TRANSPARENT MEDIA CHARACTERIZATION USING SUB-PICO SECOND DYE LASER

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ABSTRACT

A new passively mode locked laser source developed at the Center for Laser Studies yielded pulses shorter than 0.14 ps, at a rate of 250 MHz or 0.3 ps pulses at a rate of 500 MHz. The laser and its modes of operationare described. With this source and a second order cross correlation technique similar to the autocorrelation used to determine the pulse duration, time domain reflectometry measurements can be made with a resolution of 40 µm. Three dimensional images can be made by time resolving the backscattered radiation of a beam scanned through a medium. The depth resolution of 0.1 µm can be carried over to the other two dimensions by computer reconstruction. The new technique should have important applications in medicine and biology. Because of the short duration of the laser pulses, high peak intensities can be used without damage to the tissues. Therefore, light measurements can be conducted through a larger depth than with continuous radiation.

1. INTRODUCTION

New possibilities in Optical Metrology are emerging from the recent development of a picosecond laser source at the Center for Laser Studies. The two unique characteristics of our source, that are instrumental in the applications described below are :

- a pulse duration in the range of 0.1-0.2 ps, giving us the capability of making time domain reflectometry measurements with a resolving power of ≃ 50 µ ;
- a repetition rate as high as 500 MHz, which should make the recording of three dimensional images possible in fractions of seconds.

We present an experimental set up to time resolve the light backscattered as the continuous train of pulses is sent through various media. This technique of optical Time Domain Reflectometry (TDR) will enable us to localize small defects in optical fiber connectors and to determine the light intensity distribution inside scattering and absorbing media. Angular scanning of this one dimensional information can provide three dimensional images of biological objects. For instance, eyes, breasts and arteries located near the surface are regions of the body amenable to optical imaging. Through the use of computer reconstruction techniques, it should be possible to convey the unique depth resolution to three dimensions. Before discussing these applications (sections 3-5), we will give a brief description of the operation of the source, its limitations and possible improvements.

2. THE SUBPICOSECOND LASER

2.1. Description

The source of ultrashort pulses is a passively mode locked dye laser, pumped by a continuous Argon Laser. This laser differs from conventional passively mode locked system [1,2] by

1. The absence of any dispersion in the cavity around the wavelength of interest.
2. A simpler cavity - the mode locking dyes are mixed in the same solution as the laser dye, eliminating the need for an additional dye jet[1] or cell[2] inside the cavity.
3. A cavity length shorter than (optimally equal to) 60 cm.

The absence of intracavity dispersion is the most stringent requirement, and was met through elimination of all conventional wavelength tuning elements. The operation of the laser is limited to the wavelength range of 500 nm to 620 nm by the reflective properties of the output mirror. The particular shape of the reflection spectrum of that cavity mirror is a critical parameter in the short pulse operation of the laser. It is essential that the cavity losses be constant and minimal over a wavelength range broader than that defined by the pulse bandwidth. But it is also essential that the cavity losses increase sharply at wavelengths below 600 nm, to overcompensate the increasing gain of Rhodamine 6G at these wavelengths. A third order reflector centered at 610 nm ideally combined these properties, giving a constant reflectivity of 99.7 % in the wavelength range of interest.

We have made a systematic study of the influence of dye composition on the mode locking characteristics.[3] The shortest pulse durations are obtained with a solution of 2.10^{-3} M/ℓ of Rh 6G, 2.10^{-5} M/ℓ dioxadicarbocyanine iodide (DODCI), and $3.5\ 10^{-6}$ M/ℓ malachite green, in ethylene glycol (analytical grade). Aging of the solution is a serious problem that has yet to be solved.

The cavity length is unusually short compared with that of other mode locked systems leading to pulse rates hitherto unequalled for mode locked dye laser (250 to 600 MHz). Ultrashort pulse operation (≤ 0.2 ps) could only be observed for a cavity length shorter than (or equal to) 60 cm (the shortest pulses corresponding to the 60 cm cavity).

2.2. Modes of Operation

The operation of this laser is critically dependent on the pump power intensity. The average power of the dye laser is rather intensitive to changes in argon laser pump power (above threshold). However, the average power in the second harmonic (of the dye laser beam) changes by many orders of magnitude as the pump power is increased over a range of only 0.2W. Two maximas, each only a few mW wide, are observed in the variation of the second harmonic average power as a function of argon laser power. Pulses shorter than 0.2 ps at 4ns interval are measured for a pump power corresponding to the first maximum, and pulses of 0.3 ps at 2 ns interval (2 pulses per cavity round trip time) at a pump power corresponding to the second maximum. This latter mode of operation is the most attractive for metrologic applications requiring a fast data rate, because the pulses are emitted in a continuous train at 500 MHz. The first mode of operation is to be preferred when high resolution is desirable, and is described in more details below.

A second order autocorrelation of the pulse with itself, as shown in Figure 2, gives a measure of the spatial resolution that can be achieved in the optical TDR measurements described in the next sections. The FWHM of the trace reproduced in Figure 1 is 62 µm corresponding to a time delay of 0.21 ps or a pulse duration of 0.14 ps. It should be noted that the autocorrelation of Figure 1 represents an average of a distribution of pulses of different duration and even shorter pulses are present in the traint [4]. The envelope of the pulse train is seen to have a modulation at 50 kc. Boxcar integration measurements of the pulse spectrum and second order autocorrelation shows that the center frequency of the pulses oscillates between 605 and 610 nm, while their duration changes by two orders of magnitude. While the exact nature of this relaxation oscillation is not understood at this point, it is clearly directly related of the generation mechanism of the shortest pulses. It was verified that this relaxation oscillation at 50 KHz was not associated with any noise component from the pump laser. However, the stability of the ultrashort pulse operation was greatly enhanced when this oscillation was externally synchronized through an intensity modulation of the pump power. This was achieved by inserting an electro-optic modulator, driven at 50 kc in the argon laser beam.

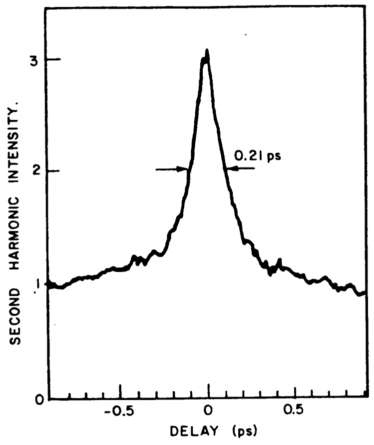

Figure 1
Second order autocorrelation trace of the pulse train.

3. TIME DOMAIN REFLECTOMETRY (LINEAR INTERFEROMETRIC DETECTION)

The expression "Time Domain Reflectometry" (TDR) generally refers to a technique for localizing and evaluating defects in electrical cables and connectors, by measuring the time delay between launching a pulse into a cable and the arrival of the reflection from a defect. The same technique can be extended to the optical field. The shortest pulses should enable us to localize a defect in a fiber connector with an accuracy of the order of a micron, or to resolve two defects only 50 μm apart. This is the highest resolution that can be achieved by optical methods through a section of glass of ≃ 10 cm long. Indeed, material dispersion alone is sufficient to "blurr" the image of a pair of defects. TDR of that accuracy requires a temporal resolution of the reflected light better than 0.1 ps. This time scale being far beyond electronic capabilities, it is necessary to use purely optical techniques to obtain the required time resolution.

The basic instrument to optically time resolve backscattered beams consists in the assembly of fused silica prisms sketched in Figure 2. The prisms 1 and 2 are optically contacted. The prisms 3 and 4 are coated with chromium spacers, and pressed against prisms 1 and 2 with an adjustable force to provide a controllable beam splitting ratio (by frustrated total internal reflection). Prism 5 is mounted on a accurate translation stage to provide the reference delay. The optical alignment is completed by a) a wedge W rotatable (through a worm gear assembly) around a horizontal axis until the cumulative error of the 90° prisms (in the plane of the figure) is exactly compensated, and b) a high precision tilt platform mount for prism 5 on the translation stage. A translation speed ranging from 0.2 µm/sec to 2 mm/sec can be selected through a combination of synchronous motors and reduction gears.

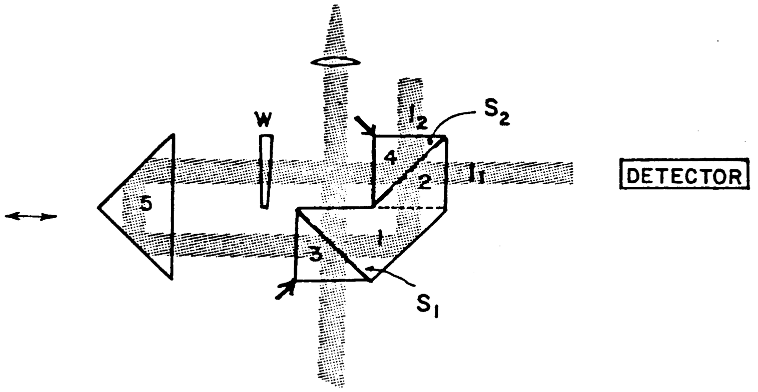

Figure 2
Prism assembly for optical time delay reflectometry

Figure 3 shows linear detection of a weak return obtained by the reflection of a anti-reflection coated glass surface, attenuated 100 x by a neutral density filter (returned intensity $\leq 5.10^{-5}$ of incident beam). With the beam splitting ratio S_1 set at 50 %, the beam splitting ratio S_2 has been adjusted for equal intensity of the reference and reflected beams impinging on the detector (a photomultiplier RCA IP28). As the optical delay in the reference beam is scanned, an interference pattern is observed for the value of the delay matching time of flight of the reflected original (Figure 3). Such a "linear method" has a few advantages (over the nonlinear methods presented in the following sections) but serious shortcomings :

1. It has a subwavelength accuracy (individual fringes can be identified with a slower scan speed).
2. Being a "non zero method", it requires adjustment of the beam splitter S_2 to match the reference and reflected signal beam intensities.
3. The dynamic range is limited to return signal intensities that are at best within a factor 100 (in amplitude) of the most intense return.
4. Since the return beam has to be coherent with the reference beams, this method is limited to the observation of reflections from sharp discontinuities.

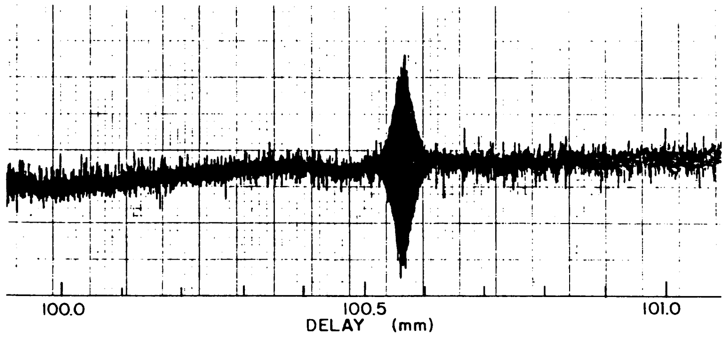

Figure 3
Localization of a weak discontinuity by TDR

4. TIME DOMAIN REFLECTOMETRY (SECOND HARMONIC DETECTION)

Ideally, the detection scheme should measure the product of reference beam intensity times the reflected signal. Then the backscattered signal is truly "sampled" by the reference signal at a preselected time (corresponding to a predetermined position in the sample to be investigated). Such a product detection can be made easily by measuring the second harmonic generation of type 2 created by colinear - orthogonally polarized - reference and signal beams, focused in an appropriately oriented frequency doubling crystal. The orthogonal polarization is obtained by inserting a $\lambda/2$ plate in the path of the reference beam (Figure 2). The basic set up is the same as in Figure 2, with a frequency doubling crystal and detection at the second harmonic frequency being substituted to the linear detection. Because of the difficulty of finding good crystals for second harmonic generation of type II at 610 nm, we choose instead a noncolinear arrangement sketched in Figure 4, where a KDP crystal cut for type I second harmonic generation can be used. Instead of being colinear, the reference and signal beams are sent with converging wave vectors into the KDP crystal. The second harmonic generated along the bisector of the small angle made by the intersecting fundamental beams is proportional to the product of the intensity in each beam.

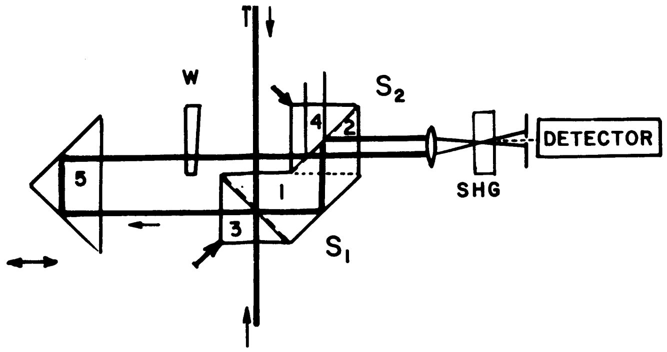

Figure 4
Prism Assembly for nonlinear TDR.

Either of the set ups described under this heading gives a second harmonic intensity proportional to the product of the intensities in the reference (I_r (t)) and backscattered original beam (I_s (t)). This product is maximum for the beam splitters reflectivities being respectively R = 2/3 for S_1 and R = 1/2 for S_2. To a first approximation, the reference short pulse can be assimilated to a delta-function ($I(t) = a\,\delta(t-\tau)$), and the detected signal is :

$$S = a \int I_s(t)\,\delta(t-\tau)\,dt = a\,I_s(\tau)$$

While the sensitivity of this technique of optical TDR is proportional to the laser source intensity squared, the signal S is a linear function of the backscattered intensity. Using fast and sensitive detection techniques, this method is potentially capable of detecting very weak backscattered signals. Unlike the interference method, the features to be observed do not need to be localized discontinuities, but can be inhomogeneous distributions of scatterers and absorbers. A large dynamic range should make it possible to apply this technique even to biologic objects. Computer reconstruction has to be used to extract the one dimensional "image" (or 'Opacity function') from the time resolved measurement of the backscattering. Let us consider a medium with a uniform scattering coefficient α_s, and an absorption coefficient α_a (z) to be determined. The opacity function $\alpha_s + \alpha_a = \alpha(z)$ can be calculated directly "on line" from the measurement S (τ) through the relation :

$$\alpha\ (z) = \frac{d}{dz}\ \{\ \tfrac{1}{2}\ \ell n\ S(\tfrac{z}{c})\}$$

In order to obtain the highest possible dynamic range with the available pulse duration, the instrumentation described in Figure 5 is being assembled at the Center for Laser Studies (USC). The laser is used in its continuous mode of operation emitting pulses of 0.3 ps at a rate of 500 MHz. A conventional all electrostatic Varian Photomultiplier Tube VPM-152D was selected for this application. The conventional tube was preferred to crossed field and microchannel photomultipliers, because of its broad dynamic range. Indeed, in the conventional tube, the gain can be varied by several orders of magnitude during the depth scan. This photomultiplier has an impulse response width of ≃ 1 ns, thus quite adequate to separate successive pulses in the train. Some signal to noise discrimination is provided by a 600 MHz preamplifier and a resettable integrator following a fast detector. The integrator provides an improvement of the signal to noise of approximately a factor of 10 by reducing the data rate to 10 MHz, a repetition rate readily accessible to A/D converters for further digital data processing. Further (digital) averaging can be made if the signal to noise need to be improved.

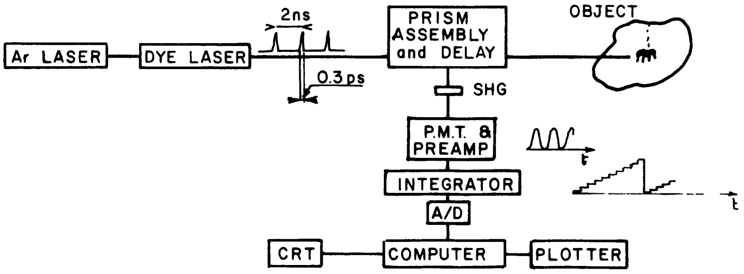

Figure 5
Instrumentation for optical TDR.

5. THREE DIMENSIONAL IMAGING

The time domain reflectometry technique described above associated with a fast scanner, can be used to obtain three dimensional images. In order to have a transverse resolution comparable with the depth resolution, it is necessary to focus the laser light in the plane ob observation defined by the reference delay. It is then necessary to change the position of lens and scanner for each field of depth (or each value of the reference delay). The motion of the scanning optics would have to be linked to the motion of the reference delay, which is impractical. Using directly parallel beam configuration eliminates the problem of depth of field adjustment, but the transverse resolution is then limited to approximately 1 mm by diffraction. It is then still possible to carry over the optical TDR resolution of 0.1 mm to three dimension by computer reconstruction of three dimensional pictures taken from various angles of illumination. Figure 6 shows schematically how this reconstruction could occur in a transaxial plane. The beam is scanned successively laterally and angularly by rotating glass plate and an optical scanner. The scanned and displaced beams are imaged inside the object to be investigated. Reconstruction is made by small areas 1 mm × 1 mm. Beams at different angle sampled every 100 mm, form intersecting grids around P. Using these samples at different angles, an iterative algorithm will be used to reconstruct the small region around P. Provisions have to be made in the algorithm to appropriately account for regions which lie outside the 1 mm reconstruction zone because these regions contribute to the projection data. To reconstruct an approximately 1 mm diameter region on a 10 × 10 grid with a grid size of ∿ 100 μm, 8 angles (around 180°) are needed. Generally, the viewing angle will be smaller, however, algorithms have been developed for reconstructing from views which cover a limited angle. A global image will be reconstructed by "sliding" the local grid across the object. This process will have to be iterated, since each local image is affected by its neighbors. It is expected that a few iterations will produce a high resolution global image.

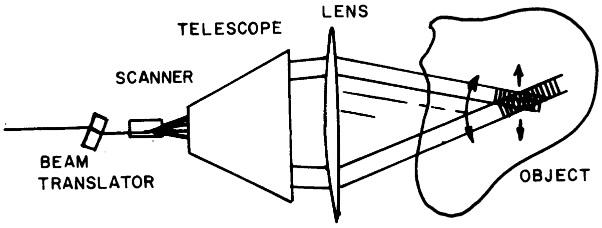

Figure 6
Scanning configuration for optical TDR.

It is interesting to compare these three dimensional imaging techniques to computed X-ray tomography. The large attenuation of the optical radiation limits its depths of penetration. On the other hand, a larger absorption cross section offers the advantage of enhanced contrast. The transmission factor is averaged over the full length of body traversed in X-ray tomography. The backscattering from a well defined depth is averaged over the beam cross section in optical TDR. The possibility of proceeding from local reconstruction is unique to the Optical TDR. Because of the low energy in the subpicosecond pulses, radiation damage should not become a factor even after amplification. The transmission factor of tissues to subpicosecond pulses have not yet been measured. Since many absorbing substances will have characteristic times longer than the pulse duration, their transmission characteristics can be expected to be different than for continuous radiation.

5.1. Acknowledgements

The development of the subpicosecond laser source was supported by NSF under grant No. ENG7721435. We gratefully acknowledge fruitful discussions with Dr. G. Huth and M. Singh on the topic of computed optical tomography. Mr. H. Sallaba provided invaluable assistance, the experimental work with the subpicosecond source.

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