PENETRATION OF IR LASER RADIATION IN HUMAN TEETH: ANGULAR DISTRIBUTION OF LIGHT AND COEFFICIENTS OF ABSORPTION AND SCATTERING

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Summary. We have developed techniques and practical set-ups and have studied comparatively the propagation of a traditional 1.06 μm laser emission and a non-familiar 1.36 μm line of the widespread Nd:YAG laser in human dentin (pure) samples and in combined enamel-dentin samples. The wavelength 1.36 μm can be obtained with high energy output using some non-complicated modification of Nd:YAG laser, as it is further shown in this work. This wavelength is of potential interest for application in dentistry due to its known higher absorption in comparison with a 1.06 μm line in human soft tissues. Thus, it is possible that it would also be highly absorbed in hard dental tissues. As a result of our investigation on human pure dentin samples and combined enamel-dentin samples, we have obtained the following parameter estimates: 1) reflectivity of these two tissue substances; 2) the full coefficient of the extinction and angular distribution of the intensity (in the cross-sections) of the penetrated light in the examined dental substances; 3) as a main point, combining the optical and calorimetric techniques, we have obtained separately the absorbed and the diffused part of the light, and have calculated separately the coefficients of absorption and scattering in the dentin. The study is based on in vitro examination of fresh teeth samples from participants from Bulgaria, Sofia region.

Key words: *Nd:YAG laser treatment, human tooth, dentin's light absorption*

INTRODUCTION

Lasers traditionally are of interest for use in different healthy procedures, including treatment of oral tissues. The technique has an enormous potential and, therefore, is expected to undergo further development [1, 2, 3, 4, 5]. As a rule, low-intensity laser radiation (with well proven effect mainly in the red and near-infrared (IR) spectral region) is used to prevent propagation of caries lesions and to treat periodontal dental problems [6, 7]. Also, the application of the high power laser radiation for the treatment of caries or other defects in hard tooth tissues, using power laser radiation is considered as a perspective procedure [3, 4]. In the different medical treatment procedures using lasers, knowledge of the exact dose is very important, as well as the parameters of illuminating radiation inside the tissues. Increase of the dose leads to adverse side effects. Thus, the application of laser radiation necessitates a careful physical investigation. Good knowledge of the penetration of the laser radiation in the dental tissues – depth, absorbed and scattered parts, characteristics of the diffusion, dependences by the light wavelength, polarization, etc. is also required. That would allow formulating manners to calculate the dose of the absorbed light into the depth of the tissue. [8, 9, 10, 11, 12]. Before the medical procedure, on the base of the knowledge of the light characteristics inside the tissue, manly determined by calculation, it is necessary to estimate the therapeutic effect in combination with the heating effects in order to prevent the destruction or necroses of the treated tooth's part during the therapeutic procedure. The short discussion given below shows that the accumulation of experimental data from investigations, related with the penetration of the laser light into human dental tissues, is of both scientific and direct practical interest. Accumulation of data from laboratories from different world regions, may be useful in establishing how human teeth tissues, including the dentin, differ as related with the composition of the corresponding traditional foods.

The aim of this work, following the noted point below, is on one hand, to reach the scientific knowledge, concerning the problem of laser propagation in dental tissue and, on the other hand, to be a contribution in the development of the possibilities (for the dentists, medical engineers, etc.) for practical estimation of the energetic parameters of the light in the treated part inside the tooth. (Our study shows that the variation of the characteristics of the same type of teeth is so large, that we can speak only for 'evaluation", i.e. with a precision of order of ~ 20-30%). On the base of developed approaches and instrumentations, our measurements permit to obtain and we present the series of systematized date, concerning the use of laser light in IR and visible spectrum about: 1) reflectivity of human tooth dentin; 2) the spatial distribution of the intensity in the cross-section of the penetrated light intensity in the tooth's dentin; 3) as a main point, combining the optical and calorimetric techniques, we have obtained separately the absorbed and the diffused part of the light that permits to calculated the coefficients of absorption and scattering in the dentin. Our investigation compares the laser light of two wavelengths, easily generated with a Nd:YAG laser emitting at 1.06 μm and 1.36 μm. This laser is commercially available, widespread in many laboratories and medical institutions and is cheaper. The typical commercially available Nd:YAG laser is produced for generation at 1.06 μm. However, the modification to generate at 1.32-1.36 μm is not complicated [13]. As it is well known, the light at wavelength 1.36 μm (more generally, in the range 1.4-1.5 μm) is absorbed better in the human tissue than the light at 1.06 μm and, thus, it is of interest for biomedical application, including dentistry. In vitro teeth fresh samples from participants from Bulgaria, Sofia region, were used in this study.

MATERIALS – SAMPLES FOR THE INVESTIGATION

Special samples for the investigations were prepared by cutting and forming as a parallelepiped with a good plane wall pieces from dentin part of the freshly extracted human tooth. The prepared samples (photograph in the inset of Fig. 4 below) had cross-section of ~ 2,5 x 2,5 mm and thickness of 1mm, 1.3 mm, 1.6 mm. Strictly speaking, the measurement showed that there was difference (up to ~ 30%) between the measured light propagation parameters for the samples of different teeth, also from different parts of one tooth. Nevertheless, the averaged results that were obtained can be used for the noted practical evaluations. The samples were specifically chosen to have no defects. They were not chemically treated after the preparation. All surfaces of the tooth samples were polished after cutting. The cutting and polishing was carried out with diamond scalpers of "Komet" Company with turbine tip and incessantly cooling with matter.

PRINCIPLE OF INVESTIGATION AND APPARATUS – GENERAL DISCUSSION AND PRESENTATION

The main question in this investigation was how to evaluate the magnitude of the coefficients of absorption and scattering of the laser light at the noted up wavelengths. The principle of the solution was the following: The incident light on the sample when passes through the sample loses part of its energy due to absorption, scattering and reflection. We could determine easily the reflected part by measuring the coefficient of the reflection of the wall of the sample-parallelepiped. The absorbed part of the illuminating energy could be evaluated by the heating of the sample of the absorbed laser light. The last measurement is possible, however, relatively complicated, due to the very small volume and mass of the sample (part of the human tooth).

In the work we have developed a specialized experimental set-ups that combined a laser with high precision with a very sensitive temperature electronic meter to study the diffused reflection and diffused penetration of the laser beam and to obtain (using the experimental data) separately the division of the lost energy as an absorbed and scattered part, and to calculate the coefficient of the absorption and the coefficient of the scattering of the laser light in the human tooth dentin.

On the base of our experience in specialized laser technique [13, 14, 15], we created the prism-selected flash-lamp pumped pulsed Nd:YAG laser that provides emission, tunable at the series of lines (1.06 μm, 1.32 μm, 1.34 μm, 1.36 μm, 1.44 μm) and, simultaneously, at two chosen line of this series [13]. The energy in the incident on the samples pulses of laser light (horizontal polarization), during the measurement, was made equal for both used wavelengths and controlled variably between 10 and 500 mJ (conveniently chosen for reliable measurement and in order to avoid the samples destruction). We also used He-Ne lasers, standard of ~ 5 mW emission and with high power of ~70 mW (at 0.63 μm) for some investigations – of the reflectivity, for the diffraction phenomenon and as a pilot-laser for the invisible IR emissions. The investigation of the penetration of the light in dentin for this laser has been reported in the literature, also by us [3, 8, 9]. However, there are many more aspects to be investigated – the action of a different wavelength, e.g. 1.36 μm, the influence of the variable properties of the dental tissue in different world regions, etc. Development and confirmation of the correctness of this new approach should be made in light of the accumulating data, investigating these differences in human tooth worldwide.

In our study we have used prepared by dental specialists (T.U., P.U) samples of dentin from freshly extracted human teeth.

The power (cw) and energy (pulsed regime) of the light was measured using high accurate commercial Powermeter (“Thorlabs”) and Joulemeter (Coherent). The temporal parameters were investigated with a two-channel storage 200 MHz oscilloscope in combination with receivers with nanosecond resolution based on pin diodes for IR (“Hamamatsu”) and for Visible. We used a special, temperature measurement electronic device that has as a sensor part, a transistor-based acceptor – sphere with a less than 1 mm diameter. This device, that assure a sensibility of 0.1 degrees and response time of order of part of the second, was very convenient to study the temperature change in our ~ 0.05 g tooth’s samples.

APPROACH AND NECESSARY MEASUREMENS TO DETERMINE THE COEEFFICIENTS OF ABSOBTION AND SCATTERING – PRINCIPLE AND DISCUSSION

To solve the main problem – point 3 below – the separate determination of the coefficients of absorption and of scattering – it is necessary first to determine the coefficient of reflection of the wall of the samples and quantitatively - the radial distribution of the scattered light in the samples. We have composed two systems to execute these two measurements and we measured the noted above quantities.

Nevertheless, as it is clear, that the coefficient of the reflection will depend on the preparation of the reflected wall of the samples, such investigation is necessary late, for correct determination of the loss of laser beam energy that passes through the dentin sample. Secondly, the angular distribution of the diffused propagated light inside and at the output wall of the dentin sample need to be determined in order to correctly determine the energy losses for the light, passing inside the axial cylindrical parts of propagation, for which the measurement is executed. Thirdly, by the noted combination of a laser beam illumination and high precision temperature measurer, using the measured light loses in the sample and its heating, we have calculated the coefficients of the light absorption and, taking into account the full energy decreasing for the light that passes through the samples, have determined the coefficient of the scattering.

MEASUREMENT OF THE COEFFICIENT OF THE REFLECTION

Schematically, the composed system is presented in Fig. 1. Using appropriate diaphragms (D in the Figure 1) with diameter of 2.5 mm, we separated from the laser beams, emitted by both lasers, theirs central parts with near homogeneous intensity distribution. The diaphragm was disposed at distance of ~ 20 cm from the illuminated tooth piece. The investigated tooth samples were disposed perpendicularly to the incident (that passed through the diaphragm) beam at the micrometric translated table. This allowed us in convenient manner to change the illuminated region and the samples. In the scheme, shown in Fig. 1, GP is a thin (~1 mm thickness) glass plate (30 mm x 30 mm) disposed at angle ~ 45° and centered with respect to the beam axis. GP reflects with its two surfaces a part of 8% to the Power-meter PM_2 that permits to calculate the power of the incident beam. The lens L_1 with a focal distance of 8 cm and large aperture – diameter of 6 cm focalize the beam through the sample, collect the reflected light and directed it after the reflection by the GP to the Power-meter PM_1. The long focal lens L_2 with a focal distance of 40 cm focalize the light on the acceptor head of the PM_1. When we known the powers, measured by PM_1 and PM_2, and taking into account the losses by the Fennel's reflection at the corresponding surfaces, it was easy to calculate the coefficient of the reflection.

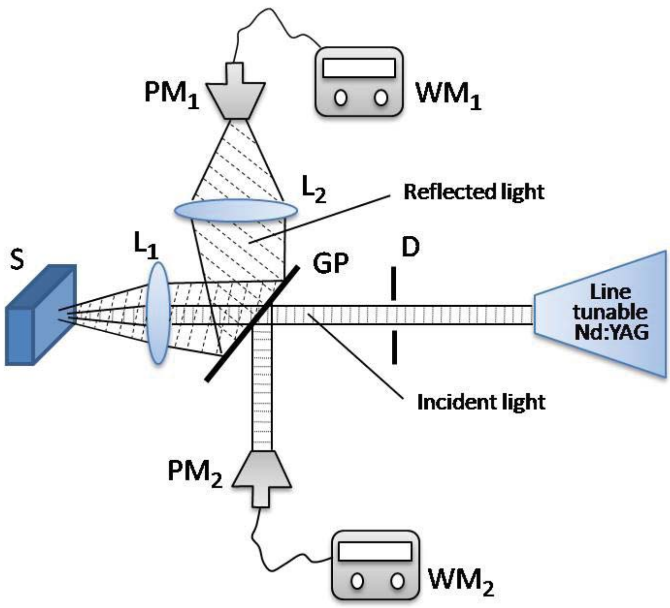

Fig. 1. Set-up for measurement of the coefficient of the reflection of the dentin samples. D is the 2 mm diaphragm, GP is glass plate, L_1 and L_2 are lenses with a focal distances respectively of 5 cm and 8 cm and with high aperture of 4 cm, S is a dentin sample, PM1 and PM_2 are power-meters for IR and Visible; the Nd:YAG laser in some measurements is changed by a 0.63 μm emission He-Ne laser

Using the described set-up and approach, we have measured the reflection coefficient for the 5 different samples and at 3 different points at each sample. The averaged results for the coefficient of diffused scattering (for the dentin sample walls) and for the wavelengths 1.36 μm and 1.06 μm coefficients were given to the value RD = 25% ± 3%.

We have not observed dependence on the polarization for the considered wavelengths.

MEASUREMENT OF THE RADIAL DISTRIBUTION OF THE LIGHT IN THE CROSS-SECTION

The principle of the measurement, and schematically two realized in the next study set-ups, is shown in Fig. 2(a) and Fig. 2(b). In Fig. 3, as an example, is plotted an actual photography of the experimental set-up, which represents the realization of the variant, given in Fig. 2(b).

The variants, given in Fig. 2(a) and Fig. 2(b) are especially convenient for use in the set-ups with a pulsed laser, when the spot intensity distribution can vary. As it is shown in the Fig. 2(b), on the opposite side of the incident beam was disposed a waveguide with an acceptance aperture of 4 mm. The working waveguide was fixed and translated by two micrometric tables with perpendicular directions of the motion. Thus, it was possible to center the waveguide aperture exactly along the incident beam axes (this first step takes place before the dentin sample is introduced). The optical signals for the receivers are taken from an averaged spheres (type Ulbricht's sphere) – noted as AS in Fig. 2(a) and Fig. 2(b) - to eliminate non-correctness of the measurement from eventual variation of the intensity distribution from pulse to pulse (independently of near-equal energy). The diaphragm between the sample and the waveguide is not shown in Fig. 2(b) that illustrates the case of maximal acceptance of the waveguide used.

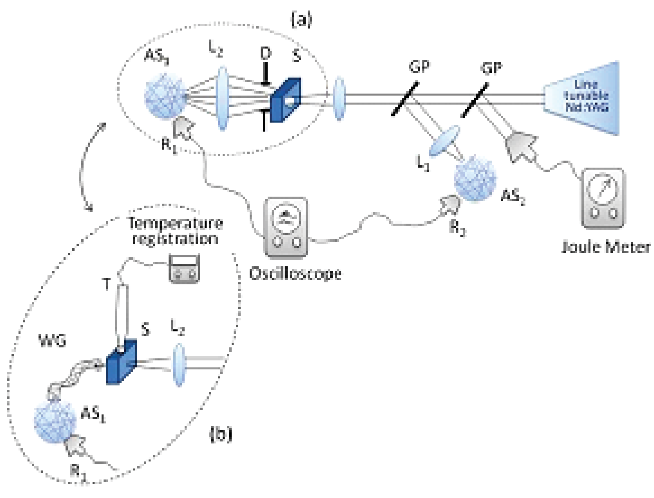

Fig. 2. (a) Principle of radial distribution measurement; (b) Principle of simultaneous measurement of the transmitted light and the temperature change of the sample – the elements, surrounded with dropped line, noted as (a) are replaced with combination of elements surrounded with dropped line, noted as (b)

For the measurement a series of diaphragms with different apertures – 0.7 mm, 1 mm, 1.5 mm 2.2 mm and 2.5 mm was sequentially introduced. In the realization, schematically given in Fig. 2 and in the photograph (Fig. 3), the GP is the glass plate, S is the sample, $D_I^{(i)}$ is variable diameter diaphragm, L_1 and L_2 are the lenses with a focal distance of 5 cm and 8 cm , L_2 is with high aperture of 4 cm, AS_1 and AS_2 are the averaged spheres, R_1 anR_2 are nano-second-resolution receivers for IR and Visible, Oscilloscope is two channels storage 200 MHz oscilloscope, Joule meter is commercial high quality device type FieldMaxII (Coherent). The specifity of our set-ups was that, when we used the pulsed Nd:YAG laser, we measured the incident and transmitted through the sample light using the oscilloscope traces (the energy is proportional to the are, limited by the oscilloscope trace) by the noted system of an oscilloscope and two equal IR optical receivers and averaged spheres (that we dispose, this measurement can be made easily with two equal IR Joule meters, our one was used for calibration).

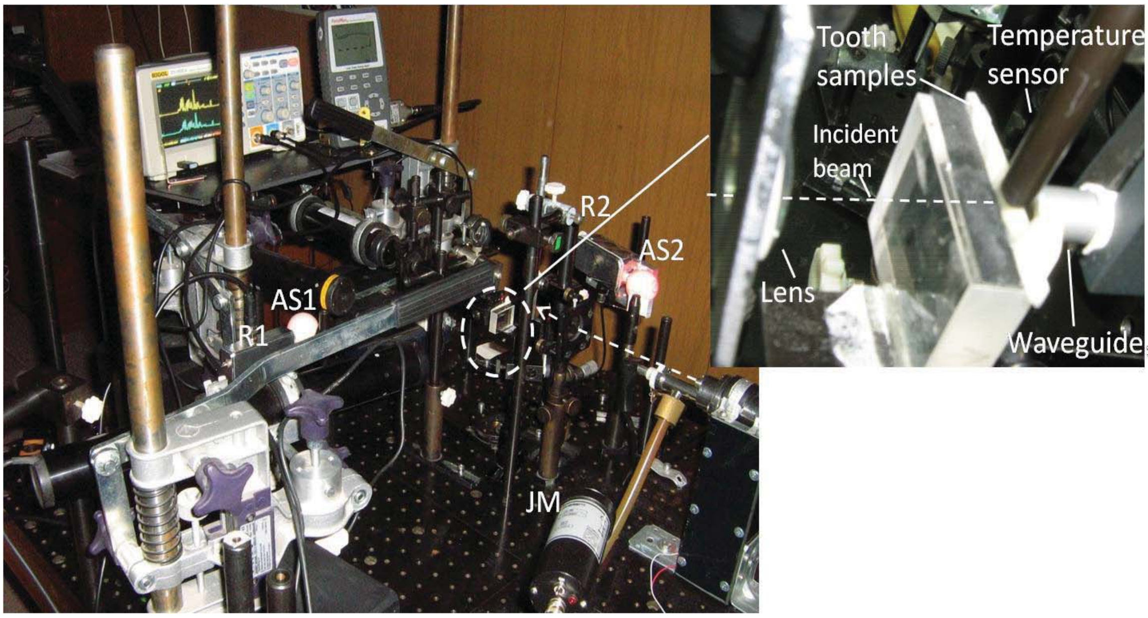

Fig. 3. Actual photograph of the experimetal set-up

Using the created installations, we measured the radial distribution of the transmitted light by introducing the convenient diaphragms. Thus, we have obtained the curves of angular distribution of the propagated light in the studied tooth sample of 1 mm thickness. The graph and figure of obtained angular distribution are shown in Fig. 4 and Fig. 5, respectively.

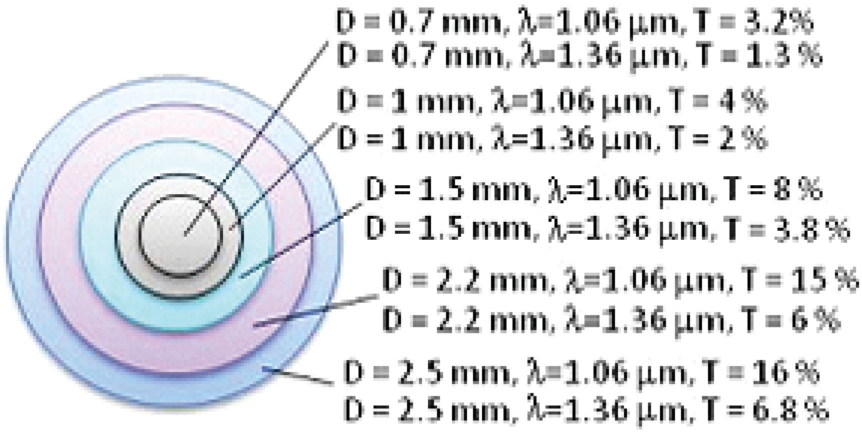

Fig. 4. The transmission for the laser light through the diaphragms D with different diameters (Fig. 2(a)) and for both wavelength 1.06 μm and 1.36 μm

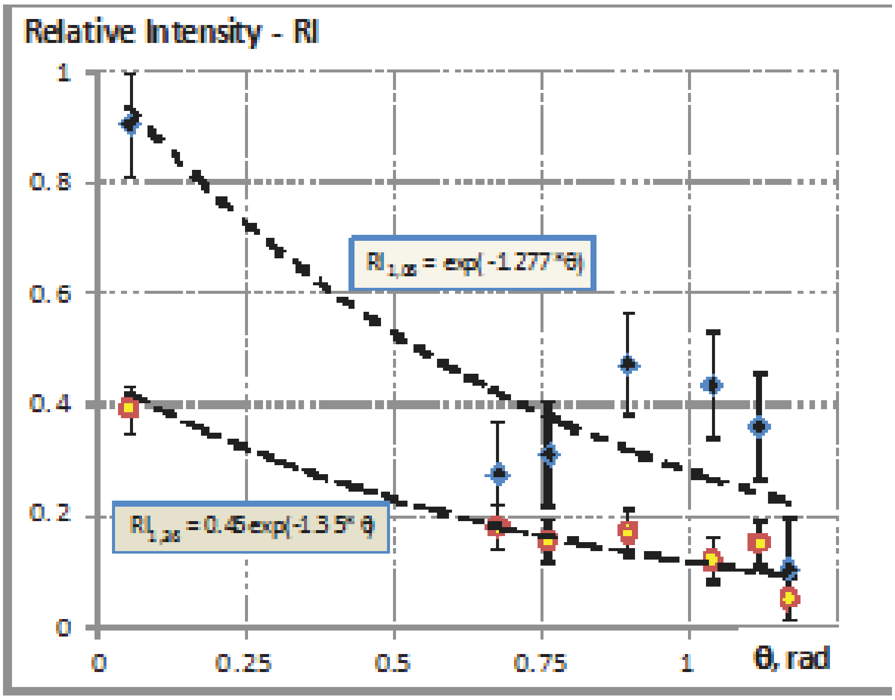

Fig. 5. Graph of the angular distribution of the relative intensity (RI) of the penetrated light for λ = 1.06 λm (top curve, squared points) and λ = 1.36 λm (bottom curve, circular points). The angle θ is measured from the incident beam axis. With the dropped line is given the approximating curves. We accept exponential approximation as more convenient

As figures 4 and 5 show, the incident beam diameter from the sample, in which was concentrated more than 95 % of the output light, was 2.5 mm. Thus, the used by us waveguide (Fig. 2(b)) with aperture of 4 mm is completely convenient to collect practically the total energy that passes through the sample. The waveguide was centered for the measurement of transmitted energy without and with the teeth samples in front of it. The incident beam was focused by a lens with long focal distance (0.5 m) on the sample. As we have discussed in the previous paragraph, the most interesting case in the medical teeth treatment is the possibility to estimate in advance the power penetrated in the tooth in small region – 1-3 mm around the incident beam axis. By using the noted waveguide of 4 mm aperture in the set-up shown in Fig. 2(b), or the diaphragm of diameter of 4 mm closely to the output sample wall in the set-up in Fig. 2(a), we have found for the coefficient of decreasing of the light in the sample $\alpha_{t1} \approx 40\ cm^{-1}$ for 1.36 μm and $\alpha_{t2} \approx 27\ cm^{-1}$ for 1.06 μm (passed light of 7% and 16%, respectively; exponential low accepted and verify using a samples wit a few noted up thickness). Our results are porch to the given in Reference [8], especially for the studied there in our work wavelength 1.06 um.

Thus, from figures 3 and 4 it can be seen that the aperture of 4 mm of the used waveguide is sufficient to accept practically all the light, transmitted through the sample and we could conclude that in the measurement in the following point of the total power (energy), lost in the sample, the waveguide with such aperture is very convenient.

The experiment, made with the prepared samples – combination of thin enamel and following dentin no essential difference from the noted coefficient of decreasing of the laser light is observed. Probably, this is a result of the fact that the enamel layer is quite thin (~ 0.1-0.2 mm), and with a high transmission [8].

EVALUATION OF THE COEFFICIENTS OF LIGHT ABSORPTION AND SCATTERING IN THE DENTIN

This was obtained by the noted combination of the measured lost power (energy) of the light in the sample as a difference of the incident beam intensity (energy) minus this one in the transmitted, taking also into account the measured reflection, the mass of the sample m and the increase of the temperature of the sample. We made this at the example of the l = 1 mm thick samples. The mass of the samples mi was measured (all of the order of 0.06 g) and using the known specific heat for the dentin (1390 ± 89 J/kg grad.) and measuring the increase of the sample temperature after illumination, we can calculate the part of the absorbed light. We related the coefficients of the absorption α_a and of the scattering α_s with an incident beam intensity (energy) with calculated decreasing by the reflection – Itr (E_{in}), and with a measured transmitted intensity (energy) I_{tr} (E_{tr}):

$$E_{tr} = E_{in} – \{E_{in}.\exp – (\alpha_a l)\} – \{E_{in}.\exp – (\alpha_s l)\}. (1)$$

Here we have made some reasonable acceptance - that the main part of the light propagate in the sample in cylinder and that there are the proportionality between the intensity and energy, also that the absorption and scattering is proportional of the incident light intensity (energy) separately – taking into account the low attribution of the scatterings, and respectively, the Buger's law can be used. Thus we can measured Etr, Ein, and by measuring the temperature increasing of the sample after the illumination by the laser pulse, we can calculated separately the coefficients α_a and α_s. For the wavelength 1.36 μm, as example, for one of the sample with length l = 1 mm and masse m = 0. 0632 g and measured increasing of the temperature of 0.1 degree (precisely measured with apparatus that we disposed) after illumination, we can calculate that the absorbed energy is 8.8 x 10^{-3} J. The Ein and Etr is measured to be 10.5 x 10^{-3} J and 0.84 x 10^{-3} J. Using this date we can calculated α_a and α_s and we have obtained 18 cm^{-1} and 0.85 cm^{-1} respectively. The calculated values for the other samples are very close to the obtained. Finally we can gives the values of (18 ± 2) cm^{-1} and (0.8 ± 0.15) cm^{-1} for α_a and α_s, respectively, for 1.36 μm. The analogical calculation gives for the same coefficients for the wavelength of 1.06 μm the values of (14 ± 2) cm^{-1} and (2.8 ± 0.4) cm^{-1} for α_a and α_s respectively. The type investigation in Reference [9], however for different tissue – soft tissue and different wavelengths – 0.633 μm and 0.751 μm, using different approach for measurement, show that the discussed coefficients depends essentially of the type of the tissue and the wavelength, that shows the need of concrete investigation for different materials and the wavelengths. The last justify our investigation.

CONCLUSIONS

Following the noted point for investigation we have developed approaches and corresponding techniques that allowed us to obtain experimentally numerical date for important parameters of perspective for use IR laser light propagation in dentin of the human tooth tissue: and Visible spectrum about : 1) Reflectivity of human tooth dentin – of ~ 25% ± 3%. 2) the spatial distribution of the intensity in the cross-section of the penetrated light intensity in the tooth's dentin – graphs in Fig. 5 and 3) as a main point, combining the optical and calorimetric techniques, we have obtained separately the absorbed and the diffused part of the light that permits to calculated the coefficients of absorption and this one of the scattering in the dentin – of (18 ± 2) cm^{-1} and (0.8 ± 0.15) for α_a and α_s respectively for the wavelength of the relatively strong line of 1.36 μm of Nd:YAG. Our investigation is for the laser light of two easily for generation wavelengths – 1.06 μm and not familiar, however as was discussed – with a perspective to use in medicine 1.36 μm line, emitted of the Nd:YAG laser. This laser is well distributed commercially, is chipper and widespread in many laboratories and medical institution. The typical, commercially available Nd:YAG laser is produced for generation at 1.06 μm, however the modification to generate at 1.32-1.36 μm is not complicated. The studied is on the base of vitro-teeth samples from the persons of Bulgaria, Sofia region.

Acknowledgement. This work is supported partially by the project RILA (01/7-19/13.12.2011; Pr. 25197 VB) – University of Versailles, France and Technical University – Sofia, NIS-NFSI.

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