GAMMA RADIATION EFFECTS IN FIBER-OPTIC DIGITAL COMMUNICATIONS

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Abstract

The paper deals with the gamma radiation effects on the fiber-optic performances in the real digital signal communications link. Plastic-clad silica (PCS) fiber was used in the link, and it was irradiated by the gamma radiation source (^{60}Co). Different wavelength LEDs were used as light sources. Optical power was measured by the optical-power meter, and the detected signal was monitored by the sampling oscilloscope. The radiation-induced loss was determined by a new method: by processing the discrete data obtained by the sampling oscillosscope. Two groups of results obtained in the experiment indicate the validity of the measuring method.

1. INTRODUCTION

Nuclear radiation effects on optical material performances have been in the focus of many researchers for a long time [1]-[8]. There exists a permanent interest for optical cables in communications, in signal processing as well as in other opto-electronic problems, so that there is a number of papers dealing with this subject. Most of the papers concern the advantages of optical fibers in the data transmission, neglecting the influence of the severe disturbing environment and nuclear radiations. However, the disturbing effects during and after the irradiation are certainly more complicated generally, as well as in the period of transmission. The starting point in studying the optical fiber exposure to nuclear radiation (gamma radiation) is induced loss, usually expressed as dB/km [1]. It depends on the number of photons captured by radiolithic electrons and holes generated by radiation photons. Electrons and holes released by the radiation occupy persisting traps in the core and behave as light absorption centers, e.g. colour centers [1]-[2]. In the gamma radiation process optical fiber induced loss mainly depends on the existence of the colour centers generated by irradiation. The experiments described in [1] show that the induced loss of the PCS fibres tends to saturate as the absorbed dose increase. It may be interpreted that the generation and decay of colour centres are proceeding during the steady-state irradiation; the recovery of transmission after the irradiation is extremely fast.

Fibers with pure undoped synthetic quartz core, exhibit the recovery from radiation feature. Besides that, the so-called “light induced annealing” is present in many irradiated fibers, generally, [3]-[4]. This effect occurs when the light propagates through the fiber. In that case the recovery rate of irradiated fiber is much faster than without the light propagation.

Recovery rate depends also on the optical power density transmitted through the fiber. For the PCS fiber at 850 nm, higher optical power results with faster recovering. It is proved also that for equal optical powers light annealing is faster on shorter wavelengths [4]. The product of the transmitted power and the time needed for half of the maximum light induced recovering is a constant, specific for the given fiber type [7].

Temperature dependence of light induced recovering is evident, too [4]. The recovering is faster at 45^0C than at 20^0C. This was proved for the PCS and the FLCS fibers in the wide temperature range from -80^0C to 80^0C, [7].

The core composition affects also the behaviour of optical fiber during and after the radiation. The pure silicate core fibers differ much from the Ge doped core fibers in the value of the annealing light power (note that it is the conclusion for the total absorbed dose) [5]. GeO_2 doped fiber exhibits high loss increase due to the gamma radiation in the case below the room temperature, while fibers with pure silicate core show relatively small loss increase under the same operating conditions [6].

This paper deals with the gamma radiation effects on the communications link performances. Induced loss was observed during and after the radiation. No excess annealing has been supposed.

Section II contains the description of the experiment setup. The determination of the radiation-induced loss using digital signal processing procedure is explained in Section III. Finally, the results obtained for different light sources and for different bit rates, are given in Section IV.

2. THE EXPERIMENT

Performances of communications link may be spoiled in the severe radiative environment. As the PCS optical fibers are supposed to have good immunity to radiation, reliable testing of their characteristics has to be done in such conditions. For that purpose a PCS multimode optical fiber (SUHNER FO 03220) of the total length of 200 m was checked in a short optical link. This fiber had a 200 μm diameter silica core, a 90 μm thick silicone rosin cladding, and

a 600 μm diameter protective coating. A part of this fiber (25 m for the first, and 20 m for the next two experiments) was wrapped on, for this occasion specially designed, mandrel (∅ 2.5 cm) and put into the 8cmx8cm chamber.

The irradiation of the fiber optic samples was performed in Standard Dosimetry Laboratory, in the Institute Vin~a (Belgrade, Yugoslavia), by using ^{60}Co radiation field. Gamma radiation sources had collimated installations so that an exposure rate from the radiation scattered by the environment did not exceed +5% of the direct radiation. The exposure doses for gamma radiation were measured with DI/4 and DL/4 PTW dosimeter (Freiburg, Germany) with ionization chambers M23331. The errors of the dose measurement were less than +2%. The dose rate in air during the irradiation was 47.699 Gy/h (calculated to doses in the material of interest — SiO_2 in our case).

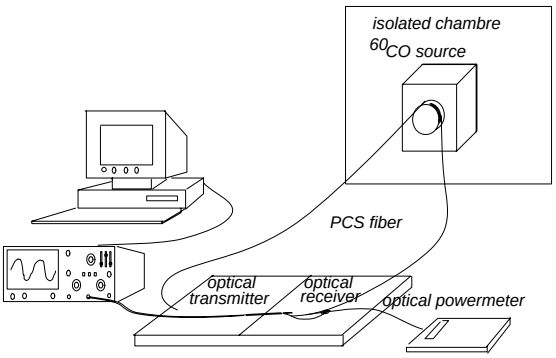

Figure 1. The experimental setup.

The communication link used in the experiment consisted of optical transmitter, optical fiber, and optical receiver. The data generator formed the pulse train with adjustable bit rate up to 10 Mb/s. The light sources were IR diode (820 nm, 1 mW), red LED (660nm, 120 μW), yellow LED (570nm, 120 μW), and a green LED (550nm, 120 μW). Received data were monitored and acquisited by a sampling oscilloscope (8 bit/1024 samples), at the photodetector output (see Fig. 1), and were processed on the computer.

The experiments were performed in strictly controlled environment. Temperature was 21(°C), humidity 28%, and atmospheric pressure 135 kPa.

3. DETERMINATION OF THE RADIATION-INDUCED LOSS

The radiation-induced loss (IL) is equal to the ratio $IL=P_B/P_A$ [5], where P_B and P_A denote average optical powers of signals before and after radiation, respectively. According to

Parseval's theorem, the actual signal power is equal to the total power of the dc component (if it exists) plus the power of all the ac components. So, if we could measure all relevant harmonics of the receiving signal we will be able to determine equivalent power and, consequently, the induced loss, using the following expression

$$IL = \left(\sum_{k=0}^{K} U_{Bk}^2 \Big/ \sum_{k=0}^{K} U_{Ak}^2 \right)^{\frac{1}{2}} \tag{1}$$

where U_{B0} and U_{A0} denote dc components while U_{Bk} and U_{Ak} are the rms voltages of k=1,2,...,K harmonics at the photodetector output, measured before and after (or during) radiation, respectively. The determination of the spectral components may be performed using digital signal processing (DSP) [8]. However, the exact determination of harmonics could be very doubtful in DSP due to some systematic errors. Besides the quantization noise, due to the finite number of quantization levels, second imperfection in the processed data is the spectral leakage as a consequence of nonsynchronous sampling [9]. Sometimes, it is impossible to obtain sampled version of a signal that is synchronous with the sampling clock. Reasons for that are either in the lack of digitizer perfect clock, or in the fact that signal to be processed has some interharmonics.

One of the techniques that improves the consequences of the spectral leakage is the use of different windows [8]-[9]. As there are a lot of promising windows, it is necessary to have some criteria for choosing the optimal one. However, exact criterion does not exist, but there are some of them that indicate which window could be useful in a specific circumstance. Solomon [10]-[11] investigated the connection between the signal-to-quantization noise ratio (SNR) and the parameters of window function used. In the case of the discrete Fourier transform (DFT) application the SNR_{DFT} for a single frequency bin, [11], is found to be:

$$SNR_{\mathrm{DFT}} = \frac{A}{Q}\sqrt{\frac{12 \cdot N}{\pi \cdot ENBW}} \tag{2}$$

where A is the amplitude of the observed harmonic, Q is the LSB value of the converter, N is the number of samples, while ENBW denotes the equivalent noise bandwidth of the window.

The values of the ENBW can be found in the text-books and papers related to the digital signal processing [8]-[9]. The amplitude of the first harmonic is usually the highest one, and it gives the highest SNR_{DFT}. The more samples of a signal we have, the higher the SNR. The more quantization levels converter has, the smaller the LSB value, and the higher the signal-to-noise ratio. Equivalent noise bandwidth has the lowest value (ENBW=1)for the rectangular (or "do nothing") window. For all other windows this value is greater than one.

Unfortunately, windows with high peak sidelobe attenuations have relatively big values for ENBW, which means lowering of the signal-to-noise ratio [12].

For the specific SNR_{DFT} value, a window is properly chosen if it has the first sidelobe attenuation greater than the accounted value for SNR. By using the window with lower sidelobe attenuation, processing will make worse signal-to-noise ratio than it could be in the ideal case. Equation (2) happens to be a convenient criterion for making the list of windows, candidates for controlling the spectral leakage. Particularly, for the 8-bit sampling oscilloscope converter with 1024 samples in a sequence and amplitude of A (in Volts) in this experiment, the SNR_{DFT} value, evaluated in dB, is

$$SNR_{DFT} = 64.05 + 20\log(A) - 10\log(ENBW) \quad (3)$$

According to Eq. (3), the three- and the four term Blackman-Harris (BH-3 and BH-4) windows could be the proper choices for the data provided by the oscilloscope. BH-4 has the 92 dB first sidelobe attenuation, and the ENBW=2.01. For the experiments mentioned above, sequence of 1024 samples includes 40 periods of signal in the 10 Mb/s case (and 20 or 10 periods in 5 Mb/s and 2.5 Mb/s cases, respectively). Under these circumstances, harmonics could be detected with great accuracy [12], so the window function may successfully control the leakage.

The radiation-induced loss was evaluated in the following way:

- The oscilloscope gives the sampled version of the photodetector output voltage. Due to the nature of the photodetection process, this voltage corresponds to the input optical power $\left(U_{\text{det}} \cong P_{\text{opt}}\right)$.
- From the measured data and applying an appropriate window function, amplitude spectrum (corresponding to the voltage value) is being derived by using the discrete Fourier transform.
- Induced loss is then derived using Eq. (1).

4. EXPERIMENTAL RESULTS

4.1. First experiment

For the purpose of investigating the gamma radiation influence on the digital transmission through the real fiber optic link, three experiments were done. In the first two, the PCS cable has been excited by the infrared diode (IR: 820 nm, 1 mW). The loss induced during the interval of 4300 seconds of radiation, and 320 seconds after, was measured by the optical power-meter calibrated at 820 nm. Sampled version of the received data was used in the

computer calculations of the loss, according to Eq. (1). Calculated values of the loss (by using the BH-4 window) slightly differ from the measured data, as we can see in Fig. 2. This difference may be the consequence of different photodetectors, the first one in optical power-meter, and the second in the optical receiver.

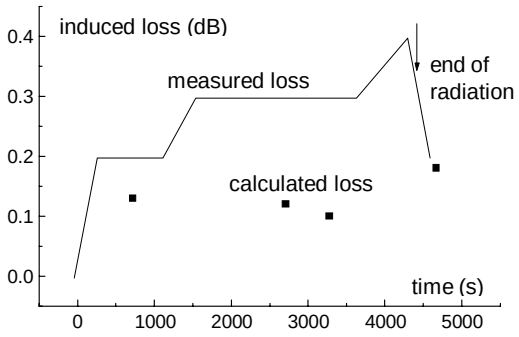

Figure 2. Induced loss during the first experiment (IR diode: 820 nm, 1 mW).

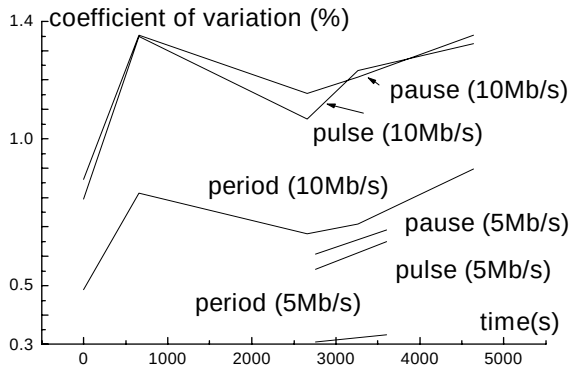

Figure 3. Pulse width coefficient of variation.

The second phenomenon under investigation in this experiment was the change of pulse width during irradiations. The coefficient of variation (the standard deviation compared with the mean value) for the pulse/pause width (dashed/dotted curve), and for the pulse period (solid curve), are depicted in Fig. 3.

4.2. Second experiment

The second experiment was performed three months later in the same environment, with the same equipment and on the same cable. This time 20(m) of the cable has been wrapped on the same mandrel. The gamma radiation source described above, was used during the interval of 6000 seconds.

The PCS fiber was excited by the same IR LED. Data generator gave the binary RZ pulse sequences of different rates. The pulse width slightly differed for various bit rates (pulse-to-period ratios were 0.6, 0.5, and 0.55 for bit rates of 10 Mb/s, 5 Mb/s, and 2.5 Mb/s, respectively).

For different duration of radiation, induced loss is acqiusited and determined using the DSP method proposed, and it is shown in Fig. 4. These results were obtained for the Blackman-Harris window. Bit rates used in the experiments could not influence some severe degradations of the transmitted signal.

Results obtained by the sampling oscilloscope are compared with the same given by the optical power-meter, Fig. 5. It is obvious that induced loss dependency from duration of radiation are of the same shape. The applied windows (BH-7, BH-4, Blackman, rectangular) gave similar results. Explanation for that is in the fact that signal was “well behaved”, meaning that there where enough periods of rather “calm” signal [12]. The BH-4 gives slightly highest induced loss. Scattered plot corresponds to the loss measured by the optical power-meter, only for 10 Mb/s.

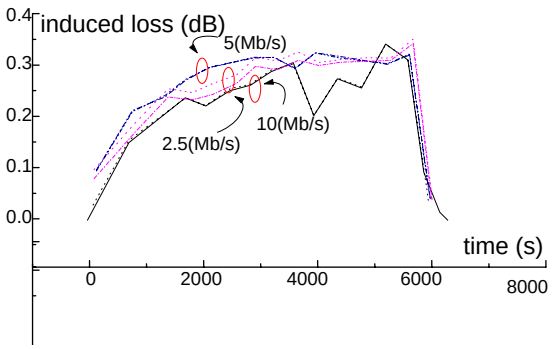

Figure 4. Induced loss for the IR range (820 nm, 1 mW) determined by the oscilloscope.

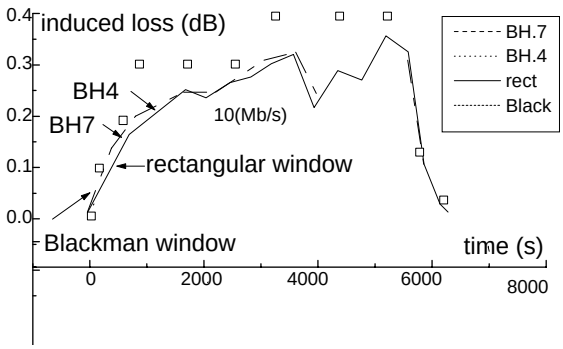

Figure 5. Induced loss determined by the oscilloscope and measured by the optical power-meter.

Figures 4-5, indicate that, after the radiation had stopped, fiber recovering was fast for the IR signal. During that period (from 6000 to 6580 seconds), very intensive redistribution of harmonics was noticeable.

The amplitude spectra of received pulses, normalized at the first harmonic, are depicted in Figs. 6-7. Comparing these diagrams one could conclude that the radiation produces the change of the harmonics distribution in the received signal, as it is intuitively expected.

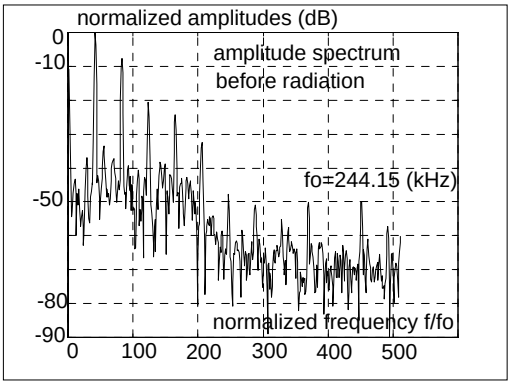

Figure 6. Amplitude spectrum of the detector signal before radiation.

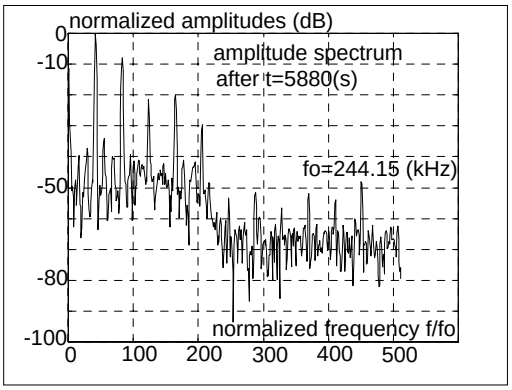

Figure 7. Amplitude spectrum of the detector signal after 5880s of radiation.

4.3. Third experiment

The third experiment was done 24 hours after the second one, in the same environment using red (660 nm), yellow (570 nm) and green (550 nm) LEDs (all having optical powers of 120 nW) as optical sources. For those sources, optical power-meter has been used. Measured optical power, and corresponding induced loss are depicted in Fig. 8, and Fig. 9, respectively.

It is obvious that induced losses for those wavelengths differ very much from the same for the IR range. Maximum loss for the red diode was 4-5 dB. Measuring of the loss for the optical signal in yellow range was very interesting, for the loss had been increasing very fast. In 100 seconds, in the interval between 1830 and 1930 seconds from the beginning of radiation, induced loss was increased by 1.4 dB.

After the 4375 seconds of radiation, the induced loss was monitored during the recovering period. This time, fiber had not recovered so quickly. The PCS got its nominal performances in the IR range two hours after the end of radiation. For the red range, and after the third experiment, fiber got its nominal optical power level, after nearly five ours. Some residual loss for the signal in yellow range (and lower bit rates, i.e. lower pulse-to-period ratios), however, was noticeable nearly two months after the end of radiation.

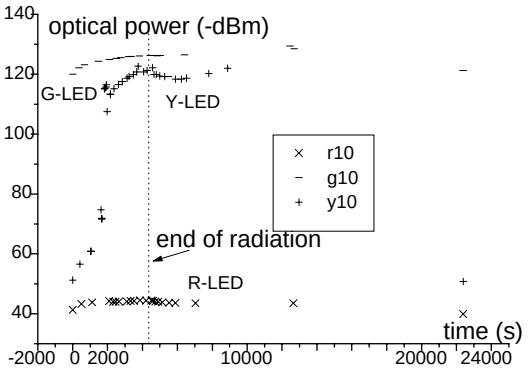

Figure 8. Optical power measured by the optical power-meter (R, G, and Y diodes).

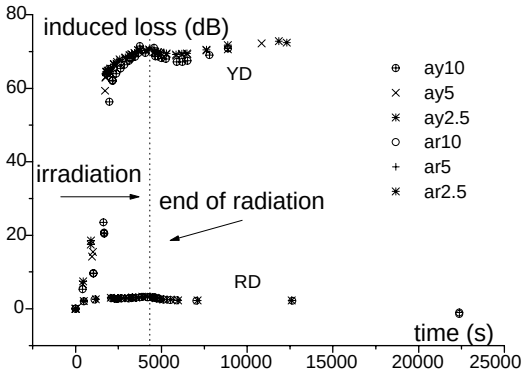

Figure 9. Induced loss measured by the optical power-meter (R, G, and Y diodes).

5. CONCLUSION

The experiments described confirm that gamma radiation introduces degradations in the digital communications over PCS optical fiber: the increased loss, the change of pulse width and the redistribution of harmonics in the received signal. It is obvious that these degradations, though not so intensive for the IR range, can produce disturbances (jitter, for instance) and errors in communications.

The results indicate the existence of the saturation effect in the induced loss during the radiation. According to [2], this is the consequence of the existence of colour centers.

The actual change of induced loss show relatively small disturbances which, according to [5], belong to mechanical relaxation and optical noise in the equipment. Compared to the known results [1],[4], these imperfections are not so intensive.

Induced loss is especially high for the optical signal in yellow range. In the first two experiments, fiber had fast recoveries (for optical signals of all of four wavelengths). The third time, experiment was repeated with less than 24 hours pause. The recovering time depends on the total dose of radiation that fiber had got during the experiments, so the recovery process, under normal conditions, was relatively long.

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