CIRCUIT DESIGN

Based on the specification of excitation circuit given in chapter 3 it was possible to design inner structure of the excitation circuit illustrated in Fig. 4.

The excitation circuit has to emit impulse beam and to provide time parameters for the control of optical time response. Signal in PECL logic (INPUT) is processed in the block where the width of the impulse is set and adjusted for excitation of the final stage. The impulse width t_W can be adjusted using current source as required. The block of final stage is a power element for direct modulation of LAD. The regulation of the signal OUT makes possible to adjust the amplitude (power) of the output optical signal. The important part of the design is the block of thermal stabilization. Input signal THERM is compared here with the reference value and consequently the current trough the thermoelectric segment (ITEC) is controlled. The block of thermal stabilization is based on the circuit MAX8520 [5].

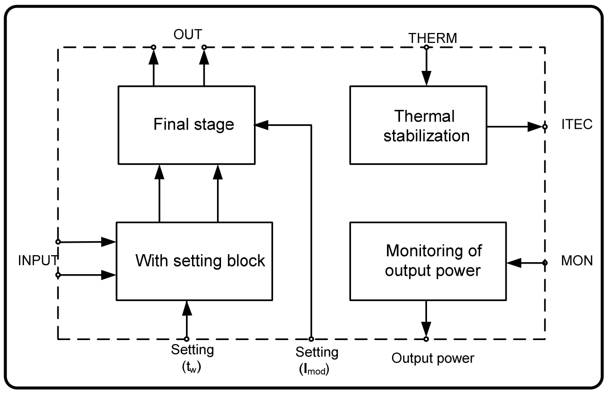

Fig. 4 Excitation circuit

The block for output power monitoring is wired to the monitoring photodiode inside the laser case. The block processes the signal from the laser diode (MON). Its output provides the signal for oscilloscope observation. The coupling is realized by impedance driven lines.

4.1. Setting the pulse width

The solution of circuit for the generation of the excitation signal for final stage is realized by the edge detector, see Fig. 5.

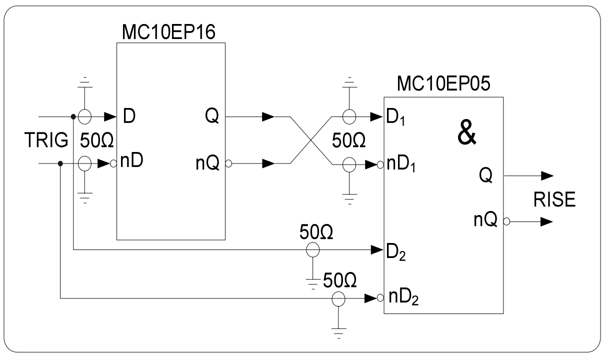

Fig. 5 Edge detector

The circuit MC10EP05 [6] acts as a differential logical AND. Through the logical conjunction of the signal TRIG and its delayed negated complement one can create the required signal RISE. The pulse width is set by a delay line with its specific propagation delay. In the Fig. 5 the scheme diagram of the line driver MC10EP16 [7] is shown. For the discrete regulation we can use more line drivers in cascade to achieve longer pulse width.

Another option is to use coaxial cable as a delay line. We have done a time analysis for this circuit using specific circuit parameters [6], [7]. The result of the analysis was obtained for room temperature 25 °C. The minimum width of output signal RISE which we achieved with the use of 1 line driver was 220ps. It is appropriate result for the demanded design of the high resolution exciter for PC - OTRD.

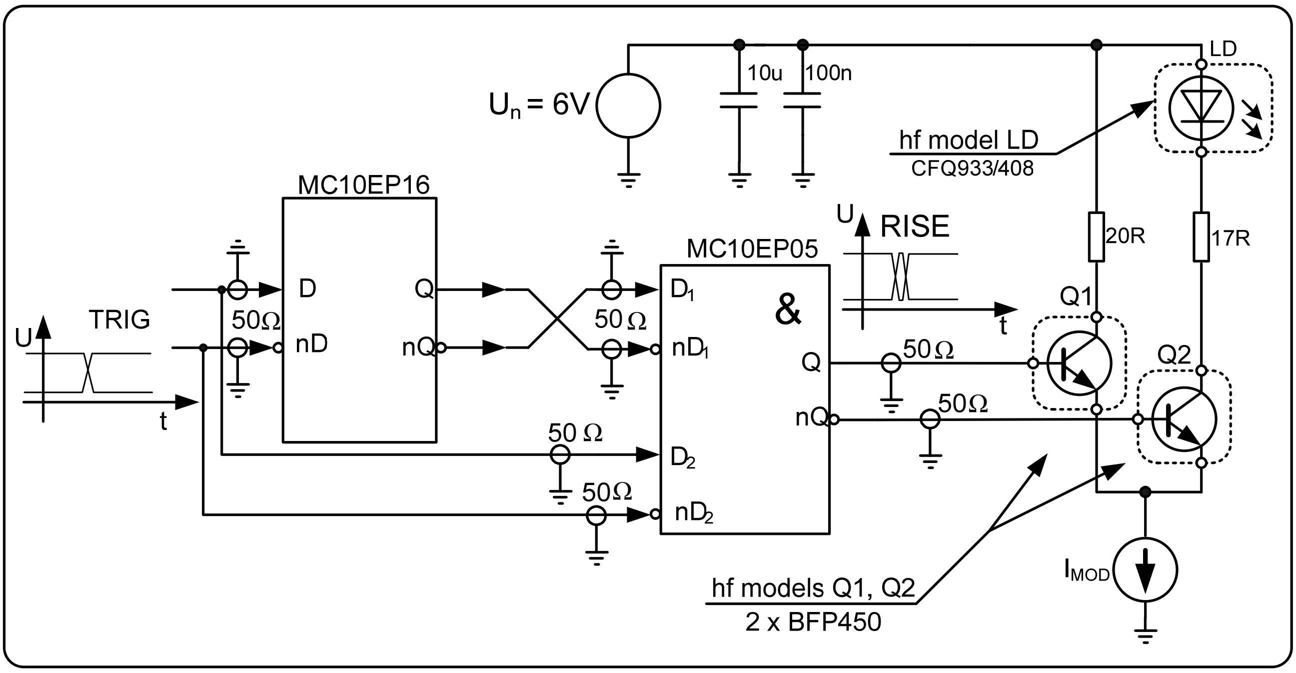

Fig. 6 Simulation model

4.2. Final stage

Taking into account the compatibility requirements with PECL logic the final stage (platform) was designed as a differential amplifier with controlled output current, Fig. 6. The high working frequencies demand the implementation of parallel capacitors and serial inductances into the models of transistors BFP450. That is the reason why it was necessary for us to reconsider the simulation model [8].

The output of edge detector is represented by two impedance driven lines with resistivity of 50Ω. Model of LD is connected to the collector of transistor Q2. Internal resistivity of LAD is 3,86Ω. The collectors had to be loaded with 20 Ω resistors so it was necessary to connect LAD with 17 Ω resistor in serial way.

If one considers the parameters of transistors Q1 and Q2 to be practically identical then the collector and emitter currents are nearly identical and the gain is sufficiently high.

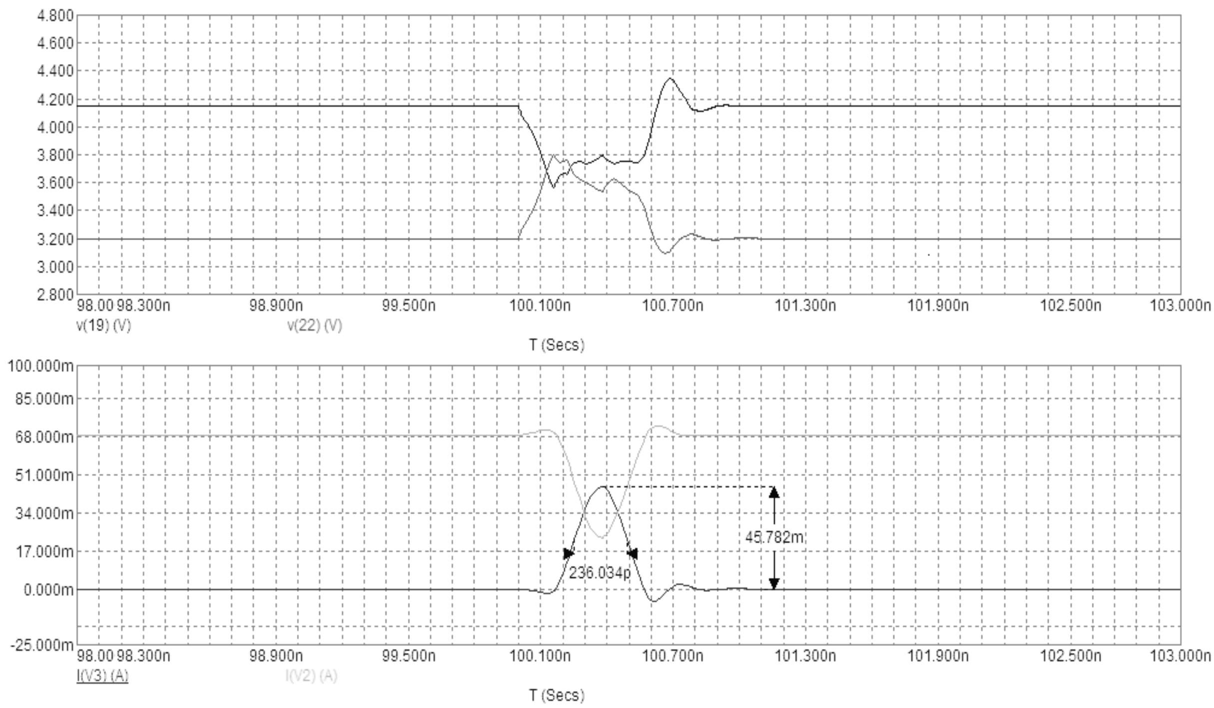

Fig. 7 Time analyze simulation of final stage

It can be said that if Q2 is switched on and output Q1 will be in state of high impedance, the source current I_{MOD}, will flow through LD. The circuit is supplied by DC supply of 6V. The current course I_{MOD} is realized as a current mirror and enables to set the amplitude of LD modulation current.

The results of the simulation of final stage for the shortest possible excitation impulse (mentioned in chapter 4.1) are illustrated in the Fig. 7. The upper graph represents the symmetrical input signal RISE. Its deformation is caused by the parasitic influences. In the lover graph the time response of the current flowing through collectors of complement transistors are shown. The current impulse width is of 250 ps at FWHM. Considering the type of modulation used the pulse width of 300ps can be achieved. It corresponds to the PC – OTDR space resolution 3cm.

5. CONCLUSIONS

In the presented work the basic process of the design of the semiconductor LAD driver for the OTDR based on photon counting is briefly described and discussed. In the introduction the application of OTDR in the field of optical fiber sensors with distributed parameters is in brief described. The principles of classical OTDR and its modification like PC–OTDR are discussed in the second part. The advantages and drawbacks of these methods are also briefly summarized. The third part deals with the specifications of the excitations circuits from the point of view of modulation, functions, thermal stabilization and usage of positive emitter coupled logic. The specific features of the design of fast PECL circuit structures are discussed. The main focus is concentrated on the design of the excitation circuit. The block structure and the particular functions of each block are described. Two key subsystems were discussed in details - the pulse width setting and final stage. The time analysis of these systems was also presented. The achieved and presented simulations results confirm a good agreement with the theory. The preliminary obtained partial experimental data have shown that the simulation tools used reflect the real conditions very well. The extended measured data will be published in a separate publication in the near future. The analyzed and designed circuits will be integrated into the prototype of the PC – OTDR reflectometer with applications in DOFS.

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REFERENCES

[1] JASENEK, J.: Optical Fiber Reflectometry, STU Bratislava, 2004, ISBN 80-227-2002-X, pp. 105-129 (In Slovak)

[2] HLAVÁČ, M. Optical Fiebr Sensors with Distributed Parameters based on OTDR, Bratislava: FEI STU, 2005. pp. 45-49. (Part of PhD. thesis).

[3] Introduction to LVDS, PECL, and CML, MAXIM, Maxim integrated products, [online]. October 11 2000. [2007-04-6]. http://pdfserv.maxim-ic.com/ en/ an/hfan10v2.pdf

[4] MECL System Design Handbook, ON Semiconductor, [online]. May 1988. [cit: 2007-04-15]. http://www.onsemi.com/pub/Collateral/HB205-D.PDF

[5] Compact DWDM laser Temperature Control with the MAX8520, MAXIM Dallas semiconductor, [online]. June 14 2004. [2007-04-16]. http://www.maxim-ic.com/an3264

[6] MC10EP05, MC100EP05 3.3V / 5V_ECL 2−Input Differential AND/NAND, ON Semiconductor, [online]. [cit:2007-03-10]. http://www.onsemi. com/pub/ Collateral/MC10EP05-D.PDF

[7] MC10EP16, MC100EP16 3.3V / 5V_ECL Differential Receiver/Driver, ON Semiconductor, [online]. http://www.onsemi.com/pub/Collateral/MC10EP16-D.PDF

[8] NPN Silicon RF Transistor, SIEGET_25 BFP450, [online]. August 20 2001. [2007-04-15]. ttp://www.infineon.com/upload/Document/smallSignal Discretes/ Transistors/Datasheets/bfp450.pdf

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BIOGRAPHIES

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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.