ULTRAFAST LASER PULSE TAILORING IN PURE WATER

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ABSTRACT

Some experimental measurements of femtosecond laser pulses propagating in water have shown an apparent absorption coefficient that is much smaller by more than an order of magnitude than even that measured using picosecond pulses in the same water with the same apparatus. The effect was found to be linear since the power density in the experiments was kept well below the threshold of any known non-linear mechanism. The lasers used in the experiments had transform limited pulses centered around 800 nm. The measured effect can be explained by viewing the phenomenon from the spectral perspective where the coherent laser pulse spectrum can be considered as inhomogeneous and subjected to a form of hole burning by the absorbing medium. This means that the absorption eats away the central portion of the laser spectrum and leaves two separate spectra that beat against one another. This way of looking at the process resolves also the apparently contradictory results to that of Fox and Osterberg, which were obtained by workers at the University of Nebraska and more recently at Texas A&M. An interesting consequence of this spectral analysis is that the apparent reduction in absorption can be directly related to the initial and evolving temporal pulse shape of the laser. The absorption curve can thus be used to infer details of the laser pulse shape. It also turns out that the temporal shape and breakup of the laser pulse can be modified in a controllable fashion by pure water or with the controlled addition of absorbing dyes. This opens up the possibility of tailoring the temporal evolution as a function of penetration distance of femtosecond laser pulses. This tailoring capability is relevant to the problem of increasing the reliability of free space underwater communication.

Keywords: propagation, absorption, underwater, water, femtosecond, laser, pulse shaping.

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14. ABSTRACT

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Ultrafast Laser Pulse Tailoring in pure water

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Ultrafast laser pulse tailoring in pure water

- It was conclusively shown two years ago by very careful experimental measurements by Anna Fox and Ulf Osterberg that 60 femtosecond laser pulses centered at 800 nm propagating in water have an anomalous absorption that is much smaller by more than two orders of magnitude than even picosecond pulses at the same wavelenght.
- Surprisingly the effect was found to be linear as the power density in the experiments was kept well below the threshold of any known non-linear mechanism.
- This effect depends only on the finite response time of water.
- A simple theoretical model relating temporal pulse shape to spectrally broadened absorption is proposed and formulae are derived that explain most of the current experimental results.

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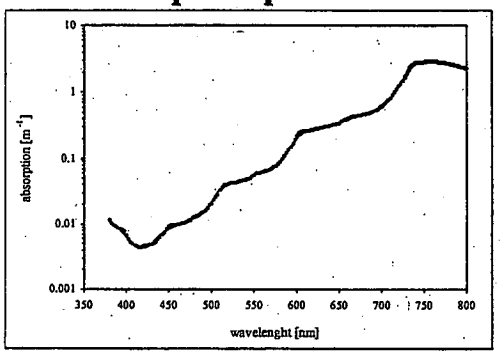
What is the source of the water response time and absorption spectrum?



The absorption coefficient of pure water at 22°C as a function of wavelength from 380 nm to 800 nm. The solid line is the fit using a set of Gaussians whose parameters are given in Table 1 and the dots are the experimental data of (Pope and Fry 1997: 380 to 727.5 nm, Kou et al. 1993: 728 to 800 nm). Note the broad quadratic shaped minimum around 420 nm.

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What is the mechanism?

- Part of the effect can explained by viewing the phenomenon from the spectral perspective where the coherent laser pulse spectrum can be considered as inhomogeneous and subjected to a form of hole burning by the absorbing medium. Note that for femtosecond pulses the spectrum is very broad and is the Fourier transform of the temporal pulse shape.
- This means that for water, the absorption eats away preferentially the long wavelenght side of the laser spectrum.
- As the pulse progresses further in the medium the leftover laser pulse power shifts towards the green and blue and the rate of absorption as a function of distance slows down giving rise to the apparent reduction in absorption.

Ultrafast laser pulse tailoring in pure water

A simple physics based laser pulse shape.

- For a single pulse or low repetition rate operation any medium with optical gain enclosed between mirrors in a cavity will behave in general as follows:
- The initial portion of the pulse will be given in general by an exponential amplification with a rise time that will come to saturate at a constant level if the power source feeding the population inversion is constant and the lower state is emptied fast enough.
- Once the power source stops, the inversion will disappear and the radiation will decay exponentially at a rate determined in general by the cavity length and mirror reflectivity.

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A simple physics based laser pulse shape.

The previously described behavior can be captured by the following model equation:

$$\frac{I(t)}{I_0} = \frac{\gamma(\alpha+\gamma)}{\alpha}(1-e^{-\alpha t})e^{-\gamma t} = \frac{\gamma(\alpha+\gamma)}{\alpha}(e^{-\gamma t} - e^{-(\alpha+\gamma)t})$$

This equation can be used to obtain flexible laser pulse shapes based on the physics of the laser cavity.

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Deriving the laser frequency spectrum.

$$\int_0^\infty z^{1/2} e^{-z/2} e^{-i\omega_1 z} dz = \frac{1}{(1+i\,2\omega_1)^{3/2}} \quad \leftarrow \omega_1 = \frac{2\pi\nu}{\beta} = \frac{2\pi c}{\beta\lambda} = \frac{2\pi c T_p}{2.44644\lambda}$$

The power normalized power spectrum is therefore:

$$I(\omega_1) = \frac{1}{[(1+4(\omega_1)^2]^{3/2}}$$

Note carefully that the frequency asymptote for a Gamma pulse is an inverse cube function.
In the other limit of a pure exponential pulse the asymptote would be an inverse square.
The full function will therefore span the space between both these limits. This is a much slower decay than for a Gaussian.

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Deriving the laser frequency spectrum.

Note that the full width at half maximum of the normalized and relative frequency spectra are:

$$\Delta\omega^1_{1/2\max} = 2\sqrt{\frac{(2^{2/3}-1)}{4}} = 0.76642 \Rightarrow \Delta\omega_{1/2\max} = 0.76642\frac{2.44644}{T_p} = \frac{1.875}{T_p}$$

According to the above, the total absorption of an ultra-fast pulse by water can be evaluated numerically by spectrally integrating the spectrum of the laser pulse by the wavelength dependant absorption of pure water.