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Interferometric laser detection of nanomechanical perturbations in biological media under ablation conditions

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I. Abstract.

This article has to do with the development of a reliable and sensitive non-invasive laser technique for assessing damage of structures and systems involved in laser ablation processes. The optical response of a Michelson Interferometer in combination with a Measuring Reflectance System has been analyzed in order to identify the stability of the mechanical properties of the sample, the physical perturbations associated with the systems and the environment where the target is contained. This test includes the use of a cyan laser system with 10 mW at 488 nm wavelength as optical source. We found out that with the inclusion of an optical feedback in a sensing system it is possible to determine the modification of the physical properties exhibited by a biological medium under sharp ablation conditions with a high accuracy degree. The results reported in this research have potential applications related to the amount of light intensity that can be tolerated by human tissue. A wide array of disciplines, such as medicine, mechanical industry and optical instrumentation can benefit from this ultrafast optical feedback for controlling high intensity laser signals. Collateral damage of tissue around the laser irradiated zones can be reduced by using intelligent lasers systems with ultra-short temporal response.

Keywords: interferometry; optical instruments; metrological applications; mechanical effects of light on material media.

II. Introduction.

A clear connection between optical science, engineering and technology has taken place during the past decades, since a huge variety of scientific and industrial problems have been solved, this advances have led to the production of operating devices, integrated circuits and hardware systems [1].

Light can be used for sensing a variety of parameters. Its field of applications is so wide that it can be used in several branches of science, such as engineering, technology, biomedicine, etc. Currently, optical principles have provided many of the essential techniques for non-invasive and sensitive measurements. For instance, optical interferometers are among the most powerful and useful tools for identifying physical perturbations [2]. A whole measurement field of a sample can be obtained from a simple study of fringe patterns resulting from changes in irradiance, phase or polarization of light. When there is a modification in the optical path of one arm associated to an interferometer, a displacement in the fringe pattern can be observed. A reliable measurement of a physical perturbation can be obtained from the evaluation of the resulting interference effect. Moreover, interference fringes patterns can also be induced by more complex methods which involve holography, phase-shifting, heterodyning, speckle pattern interferometry or Moiré techniques [2]. The variation of the electric field can be evaluated by,

$$\vec{E} = \sum_{h=1}^{k} \vec{E}_h$$

where \(k\) is the number of interfering waves, \(\vec{E}_h\) represents the electric field of the wave \(h\) is the interference zone, and the \(\vec{E}\) is the total electrical field of the resulting superposition of the waves.

In recent years, the use of many techniques for assessing damage structure with a high accuracy degree has grown dramatically [3]. The environment where some systems are
contained can dramatically change the operation of certain functions. Therefore a constant monitoring process is needed in order to achieve a high precision degree of measurements. For instance, in medical imaging and laser surgery, knowing that several properties may vary in real time during some medical operations is a most [4]. The microscopic changes associated with surgeries ought to be controlled in order to prevent unnecessary damage from happening during different treatments [5-7]. A variety of effective and ablative laser methods has been recommended to treat many health problems [8, 9]. Some of these methods completely disrupt or remove the epidermis with fatal consequences as a result of a misaligned or damaged laser system [10-13].

In the past decade, significant research efforts have led to the development of a non-invasive measurement to reduce bad results during laser surgery [14]. Physical perturbations of the laser systems usually result in a malfunction of the system itself, or even worse, damage to the patient. The difficulties arise when light scatters depending on nature of the skin, which varies dynamically due to changes in hydration as well as long term thickness changes of its different layers [15].

To overcome the difficulties, an understanding of possible physical perturbations of the skin and light produced by laser systems is absolutely necessary. In order to understand how light interacts with skin, the optical transport properties of absorption and scattering need to be determined. These features will improve the understanding of the tissue and help us determine some mechanical properties of the skin. In addition, they will help us define the critical parameters to prevent optical injuries related to misalignment or damage in ablation laser systems. Thus, the aim of this study is to estimate the optical properties of human skin and to implement a non-contact technique of damage assessment during an ablation process. Estimating the mean optical properties of reflection and transmission on the skin enables us to improve the results in a laser surgery and determine its mechanical properties.

III. Experimental calibration.

Interferometric System.

Figure 1 illustrates the configuration of a Michelson interferometer [16]. The light source used in this experiment was a Coherent Cyan Laser System externally doubled diode with single frequency, 488nm wavelength, 10mW and a very high stability. The adjustable mounts for mirrors 1 and 2 allow us to make the fine alignment adjustments needed to get a stable and nice fringe pattern. The beam splitter, BS, used here, splits the amplitude of the electric field generated by the laser and two separate beams are obtained; later this BS also recombines the beams after they strike the mirrors. A focusing system of lenses, F, spreads the laser interference pattern out for easy viewing or detecting at the place of photodector camera connected to a computer. To perform this experiment the use of planoconvex lenses are recommended.

![Figure 1. Configuration of the experiment.](image-url)

Suppose that M1 is moveable in the experimental setup represented by Fig. 1. The optical path difference is \(2\Delta d\) between the rays reflected from M1 and M2. A point of the pattern section at the photodetector will be bright if

\[2\Delta d = m\lambda,\]

where \(2\Delta d\) represents the optical path difference, \(m\) is related with the number of fringes and \(\lambda\) is the wavelength of the light.

and dark if

\[2\Delta d = (m + 1/2)\lambda.\]
If the two mirrors are precisely parallel, then the whole illuminated area of the pattern section will be uniformly lit. The condition for a maximum of intensity at the center of the screen is the one showed in equation 2[16].

Different interference patterns were captured for the calibration of the system. In Fig. 2 are clearly shown the interferences fringes obtained when the physical perturbation of temperature, pressure and vibration are well controlled in the lab where the system was performed.

To perform the calibration of this device, M1 was moved with ±0.0001mm precision, in order to measure the distance of the patterns. Experiments with the interferometer were made in order to check the performance of the calibration. According to equation 2 and after moving M1 a distance of 0.00508mm, the theoretical number of fringes was \( m = 20.81 \). After recording the patterns it was observed that the patterns had 20 complete displacements of fringes. Figure 2 shows the final fringe pattern \( m = 0.81 \).

**Figure 2. Interference fringe pattern.**

### System for measuring reflectance.

Figure 3 illustrates the experimental setup. It consists of the same laser source describe in the last section, a linear polarizer and a photodiode PIN with signal amplification as a photosensor. This system is able to measure the light that is reflected by a sample. The absorbance is calculated considering the Fresnel reflective measurement and the scattering losses [16].

The calibration was performed by means of a linear polarizer in order to control the intensity of the light. When the polarization of a beam is linear and perpendicular to the incidence plane, no light is reflected when the beam is incident at the Brewster’s angle on a well known plane dielectric surface [16]. The equation that satisfies these conditions can be expressed as,

\[
tg\theta_p = n_t / n_i .
\]  (4)

where \( n_t \) and \( n_i \) are the refractive index for the transmitted and the incident beam, respectively; and \( \theta \) is the angle of incidence.

The output intensity, \( I_s \), resulting after the propagation of a linear polarized optical beam through a polarized can be calculated by invoking the Malus law [16],

\[
I_s = I_o \cos^2 \theta .
\]  (5)

where \( I_o \) represents the input intensity and \( \theta \) represents the angle between the light’s initial polarization direction and the transmission axis of the polarizer. Figure 4 shows the linearity of the optical power that was applied at 12 different angles of the polarizer.
Different mechanical perturbations were induced in the controlled environment. The System for measuring reflectance generates the same optical signals for mechanical perturbations below 4.9 (N). However significant differences in the fringe patterns obtained by the Michelson interferometer were obtained by nanomechanical perturbations. Figure 6 exemplifies the typical interference pattern obtained with the configuration described by Fig. 1 when a biological sample is tested.

Comparing the pattern showed in Fig. 6 obtained with the one shown in Fig. 2, we observed a variation of $m=0.90$ of fringe originated by thermal perturbations from the environment and from the laser system.

It was noted that specific factors influence the measurements of the biological medium, such as pigmentation, thickness, the zone where the measurement was made and the texture of the medium, in other words the optical properties, absorption, reflection, transmission and refraction. In addition, a biological medium had different optical responses due to the multiple skin layers.

In order to test the interferometric system, a well controlled force of 1.06 Newton (N) was induced on the base of the interferometric system. Precisely on the place where the ablation laser system is proposed to be located. Figure 7 shows a fringe displacement during this mechanical perturbation.
Comparing the pattern generated when an external nanomechanical perturbation was present on the biomaterial/skin (figure 6) versus the pattern generated by a force induced of 1.06N, (figure 7) we observed a difference of $m=0.2$. It can be inferred that the skin suffered a nanomechanical perturbation of 1.36N. The skin was measured with a legibility of ±0.15 N.

V. Discussion.

As it was expected, lighter-skinned tones will absorb less light energy than darker-skinned ones, which will absorb a greater amount of energy. In other words, lighter-skinned tones reflect more light than darker-skinned ones. This situation means that the change in the ablation parameters in laser surgery must be different for each person, so it is necessary to control the optical characteristics in each process, even if the same person is tested for different body measurements, the color skin of a patient appears to have considerable variations of optical properties for each point. In this work it was found that the skin is a non-uniform medium even in the spot area of the beam.

A similar situation could be observed for assessment damage of structures and systems involved in laser ablation processes like biomaterials (skin). The optical properties could depend on the zone where the target will be measured. It appears to be consistent because some areas of the objective, in the case of the skin, could be exposed to the sun or different factors. For instance, hands and face are darker areas than the abdomen or the femur areas, which are protected from the sun by the clothes that we wear.

According to the results, for the case of the human tissue there is not a strong dependence of the optical properties analyzed in terms of the age; however there are variations of the properties at each point of the sample.

Using these results, it could be measurable the absorbance of the skin in vivo, and even better, for each point. These parameters seem to have a very important application for the practices made in the field of medicine and biomechanics, for example in the process of implementation and development of custom prostheses. However, in this research, the measurement of the nanomechanical perturbations using the interferometric system is an average value due to this magnitude is inferred according the displacement of the fringe pattern.

Other optical methods have been done to treat skin disease. Weiss et al found that after 6 months, there was an improvement in objective skin tightness (Young’s modulus $p<0.01$) at specific reproducible points on the lower face [17]. The method proposed here provides a fast response inferred in a biological medium during an ablation process. Nevertheless a precalibration of the physical perturbation need to be made in order to guarantee the trustworthy of the result of the interferometric system. This is not the case of the measuring reflectance system.

Both efficacy and good results in laser surgery patients depend on the control of mechanical perturbations in the room. Because of these perturbations, scarring and thermal damage could be observed during the laser surgery. We propose a feedback for monitoring laser alignment and assessment of specific damage of samples. In addition, this proposal can be helpful for identifying different perturbations related with specific dynamic modifications of the condition during an ultrafast ablation process. Further studies are needed to make the Interferometric response faster.

VI. Conclusions.
These results have potential applications for assessment damage of structures as well as the knowledge of the optical properties of a sample that is under laser ablation. Besides, with and appropriated ultrafast feedback system, the prediction of the ablation threshold can be estimated in vivo. In addition, other applications could include not only laser surgery procedures, industrial processes including laser cutting or monitoring the optimal conditions for a fine ablation system as well.

The simultaneous action of an interferometric system and a measurement reflectance system can introduce the development of other measurement techniques to detect physical parameters, like pressure, temperature, strain, etc., in other areas.

The study of the feedback and the optical response of a target involved in an ablation process could generate finer results. We consider that the information gained from the interferometric sensor in combination with the measurement reflectance system could be sent to an ultrafast sensor and actuator to control the intensity of the laser system that produces the ablation in ultrafast processes.

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