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Application of Software-Defined Radio for Rayleigh and Raman Scattering Measurement in Optical Fibers

Abstract

A laboratory system for measuring the Raman scattering light in optical fiber is presented. The system is equipped with the developed driver for 5 mW/1550 nm laser diode, optical circulator, WDM filters to separate Rayleigh and Raman scattered light and InGaAs cooled photodiode to detect the weak scattered radiation. Instead of using expensive network analyzer we propose to use Software-Defined Radio, which ensures the necessary sensitivity and selectivity of detected signals. The preliminary results are presented for about 3 km – length single mode silica optical fiber.

Keywords: Rayleigh and Raman scattering, synchronous detection, silica optical fiber, optical frequency domain reflectometry.

1. Introduction

Analysis of scattered light in optical fiber provides valuable information. It can be used for detection of breaks and bends as well as for measurement of strain and temperature along a fiber. This phenomenon is applied in structure monitoring, hydrology and remote sensing. Brillouin scattering stands out for strain measurements, while the spontaneous Raman Anti-Stokes scattering allows getting temperature profiles along the fiber due to its high dependency on temperature [1].

Scattered light could be analyzed through either the Optical Frequency Domain Reflectometry (OFDR) or the Optical Time Domain Reflectometry (OTDR). Nowadays, OFDR-based systems are still not used commercially due the higher cost and more complex signal processing, besides the limitations in spatial resolution and dynamic range [2]. OFDR uses continuously working lasers, while OTDR needs impulse high-power lasers. The important benefit of OFDR is its lower optical power. It guaranties safety while being used [3]. On the other hand, there are applications, where high-power systems may not be used. One of them is measurement of temperature in mines where an explosive atmosphere may occur.

Software-Defined Radios (SDR) allow users to apply preferred settings for filters, amplifiers, detectors and modulators via software, thus they make it easier for users to test various settings without the need to construct individual system for each setting [4].

The aim of this paper is to present the application of SDR in the detection of scattered light basing on the OFDR analysis.

2. Optical Frequency Domain Reflectometry

Optical Frequency Domain Reflectometry (OFDR) is an analyzing method based on the reads of frequency changes of the backscattered light, resulting from breaks, bends and strain or temperature changes. OFDR can provide valuable information about the position of scattering factors, with less than 1 m spatial and 1°C temperature resolution. There are two main types of OFDR analyzing: coherent (C-OFDR) and incoherent (I-OFDR) [5].

The principle of the C-OFDR (Fig. 1) is detecting of a beat frequency (interference frequency) between the distributed scatters from the tested fiber and a local oscillator. In this case, the frequency of the laser is linearly swept without mode hops in order to map the beat frequencies positions along the fiber. The coupler splits the laser signal to the tested fiber and to another arm of an interferometer where is reflected – Fig. 1. The backscattered light from the fiber and reflected from the mirror coherently interfere at the coupler, creating an interference signal that contains the beat frequencies. The spectrum analyzer performs Inverse Fast Fourier Transform (IFFT) and displays the beat frequencies as peaks in the spectrum of the impulse response. One must notice the dependency of the signal on the polarization of the scattered light, thus a polarization diversity detection scheme implementation is a must [6].

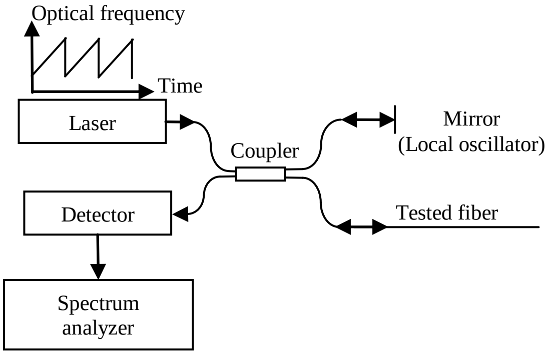

Fig. 1. Block scheme of the C-OFDR analysis

I-OFDR (Fig. 2) uses a frequency modulated continuous wave (CW) optical carrier. The frequency range is changed either stepwise (step frequency method) [7] or continuously (sweep frequency method) [8]. The scattered signals are detected as a function of modulation frequency. The vector signal analyzer obtains the frequency response of the fiber. Applying IFFT allows moving the signal from frequency to spatial domain.

It is worth mentioning that OFDR can be also applied using an incoherent frequency-modulated continuous light waves. The modulating signal is swept in frequency and the scattered light is detected. Then both signals are mixed electrically and the analysis is performed using spectrum or network analyzer [9].

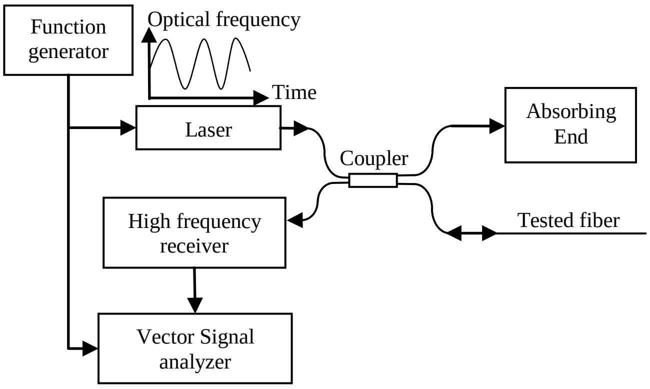

Fig. 2. Block scheme of the I-OFDR analysis

3. Software-Defined Radio (SDR)

The aim of the Software-Defined Radio is to replace the hardware components traditionally used in radios, such as filters, amplifiers, detectors and modulators, with a software controlled programmable devices that can be chosen on user's preference through PC or embedded systems. SDR main advantage is the avoidance of interferences between transmission channels thanks to the facility of dynamic configurations of the system by the software. This is actually implemented in Cognitive Radios (CR) [10].

According to Mitola [10], SDR relies on the advance of high-resolution Analog-to-Digital (ADC) and Digital-to-Analog (DAC) converters, as well as the appliance of the recently developed Digital Signal Processors (DSP). It is remarkable, that the receive digitization occurs at the same stage downstream from the antenna [11]. The antenna is followed by a filter, which has a tunable pass-band. It allows the digitization of the channel's signal at an acceptable SNR for the demodulation [12]. For multi-mode terminal applications, the SDR architecture involves the use of mixers to reduce the ADC sampling rate [13], where the broadband RF signal containing the desired channel is converted to a baseband with a single broadband analog stage. Another approach of SDR architecture relies on the implementing of subsampling in order to perform down-conversion, which requires a strong anti-aliasing filter [14].

The main advantage of SDR is the high configurability that allows radios to be upgradeable in order to adapt to newly emerged standards [15]. This also ensures the reduction of cost due to the long service time and higher reliability of these radios for military, space and mobile communication applications [16].

4. Experimental setup

In order to perform the research presented in this paper, a laser diode driver board was developed. The block diagram of the laser driver control board is shown in Fig. 3. This board allows setting the laser diode operating frequency. The communication between the board and the PC is through USB FTDI FT2232HL module [17]. The PIC18F4520 microcontroller [18] receives the user's settings for the frequency through RS232 port from the FTDI module and passes it to FPGA XILINX Spartan 6 XC6SLX9 digital controller [19]. The system uses the PPL programmable clock generator ICS512MILF controlled by the software from the host [20]. PLL generator allows setting the maximum frequency of 160 MHz. In addition, the standard 50 MHz quartz generator can be used. Software controls the frequency dividers implemented in FPGA in order to set the laser diode operating frequency. The operating frequency is then transferred through the FPGA to the dedicated laser diode driver MAX3766 [21]. This driver operates in a wide frequency range. The PIC15F4520 microprocessor is also responsible for switching the laser diode ON/OFF. The board also contains S25Fl127 flash memory to save the configuration of FPGA [22].

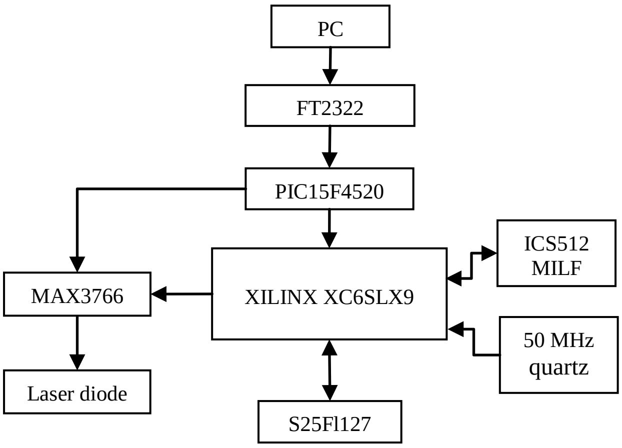

Fig. 3. Block scheme of the laser driver control unit

The block diagram of the experimental system setup is presented in Fig. 4. This setup is based on the I-OFDR analysis method. The emitted light is provided to the fiber optic through an optical circulator, which guarantees the guidance of the emitted light only to the light guide, and the guidance of the scattered light to the Wavelength Devision Multiplexing (WDM) filters. The WDM separates the scattered light depending on the its wavelength to: Rayleigh (R), Raman Stokes (S) and Raman Anti-Stokes (AS) scattered light. Each of these signals is then detected by the photodiode (PD), which converts them to electrical signals, creating a modulating wave.

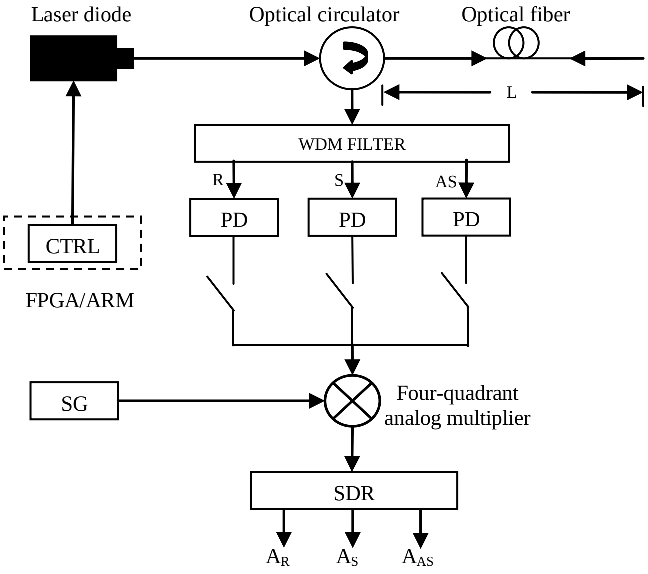

Fig. 4. Block scheme of the experimental system setup

The carrier wave is provided by a signal generator (SG). Both the carrier and the modulating waves are then provided to a four-quadrant analog multiplier AD834 [23]. The output signal of the multipliers is then connected via antenna to the RSP1A SDRplay radio [24] (Fig. 5), which covers a wide RF spectrum from 1 kHz to 2 GHz, and has a 14-bit ADC. The SDRPlay radio performs IFFT, which result is a complex number (I – Real number, Q – Imaginary unit). The analysis of the obtained signals is performed using the freeware software "RSP-Spectrum Analyser" available at the radio's manufacturer website [25]. The photo of the system is presented in Fig. 6.

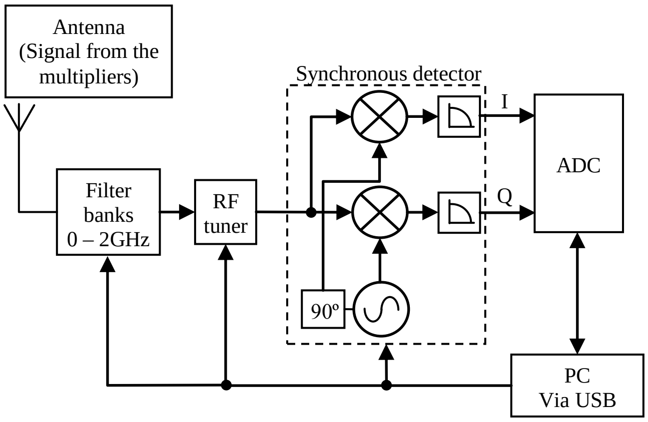

Fig. 5. Block scheme of the SDR

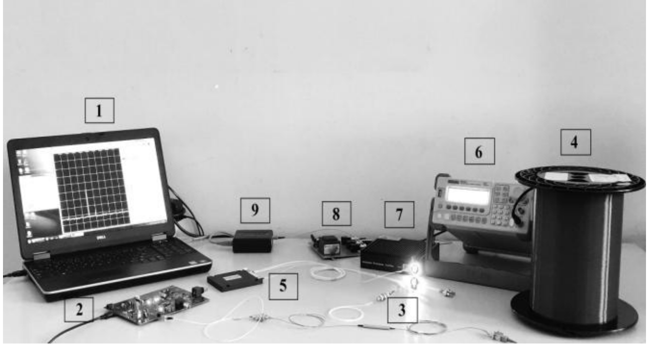

Fig. 6. The developed light scattering measurment bench based on SDR: 1 - PC, 2 – laser diode control unit, 3 – optical circulator, 4 – optical fiber (SMF28-e), 5 – WDM filters, 6 – signal generator, 7 – avalanche photodiode module, 8 – analog multiplier, 9 – SDRPlay radio

5. Results

In this research, an experiment with 3 km-length single mode silica optical fiber was performed (Fig. 6). The system operates at the wavelength 1550 nm with the low power laser diode (P=5 mW). All experiments were carried out in room temperature T=25°C. Only amplitude characteristics are presented here. The phase of the back-scattered signal at the modulating frequency is not mentioned because there was a uniform temperature profile along the light guide without any hot spots. Phase of the scattered light is only useful to locate such hot spots through IFFT appliance [3].

Figures 7, 8 and 9 present the results obtained from the "RSP-Spectrum Analyser" software, which shows the signal spectrum of the SDRplay radio in the frequency domain. The x-axis displays the frequency in MHz, while the y-axis displays the signals amplitude in dB. The carrier wave frequency of the local oscillator was set to 13 MHz, while the laser modulating wave frequency was 5 MHz. These frequencies were chosen randomly.

The same frequency set up was chosen for measurement Rayleigh, Raman Stokes and Raman Anti-Stokes scattered radiation. The backscattered light has the same frequency as the modulating wave. One must notice that the Raman shift occurs in the wavelength, thus the frequency is the same for Rayleigh, Raman Stokes and Raman Anti-Stokes. The obtained results fit in with the theory of light scattering, since the Rayleigh scattering signal is the highest, and the Raman Stokes scattering signal is greater than the Raman Anti-Stokes one.

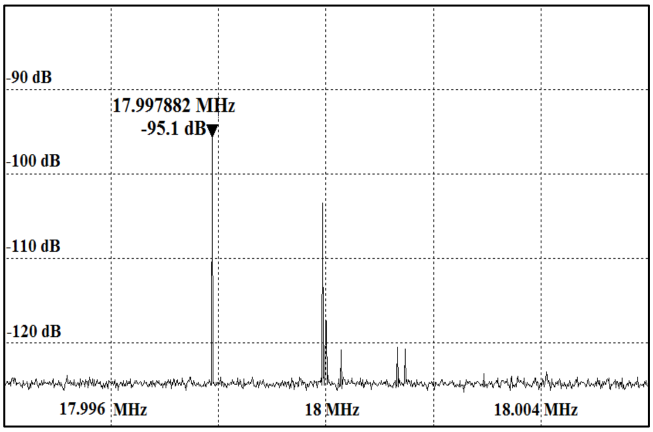

Fig. 7. Measured spectrum for Raman Anti-Stokes signal at room temperature (T=25°C)

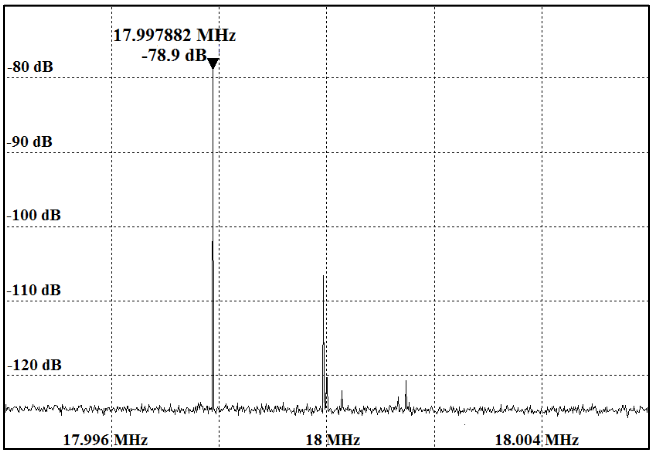

Fig. 8. Measured spectrum for Rayleigh signal at room temperature (T=25°C)

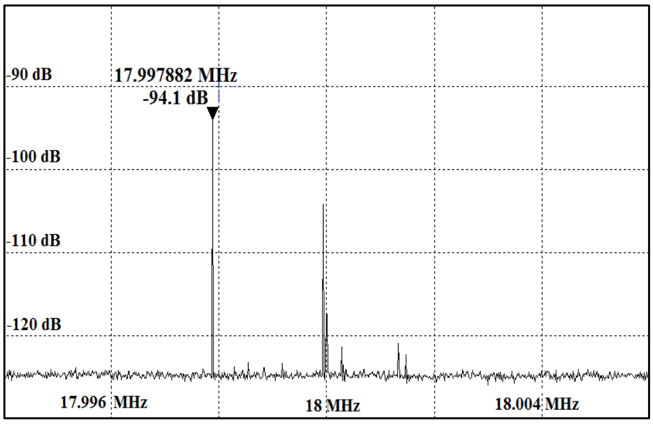

Fig. 9. Measured spectrum for Raman Stokes signal at room temperature (T=25°C)

In order to confirm the obtained results, the amplitude characteristic of the scattered signal using modeling are presented [3]. For 3 km optical fiber in room temperature, for wavelength λ = 1550 nm, the characteristic as the function of modulating frequency is presented in Fig. 10.

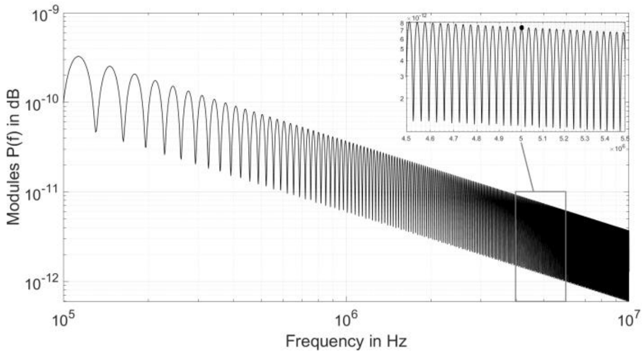

Fig. 10. Amplitude characteristic of Raman Anti-Stokes back-scattered signal obtained from the model [3]

6. Conclusions

In this paper, a low-cost system for the measurements of the intensity of back scattered light in 3 km single mode optical fiber was presented. The novelty of the proposed measurement system is the application of Software-Design Radio in it. SDR acts as a low-cost network analyzer. In order to implement the SDR in this approach, the high frequency carrier was modulated by the signal of back-scattered light. This concept was successfully validated for a single modulating frequency, and now the complete OFDR system for temperature measurement in long optical fiber with low power continuous lasers is ready to be implemented.

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