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A NEW TECHNIQUE FOR MEASURING TEMPORAL PROFILE OF PICOSECOND AND FEMTOSECOND LASER PULSES USING SELF-INDUCED DEFLECTION IN A SEMICONDUCTOR WEDGE

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Abstract

A technique is described for measuring the temporal profile of short laser pulses. By passing the laser pulses through a suitable semiconductor material, electron and hole plasmas are excited which modifies the refractive index of the semiconductor. When the semiconductor is in the form of a wedge, these electron-hole plasmas produce a spatial scanning of the laser pulse. By choosing an appropriate detector, the laser temporal profile can be directly determined from this self-induced spatial scanning.

So far there are basically two ways to determine the length of picosecond laser pulses. The most widely used method is the autocorrelation technique[1] in which the laser beam is separated into two beams with a variable delay between them and then recombined in a second-harmonic (SH) generating crystal. The SH generated as a function of the delay is proportional to the intensity autocorrelation function of the laser pulse. This technique has the advantage of being relatively cheap and easy to implement, and that it works even for femtosecond pulses. Its main disadvantage is that in general the pulse profile cannot be uniquely determined from its autocorrelation function alone. The other method is to use a streak camera.[2] Streak cameras can measure directly the pulse profile, but, unfortunately, their time resolution is limited to one picosecond or longer, and it is unlikely that their resolution can ever be extended to the femtosecond regime.

In this article we will propose a new technique which complements the autocorrelation method in that it is capable of determining the temporal profile of picosecond and femtosecond laser pulses.

The basic idea of this technique is very simple. Laser pulses have been shown to excite electron-hole (e-h) plasmas in semiconductors. This electron-hole plasma then modifies the refractive index of the semiconductor. The change in the refractive index has been detected, for example, by change in the reflectivity of the sample.[3] If the sample is in the form of a wedge, then this self-induced refractive index variation can also be determined by the change in the deflection of the laser beam as it emerges from the wedge (see Fig. 1). We will demonstrate that, by using an appropriate detection scheme, the temporal profile of the beam pulse can be determined by its spatial variation after emerging from the wedge.

The theoretical basis of our technique can be understood by the following analysis.

1. Excitation of electron-hole by the laser pulse

Let us assume that the absorption coefficient of the sample is α, the incident photon energy is $\hbar\omega$, the laser intensity is I; then the rate equation governing the creation of electron-hole pairs in the sample is given by:

$$\frac{\partial N}{\partial t} = \alpha\frac{I(t)}{\hbar\omega} - R \qquad (1)$$

where N is the concentration of photoexcited electron-hole pairs and R is the recombination rate. In Eq. (1) we have neglected the diffusion of electron-hole pairs. This is because we will assume that the duration of the laser pulse is $\lesssim 10^{-11}$ sec and the penetration depth of light (α^{-1}) is $\gtrsim 0.1$ cm. Thus for typical ambipolar diffusion constant D of $\lesssim 100\ cm^2/sec$ in semiconductors, the diffusion length of the e-h plasma $\sqrt{D\tau}$ is $\lesssim 0.3\mu$ and is negligible compared to α^{-1}. R represents the recombination rate of e-h pairs in the sample. Typically R contains contributions from radiative recombination, nonradiative recombination at deep traps and Auger processes. Since we are mainly interested in laser pulses of $\lesssim 10$ psec durations, the first two processes can be neglected. For reasons to be discussed later, we will assume that the highest e-h plasma density excited will be kept below $10^{19} cm^{-3}$. Assuming that the Auger recombination rate is given by CN^3 where $C \lesssim 10^{-30}\ cm^6/sec$[4], we find R to be negligible compared to the generation rate. Within this assumption we obtain from Eq. (1):

$$N(t) = \frac{\alpha}{\hbar\omega} \int_{-\infty}^{t} I(t')dt' \tag{2}$$

2. <u>Change in refractive index induced by the photoexcited e-h plasma</u>

It is well-known that the contribution to the dielectric function by a plasma is given by:[5]

$$\varepsilon(\omega) = \varepsilon_b \left[1 - \frac{\omega_p^2}{\omega(\omega+i\Gamma)}\right] \tag{3}$$

where ε_b is the background dielectric constant due to the bound electrons, ω_p is the plasma frequency defined by

$$\omega_p^2 = \frac{4\pi Ne^2}{m^* \varepsilon_b} \tag{4}$$

and Γ is the damping constant of the plasma. In Eq. (4) m^* is the effective mass of the carrier. In case of an e-h plasma $(m^*)^{-1} = (m_e)^{-1} + (m_h)^{-1}$ where m_e and m_h are, respectively, the electron and hole effective masses. For simplicity we will assume that the real part of ε_b is much larger than its imaginary part. For example, if we assume the laser wavelength to be 1.06μm ($\omega = 1.78 \times 10^{15}$ sec^{-1}) and the sample to be Si, then the real part of ε_b is ~ 11.9,[6] while the imaginary part of ε_b is only $\sim 1.2 \times 10^{-3}$.[7]

Using Eq. (3), we conclude that as the laser pulse I(t) passes through the sample the dielectric constant of the sample changes with time as

$$\varepsilon_{real}(\omega,t) = \varepsilon_b \left[1 - \frac{\omega_p^2(t)}{\omega^2+\Gamma^2}\right] \tag{5}$$

$$\varepsilon_{imaginary}(\omega,t) = \varepsilon_b \left[\frac{\omega_p^2(t)\Gamma}{(\omega^2+\Gamma^2)\omega}\right] \tag{6}$$

if we assume that the laser pulse affects the dielectric constant by changing the plasma frequency only and neglect the effects of the e-h plasma on sample properties such as the band gap. In case of Si it has been found that the band gap shrinkage induced by free carriers is negligible for carrier concentration $\lesssim 5 \times 10^{18}$ cm^{-3}.[8] For such concentrations, the free carrier absorption coefficient has been determined to be $\lesssim 10$ cm^{-1}.[9] This free carrier absorption depends on the quality of the sample. For carriers introduced by doping we expect this absorption to be stronger than when the carriers are photoexcited, since in the latter case there will be no ionized impurities. As a result we will neglect the contribution of the photoexcited plasma to the imaginary part of ε as long as the plasma density is kept below $\sim 5 \times 10^{18}$ cm^{-3}. Hence the net effect of the e-h plasma is to alter the refractive index of the sample by amount $\Delta n(t)$ given by:

$$\frac{\Delta n(t)}{n_b} \simeq - \frac{2\pi N(t) e^2}{m^* \omega^2 \varepsilon_b} \tag{7}$$

where $n_b = \sqrt{\varepsilon_b}$ is the refractive index of the sample in the absence of e-h plasma.

3. Deflection of laser pulse in a wedge-shaped sample

We will now assume that a laser pulse with a uniform spatial intensitv profile:

$$I\ (z,t) = \begin{cases} I(t) & -d \leqslant z \leqslant d \\ 0 & \text{elsewhere} \end{cases} \tag{8}$$

is incident upon a wedge-shaped sample as shown in Fig. (1). The thickness of the wedge ($\sim \alpha^{-1}$ cm) is assumed to be negligible. When the laser intensity is low (i.e. no e-h plasmas excited), the laser beam will be deflected by an angle Ψ due to the refractive index, n_b, of the sample with Ψ given by:

$$\sin \Psi = n_b \sin \theta \tag{9}$$

θ being the apex angle of the wedge. In the presence of the e-h plasmas, the refractive index of the wedge changes to $n_b + \Delta n\,(t)$, so correspondingly Ψ changes to $\Psi + \phi\,(t)$. For $\Delta n << n_b$ we obtain:

$$\phi(t) \simeq \left[\frac{\Delta n(t)}{n_b}\right] \left[\frac{n_b \sin\theta}{(1-n_b^2\sin^2\theta)^{1/2}}\right] \tag{10}$$

Combining Eqs. (2), (7) and (10) we arrive at

$$\phi(t) = -\kappa \int_{-\infty}^{t} I(t')dt' \tag{11}$$

$$\text{where} \qquad \kappa = \frac{2\pi e^2 \alpha \sin\theta}{\hbar m^* \omega^3 n_b (1-n_b^2\sin^2\theta)^{1/2}} \tag{12}$$

4. Spatial profile of laser pulse after passage through wedge

We assume that after passing through the wedge the laser beam is focussed onto an array detector with a lens of focal length f. Because of the change in Ψ induced by the e-h plasmas the laser will produce a streak instead of a point on the detector. Let $\tilde{I}\,(z',t)$ be the laser intensity at point z' and time t, then the detector (assumed to have very slow time response) signal at z' will be given by

$$S(z') = \int_{-\infty}^{\infty} \tilde{I}(z',t)dt \tag{13}$$

If we assume the width of each element of the detector array to be Δ then the signal of the element centered at $z' = z_o'$ is:

$$S(z_o') = 2d\int_{z_o' - \frac{\Delta}{2}}^{z_o' + \frac{\Delta}{2}} dz' \int_{-\infty}^{\infty} I(t)\ \delta\ (z'(t) - z_o')\ dt \qquad (14)$$

Let t_o be defined as $z'(t_o) = z_o'$ then Eq. (14) can be written as:

$$S(z_o') = 2d\int_{z_o' - \frac{\Delta}{2}}^{z_o' + \frac{\Delta}{2}} dz' \int_{-\infty}^{\infty} \frac{I(t)\delta(t-t_o)dt}{\left|\frac{dz}{dt}\right|_{t_o}} \qquad (15)$$

For $\phi << \Psi$, z' can be related to θ by $z' = f\phi$. From this relation and Eq. (11), we get

$$\left|\frac{dz}{dt}\right|_{t_o} = f\left|\frac{d\phi}{dt}\right|_{t_o} = Kf\ I(t_o).$$

Substituting this result into Eq. (15) gives

$$S(z_o') = \frac{2d\Delta}{Kf} \qquad (16)$$

and is independent of z_o'!

This suggests that if we place instead a SH generating crystal in front of the detector array and measure only the resultant SH signal $S^{(2\omega)}(z_o')$, we would obtain

$$S^{(2\omega)}\ (z_o') = A\int_{z_o' - \frac{\Delta}{2}}^{z_o' + \frac{\Delta}{2}} dz' \int_{-\infty}^{\infty} [2dI(t)]^2\delta(z'/t) - z_o')dt \qquad (17)$$

where A is a constant giving the efficiency of the SH generation process. By integrating Eq. (17), we obtain

$$S^{(2\omega)}(z_o') = \frac{4d^2A\Delta}{Kf} I(t_o) \qquad (18)$$

Since there is a one-to-one correspondence between z_o' and t_o, one can in principle determine I(t) by measuring $S^{(2\omega)}$ as a function of z_o'. To illustrate how this can be accomplished, let us write Eq. (18) as:

$$S^{(2\omega)}(z') = JI(t) \tag{19}$$

where J is a parameter which can be determined experimentally. Equation (11) can be expressed as a differential equation

$$\frac{d\phi}{dt} = -\kappa I(t) = \frac{1}{f}\frac{dz'}{dt}.$$

Combining this equation with Eq. (19), we get

$$\frac{dz'}{dt} = -\frac{\kappa f}{J} \; S^{(2\omega)}(z') \tag{20}$$

Thus from the experimentally measured $S^{(2\omega)}(z')$, one can always integrate Eq. (20) numerically to obtain z' as a function of t. Substituting z' (t) back into Eq. (20) will enable I(t) to be determined.

As an example for demonstrating this technique, we will consider the use of Si with a modelocked Nd:YAG laser. For this system we will assume that $m^* \approx 0.18$ free electron mass, $\alpha \approx 20$ cm^{-1}, $\varepsilon_b = 11.9$, and $\theta = 15^\circ$. For a laser pulse of full width at half maxima of ~ 30 psec, a peak laser intensity of ~ 1.3 x 10^9 W/cm^2 will be needed to create a plasma density of ~4.3 x 10^{18} cm^{-3}. The resultant maximum deflection of the laser beam in the Si wedge is ~ 2.1 mrad.

From the above example, we see that one disadvantage of using Si as the deflector is its small deflection angle. This is limited by the density of the e-h plasma one can excite in Si without producing saturation effects. Presumably, by using instead direct band gap semiconductors such as InGaAsP alloys, much larger deflections at comparable e-h plasma densities can be produced because of the smaller effective mass of the electrons in these semiconductors.

Other applications of this technique which we cannot consider in detail here include: shortening of a femtosecond laser pulse by deflecting it in a wedge and using an aperture to extract a fraction of the laser pulse out, and generation of a femtosecond infrared pulse from a long pulse by deflection with e-h plasma generated by a femtosecond visible laser.

In conclusion, we have demonstrated that the e-h plasma generated bv a short laser pulse can be used to scan the laser beam, and from the resultant spatial profile the temporal distribution of the laser pulse can be determined. This technique can be used in conjunction with an autocorrelation measurement to determine completely the temporal characteristics of picosecond and femtosecond laser pulses. The ultimate time resolution of this technique is determined by the time it takes photoexcited carriers to equilibrate in semiconductors. This time is estimated to be $\lesssim 100$ fsec from the latest measurements.

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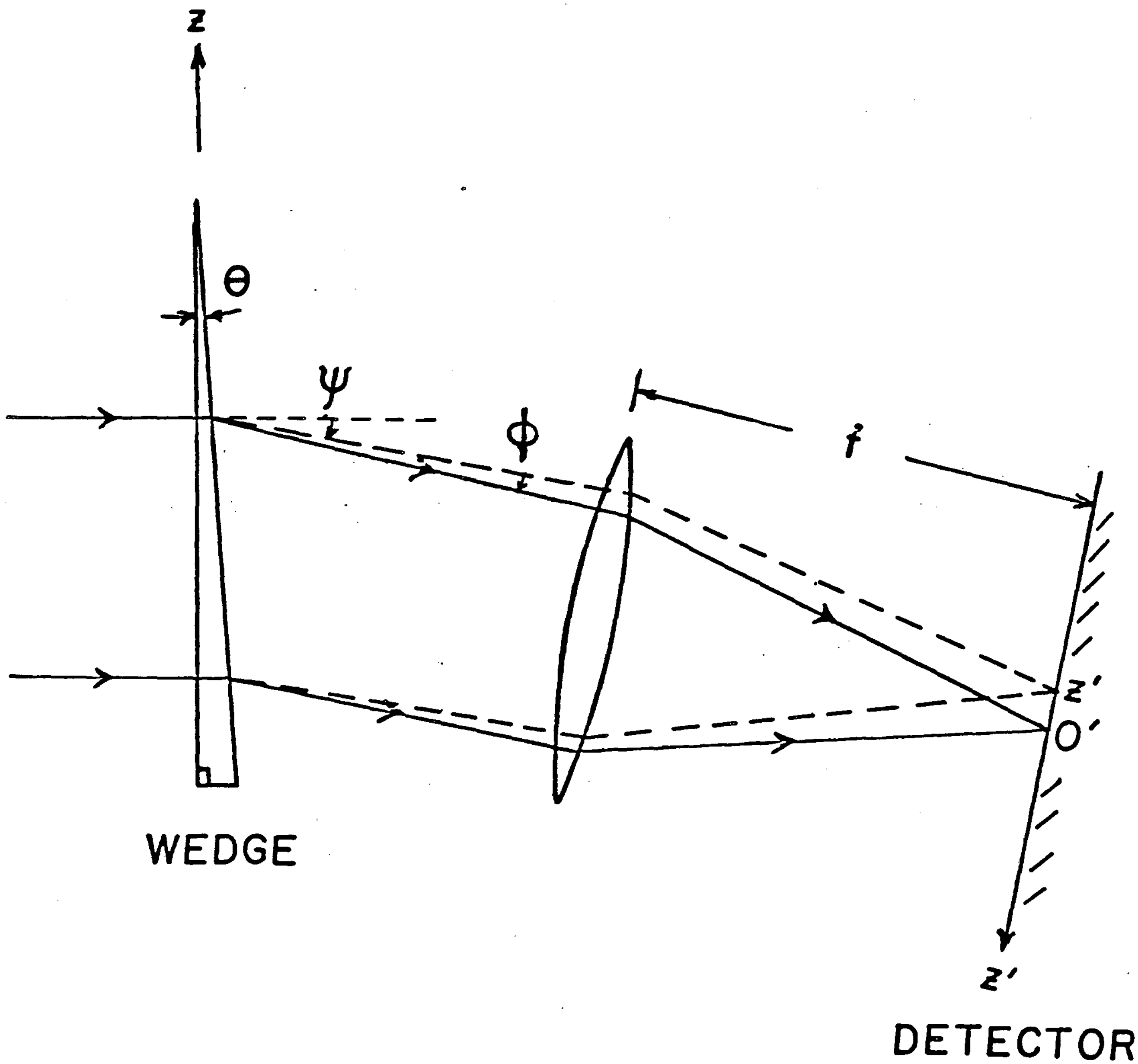

Fig. 1 Schematic experimental setup for observing the deflection of a picosecond laser pulse through a semiconductor wedge.

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