DINAMICS OF AMORPHOUS DIELECTRICS LYUMINESCENCE INDUCED BY PULSE ELECTRON BEAM

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A method has been developed and experimental investigation conducted on time dependence of intensity of the cathodoluminescence (CL) induced in technical dielectric materials by high-energy pulse electron beam. At a LU-10 accelerator, the optical path and measuring channel were designed for remote recording CL signal. As optical sensor, a SFH203P photodiode was used with an amplifier on the basis of a HS special-purpose op amps. Preliminary study of conditions of CL registration was performed at a bench. For a number of materials, coincidence of signals of the beam current and CL, as well as dependence of CL amplitude from thickness of the CL radiator have been established. Possibility is shown to use CL signal induced by scanned electron beam for on-line monitoring the beam current density and absorbed dose distributions on the surface of a processed object.

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INTRODUCTION

Nowadays, radiation technologies with the use of electron accelerators and γ-plants are among of those the most promptly developing worldwide [1]. Considerable part of the radiation installations provides the processes of radiation sterilization of the medical devices, and also of outputs of the pharmaceutical and food industry [2]. Radiation sterilization is regulated with the international standards (see, e.g., [3]). The principal requirement of a sterilization regime is providing the distribution of the radiation absorbed dose with its minimum $D'_{\min}$ and maximum $D'_{\max}$ values over the volume of a processed loud meeting the conditions

$$D_{st} < D'_{\min}, \quad D'_{\max} < D_{\max}, \tag{1}$$

where D_{st} – is the sterilizing dose, $D_{\max}$ – is the maximum tolerable dose keeping the specified characteristics of the end- product.

To provide the uniform dose distribution at an electron accelerator complying with the condition (1), the treatment is performed with scanned beam at simultaneous movement of the product, placed into a transport container, via the irradiation zone using a conveyor. In this work, the features of optical radiation excitation in the technical materials by scanned pulse electron beam (cathodoluminescence, CL), and also the conditions of application this effect for on-line diagnostics of regime of the industrial product processing are studied.

1. CL OF AMORPHOUS DIELECTRICS

1.1. MODEL

1.1.1. As a rule, product treatment by scanned electron beam is performed directly in the transport boxes, ordinary manufactured from cardboard. A sticky tape (the Scotch) maid on the basis of the polypropylene film is also the widespread constituent of the package. Both materials are the amorphous dielectrics. Commonly, the package thickness is much less than the electron range in its material, when the size of a processed object exceeds the cross-section of the beam. So the subsequent analysis will be restricted by the case of exposure of a thin plane layer of the dielectric to the normal flux of the accelerated electrons.

Feature of amorphous dielectrics as compared with those crystalline is presence of electron traps with high concentration in the prohibited zone. Depending on level depth relative to the bottom of the conduction band, it is adopted to subdivide the traps into shallow (ST) and deep (DT) ones [4]. It is considered also, that the shallow trap's depth, $\varepsilon_{ST} \sim kT$, where k – is the Boltzmann constant, T – is the temperature (°K), when those deep have the depth ε_{DT} ~эВ. It should be noted, that the traps division into shallow and deep ones is rather relative, because their actual depth distribution seems to be quasicontinuous [5]. At the same time, such approach allows to mark out the principal processes determinative the CL yield, particularly its dependence from the time, and also the temperature of a material [6].

1.1.2. Optical radiation excited in the amorphous dielectrics, exposed to the accelerated electrons, belongs to incoherent type of CL [7]. It is caused by interaction of the irradiation induced non-equilibrium charge carriers with the electron traps. So the electrons of a primary beam are losing their energy in the inelastic collisions with the atoms of a dielectric resulting in the transition of the recoil electrons from the valence band into the conduction band, and also in the hole formation in the valence band. For a period of $<10^{-9}$s, the irradiation induced non-equilibrium charges are thermalized and their mayor part is recombined right away through the non-irradiative channels. The remained free electrons are drifting nearly the conduction-band bottom interacing with the traps [4].

CL of a dielectric in the optical region can take place as a result of several pathways [6]:

- at direct trapping the non-equilibrium electrons from conduction zone into the deep traps;
- with intermediate accumulation of electrons at the shallow traps, thermally activated repeat transition into the conduction zone and following recapture by the deep traps;
- in consequence of radiative charge recombination.

The first process is caused by presence of electrons in the conduction zone injected directly by irradiation. Its de-excitation period does not exceed $\sim 10^{-8}$s. In the majority of cases, it provides the coincidence of luminescence with the action of the external electron flux. Such type of optical radiation is named *fluorescence.*

Termal release of the electrons from the shallow traps, and also recombination of the electron-hole pairs cause luminescence delayed relative to activating radiation by the period up to ~s and more (*phosphorescence)* [8]. Whence, the dependence of the CL intensity, induced with a pulse electron beam, from time can be presented in a qualitative form shown in Fig. 1. Thus, a fluorescence signal coincident with the beam pulse, is just a source of information on the beam current density and absorbed dose rate, when a delayed component of CL is background. So the accuracy of the absorbed dose assignment against the CL flux is determined by the ratio of intensities of the both CL components.

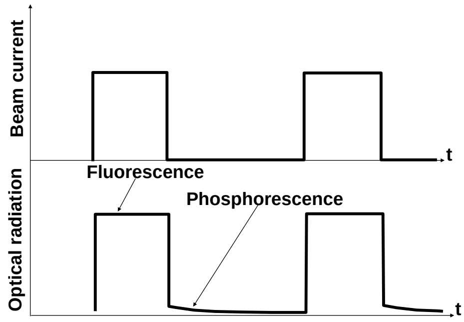


Fig. 1. Dynamics of luminescence excited with pulse electron beam

1.2. STUDY OF CL DYNAMICS

1.2.1. One of the conditions of a stable registration of CL induced with a high-current electron beam is radiation shielding of a measuring device. This problem can be solved by it distance from a region of the beam action on a CL radiator, and also by using a protective screen. Moreover, there is the problem to pick out a relatively week microsecond signal of a photoelectric sensor against the background of the high-power pulse electromagnetic radiation generated by the accelerator systems. Considering those conditions, the CL registration circuit, given in Fig. 2, was designed.

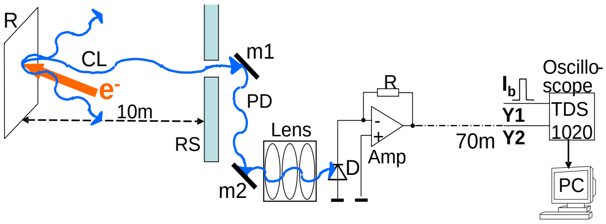


Fig. 2. Circuit for registration of pulse CL signal

The distance from an accelerator exit window to the front plane of a transport container, housing the samples of the CL radiators, makes 920 мм. It provided capability to record a signal of the CL radiator on-the-mitre of about 90°. A photodetector D (pin – photodiode) was situated behind a radiation shield RS, located at a distance of 10 м from a conveyor. For passing optical radiation, a loophole in the shield has been made. A periscopic device PD comprising the two mirrors, m1 and m2, was positioned just behind the shield. The luminous flux at its exit was focused on the sensitive surface of the photodetector using an objective Lens. The photo of the elements of the CL signal registration tract comprising the periscope, photodiode and its power supply, is presented in Fig. 3.

Fig. 3. Exit devices of the optical tract

1.2.2. In Fig. 4, the scheme of the optical tract implemented in the experiment is given.

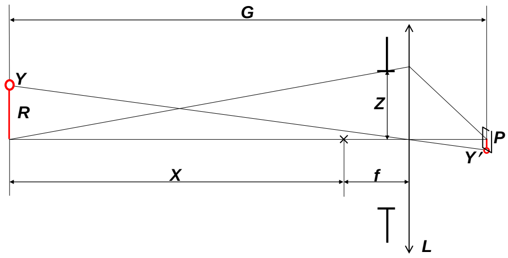


Fig. 4. Layout of optical tract for CL signal recording

The sensitive surface P of the photodiode is located at a distance G from the radiator R. *Y* – is the linear size of the CL region ("the beam imprint"), Y^1 – is the size of its image at the sensitive surface P. The objective can be represented as a single lens L. Its focal distance, *f*, can be determined using the formula:

$$f = k \cdot G/(1+k^2), \qquad (2)$$

where *k* – is the coefficient of the image linear enlargement

$$k = f/x, \qquad (3)$$

x – is the distance from the object to the front focus point.

The illumination of the photodiode *E′* depends from *k* as

$$E'(k) = i \cdot A^2/(1+k)^2, \qquad (4)$$

where $A = 2Z/f$ – is the relative inlet hole, *i* – is the brightness of the radiator.

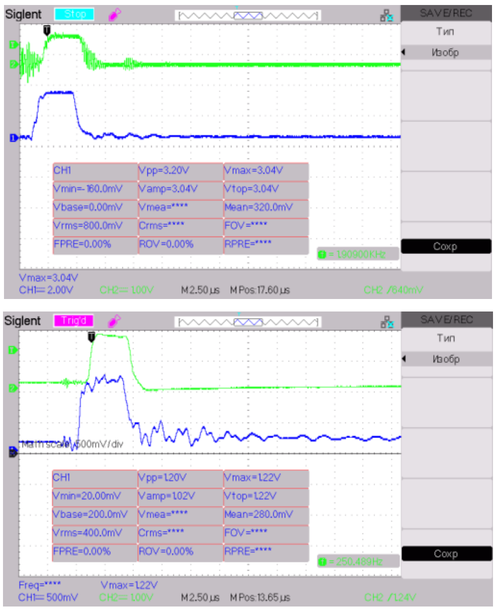
Thus, at a distance to radiator of 10.5 m, the diameter of the beam imprint of about 100 мм and a photodiode with sensitive surface size of 2.5×2.5 мм, the objective is necessary having focal distance no more than 250 мм and the highest possible lens speed.

1.2.3. Preliminary study of the CL registration conditions was carried out at a bench. A beam imprint was imitated with the help of a matrix from 26 LEDs of 2830 type. The matrix was stimulated with the voltage impulses at a width of 4 µs. A number of HS high-sensitive photodiodes were tested as a photoelectrical sensor. The pin-photodiode SFH203P, providing the pulse rise and fall times no more than 5 µs, has demonstrated the best results. A photocurrent amplifier Amp was developed with the use of the dedicated microcircuits (Analog Devices). The bench-test has shown, that an objective Yongnuo 50/1.8 having the maximal lens speed provides the greatest magnitude of the desired signal.

1.2.4. In the course of the experimental investigation, a signal from the exit of the Amp amplifier stimulated the input of a digital oscilloscope Tetronix TDC1020, located in a control room of the LU-10 accelerator [9] at a distance of 70 м from an irradiator's vault. A signal from a magnetic induction sensor of pulse beam current stimulated the second input of the oscilloscope. As the luminescent radiators, polystyrene with a scintillating additive, and also a system "cardboard (CB)+ polypropylene (PP)", the latter in the form of tape 32 µm thick and bent into *n* layers, were used. The radiator patterns were positioned in the transport containers and moved into the irradiation zone using the conveyor (Fig. 5).

Fig. 5. CL signal generated with electron beam of LU-10 accelerator

In Fig. 6, the characteristic oscillograms of the CL signals for every type of the radiator (the bottom sweep) are displayed. The upper sweep corresponds to the signal of the beam current. It is seen, that the both signals practically coincide within the uncertainty of the record conditions.



a

b

Fig. 6. Oscillograms of CL signals, induced by electron beam in polystyrene (a) and "CB+PP" system (b)

In Fig. 7, the dependence of the CL signal magnitude from the sickness of the PP radiator is given. It is obvious, that the dependence obtained is close to linear, as it follows for the case of a thin radiator [6].

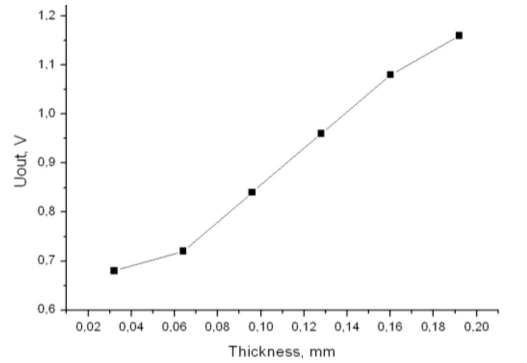


Fig. 7. Dependence of CL signal magnitude from thickness of PP radiator

2. MONITORING OF BEAM SWEEP PROFILE

2.1. Accelerators with scanning beam operating in a regime with pulse duration of $10^{-6}...10^{-5}$ s and particle energy of up to 10 MeV are widely used in industrial processing [2]. The mean beam power of such installations makes of about tens kilowatt, when the necessary treatment dose of about tens kilogayss (e.g., at radiation sterilization of medical devices).

As investigations have shown, practically every package material of a product processed with an electron beam can be regarded as a luminescent radiator. In particular, cellulose being a basis of such widespread package material as CB has this property [10]. Taking into account the beam power and dose obtained by an object, its dwelling time in the irradiation zone does not exceed commonly several sec. At such conditions, the mayor contribution to the CL registration provides fluorescence.

As a rule, the beam parameters during processing are held invariable, and to provide the necessary absorbed dose the treated products are moved through the irradiation zone with specified velocity. Apart from the conveyor speed and electron energy, the current density distribution .over the beam sweep on the object surface is one of the critical process parameters [3].

2.1.2. For the assessment of possibility of this parameter monitoring on the CL signal, a scheme demonstrated in Fig. 8 was used.

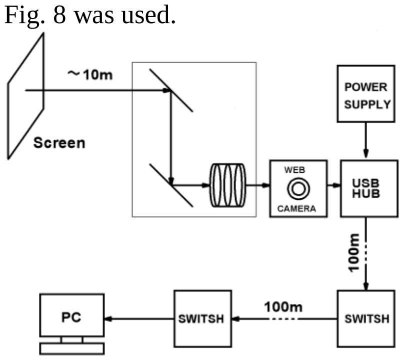


Fig. 8. Scheme for recording CL intensity distribution along beam sweep on object

In contrast to the scheme in Fig. 3, this time a photodiode was substituted with a digital WEB registrator. Its signal was transmitted using a twisted-pair cable via the USB HUB operated under a TCP IP protocol into LAN. Such an approach provided possibility to record in on-line mode the CL intensity along the beam scan in the conditions corresponding to a regime of the industrial product processing. The cursors with interval 5 cm were plotted on the carton along the beam sweep line. The CL profiles for CB (from the left) and a “CB+PP” system with the PP film 32 µm thick (from the right), obtained in such conditions, are presented in Fig. 9. It is evident, that presence of the PP film increases considerably the CL yield.

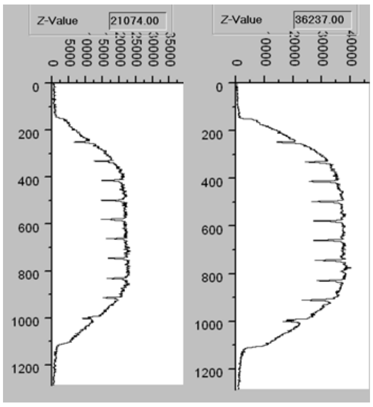


Fig. 9. Distribution of CL intensity along beam scan (with the cursors)

3. ABSORBED DOSE MONITORING

As it follows from a CL model stated in the work [6], the density of the fluorescent photon flux is proportional to the absorbed dose rate Whence one can expect, that the photon fluence for the target exposure to the beam is proportional to the absorbed dose. To check this assumption, in the scheme presented in Fig. 8 the WEB registrator was replaced by a digital reflex camera Canon operated with exposure of 2 s. As a target-radiator, a vertical PP strap by 32 µm in thickness was fixed on a CB sheet. Parallel to it, a segment of a B3 dosimetry film 18 µm thick on the basis of the cellulose triacetate (GEX Corporation, USA) was positioned. In the following experiment, the electron energy maid 8.4 MeV, and also pulse beam current – 810 µA, impulse frequency-250 Hz, beam scanning frequency 3 Hz, scan width at the target 36 cm. The obtained beam imprint was digitized in an Origin environment (Fig. 10).

The B3 film was processed by a standard technique [11]. The distributions of the absorbed dose and CL intensity obtained in such a way are displayed in Fig. 11. It is seen, that the both curves coincide within the accuracy of the absorbed dose measurement (±6%).

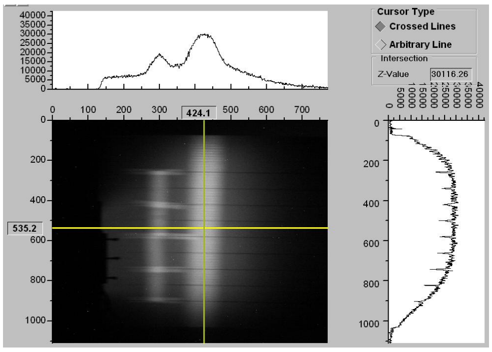


Fig. 10. Luminescent image of “CB+B3+PP”system (below on the left). Crosscut profile of the CL intensity (at the top). Longitudinal distribution of CL intensity in “CB+PP” system (on the right)

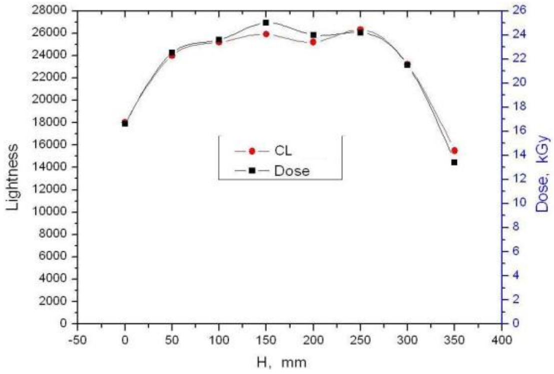


Fig. 11. Distributions of CL intensity in “CB+PP” system and absorbed dose along the beam scan

CONCLUSIONS

The coincidence of pulse signals of the beam current and fluorescence observed in the experiment makes evident that the flux of the optical radiation can be an adequate source of information on distribution of the beam current density and absorbed dose on the surface of the object under processing.The yield of the optical radiation can be readily controlled by option of radiator’s material and its thickness without essential influence on the volumetric dose distribution in a processed product.

The proposed scheme of optical record of the scanned beam imprint in the digital form provides possibility its transfer for a distance of up to 100 m and following signal processing by any computer of the net. By using the preliminary installed SW and proper calibration, one can reproduce the width and position of the beam scanning zone, and also absorbed dose distribution on the surface of the processed object.

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ДИНАМИКА ЛЮМИНЕСЦЕНЦИИ АМОРФНЫХ ДИЭЛЕКТРИКОВ, ИНДУЦИРОВАННОЙ ИМПУЛЬСНЫМ ПУЧКОМ ЭЛЕКТРОНОВ

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Разработана методика и проведено экспериментальное исследование зависимости от времени интенсивности катодолюминесценции (КЛ), возбуждаемой высокоэнергетичным импульсным пучком электронов в технических диэлектрических материалах. Для дистанционной регистрации сигнала КЛ на ускорителе ЛУ-10 разработаны оптический и измерительный тракты. В качестве фотоприемника КЛ использован фотодиод типа SFH203P со специально разработанным усилителем. Предварительные исследования условий регистрации КЛ проведены на стенде. Для ряда материалов установлено совпадение сигналов пучка и КЛ, а также получена зависимость амплитуды сигнала КЛ от толщины радиатора. Показана возможность использования сигнала КЛ, возбуждаемого сканируемым пучком электронов, для on-line мониторинга распределения плотности тока пучка и поглощенной дозы на поверхности обрабатываемого объекта.

ДИНАМІКА ЛЮМІНЕСЦЕНЦІЇ АМОРФНИХ ДІЕЛЕКТРИКІВ, ІНДУКОВАНОЇ ІМПУЛЬСНИМ ПУЧКОМ ЕЛЕКТРОНІВ

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Розроблено методику і проведено експериментальне дослідження залежності від часу інтенсивності катодолюмінесценції (КЛ), що збуджується високоенергетичним імпульсним пучком електронів у технічних діелектричних матеріалах. Для дистанційної реєстрації сигналу КЛ на прискорювачі ЛУ-10 розроблені оптичний і вимірювальний тракти. Як фотоприймач використаний фотодіод типа SFH203P зі спеціально розробленим підсилювачем. Попереднє дослідження умов реєстрації КЛ проведено на стенді. Для ряду технічних матеріалів встановлено збіг сигналів пучка і КЛ, а також отримано залежність амплітуди сигналу КЛ від товщини радіатора. Показано можливість використання сигналу КЛ, індукованого скануючим пучком електронів, для on-line моніторингу розподілу щільності струму пучка та поглинутої дози на поверхні об’єкту, що оброблюється.

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