Light-emitting diodes as measurement devices for femtosecond laser pulses

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We present results showing that, when it is used as a photodetector, a light-emitting diode (LED) has a power-dependent response that can be used for sensitive detection and characterization of picosecond and femtosecond laser pulses. A characterization of a typical LED is presented at 800 nm, and we demonstrate how this effect can be used to construct an extremely compact novel autocorrelator based on a Wollaston prism.

In this Letter we describe results showing that a light-emitting diode (LED) used as an unbiased photodiode exhibits a nonlinear power-dependent response that can be used for sensitive detection and characterization of mode-locked femtosecond and picosecond laser pulses. This hitherto apparently unreported effect has an application in the construction of an inexpensive, robust, and compact autocorrelator, and we demonstrate a novel design based on a Wollaston prism that permits characterization of femtosecond pulses.

The LED used for this study was an ultrahigh-brightness AlGaAs diode (RS Components, stock number 564-015, catalog price ~\$2) that had a peak emission at 660 nm. Used as an unbiased photodiode, the LED was blind to radiation at 800 nm, as this wavelength corresponded to photon energies smaller than the band gap. In a preliminary experiment in which unfocused light from our Ti:sapphire laser was used, we measured negligible photovoltage when the laser operated cw, but when the laser was mode locked we observed a photovoltage of several millivolts. This peak-power-dependent behavior can be attributed to either direct two-photon absorption in the diode or, alternatively, second-harmonic generation over one coherence length (bulk GaAs has a nonlinear coefficient of approximately 90 pm/V), followed by absorption of the generated photon. The mechanism has at present not been identified to our knowledge, but it is possible that a combination of both effects exists, and the effect is very similar to one that we demonstrated at 3.5 μm.[1] In that study we used an InGaAs photodiode to perform autocorrelation measurements without using a frequency-doubling crystal. A similar effect was exploited to autocorrelate pulses at 1.5 μm by use of a silicon photodiode.[2] To our knowledge there have been no previous demonstrations in which a LED was used as a detector.

The results presented in Fig. 1 show the voltage response of the LED to mode-locked and cw incident light at a wavelength of 800 nm. In contrast with the preliminary experiment outlined above, we obtained the results described here by focusing light onto the LED, using a microscope objective with a nominal focal length of 15 mm. The mode-locked output was obtained from two separate lasers operating with pulse durations of 80 fs and 1 ps. The cw results also correspond to each individual laser, but in this case the mode locking was deliberately interrupted. The laser output was attenuated with a variable neutral-density filter and was then focused onto the diode surface. In the mode-locked cases the repetition frequencies of the lasers were both close to 80 MHz.

Analysis shows a near-quadratic response for a substantial range of incident powers in both picosecond and femtosecond operation. Below saturation a quadratic behavior is expected if either two-photon absorption or second-harmonic generation is the mechanism responsible for producing the photocurrent in the diode. For high incident powers, saturation of the output occurred near 1.4 V, which corresponds to the difference in Fermi energies between the p-type and n-type materials in the diode. The response to cw radiation was generally 2 orders of magnitude smaller than the mode-locked signal and can be attributed to

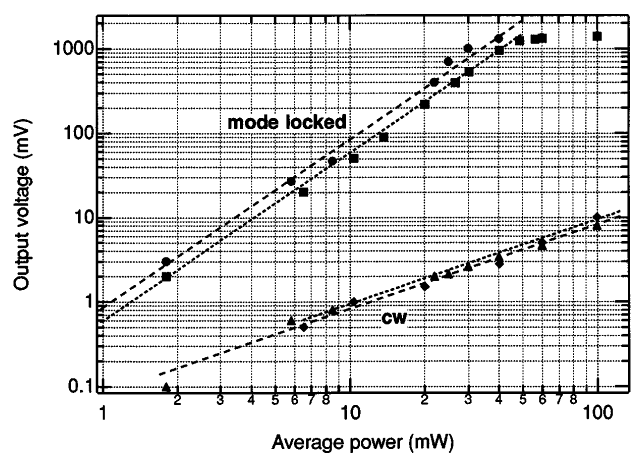

Fig. 1. Response of the AlGaAs LED to focused laser radiation at 800 nm. Circles, 80-fs pulses; squares, 1-ps pulses, triangles, cw output (femtosecond laser); diamonds, cw output (picosecond laser). Best-fit quadratic profiles are shown for femtosecond mode-locked pulses (dashed diagonal lines; 2% error) and picosecond mode-locked pulses (dotted diagonal lines; 1% error). Also shown are best-fit linear profiles for cw illumination from the femtosecond laser (dashed diagonal lines; 1.6% error) and the picosecond laser (dotted diagonal lines; 5% error).

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very inefficient direct detection of light at 800 nm by the diode. Best-fit profiles (see Fig. 1) illustrate an almost linear response to cw light. Although the results recorded for constant pulse durations show a quadratic response to incident power, this is not reflected in the measurements recorded at different pulse durations. The relative pulse durations imply that the diode response to 1-ps pulses should be more than 100 times smaller than that caused by 80-fs pulses, but instead our results indicate only slightly lower sensitivity. We are currently unable to present an adequate explanation of this behavior, but it seems likely that carrier recombination processes act to moderate the net number of carriers available for conduction.

Traditional autocorrelator designs use a Michelson interferometer to introduce a relative delay between two replica laser pulses, which are then recombined in a nonlinear mixing crystal to derive a correlation signal that is proportional to the square of the instantaneous intensity.[3] An autocorrelator based on a LED has several advantages over the conventional nonlinear crystal and photomultiplier tube combination. The LED is inexpensive, compact, extremely robust, and non-polarization dependent and gives nonphase-matched (and therefore broad pulse bandwidth and wide wavelength coverage) detection for photon energies from one-half band-gap to full band-gap values. To demonstrate the potential of a LED in an ultracompact autocorrelator, we used a novel scheme in which a Wollaston prism was employed to introduce relative delay between two orthogonal polarization components of the pulse. Recently studies reported on the development of compact Fourier-transform spectrometers in which the Michelson interferometer that is usually adopted was replaced by a polarizing interferometer based on a Wollaston prism.[4,5] Here we extend this approach to replace the Michelson interferometer that is usually found within an autocorrelator.

A Wollaston prism comprises two similar wedges of birefringent material joined by their hypotenuses to form a rectangular block. The optic axes within the two wedges are aligned perpendicularly to each other and parallel to the entrance–exit faces of the composite block. The angle of refraction at the internal interface of the prism depends on the polarization state of the light and hence leads to the customary use of a Wollaston prism as a polarizing beam splitter. The splitting angle is given by[6]

$$\alpha = 2(n_e - n_o)\tan\theta\,, \qquad (1)$$

where n_o and n_e are the ordinary and the extraordinary refractive indices, respectively, of the Wollaston material and θ is the wedge angle of the prism. In addition, the varying wedge thickness across the aperture introduces a path difference Δ between orthogonally polarized components that is given by[6]

$$\Delta = 2d(n_e - n_o)\tan\theta\,, \qquad (2)$$

where d is the displacement from the center of the prism. Note that because a refraction of the two polarization states occurs both at the interface and at the exit face of the prism the effective splitting point of the two orthogonally polarized rays lies on a plane midway between the interface and the exit face of the prism. The angle of this plane with respect to the exit face of the prism is given by[6]

$$\beta = (n_e + n_o)\theta/2n_e n_o\,. \qquad (3)$$

The Wollaston prism is angled such that this plane is perpendicular to the beam-propagation direction through the prism.

We used a quartz Wollaston prism (wedge angle 26°) to introduce a variable delay between the two pulse trains within an autocorrelator. The incident light was polarized at 45° to the optic axes of the prism and was focused at the effective splitting plane. For fringe-resolved interferometric resolution the delay introduced across the focused beam diameter must not exceed one-half wavelength of the incident light. For our system the required 40-μm spot size was easily achieved at 800 nm by use of a 30-mm focal-length lens. After the beam was split, the two orthogonally polarized rays experienced a relative delay [see Eq. (2)] that varied by ± 300 fs across the 20-mm prism aperture. On leaving the prism the rays were collimated by a 30-mm focal-length lens and propagated along parallel paths separated by 250 μm. A second polarizer at 45° selected a common polarization component, and a 15-mm focal-length microscope objective imaged both beams to the same point on the LED detector. The Wollaston prism was translated across the incident beam by an electromagnetic actuator, and the resulting interferogram was acquired in synchronism with the prism motion. A schematic of the autocorrelator is shown in Fig. 2.

The interferometric autocorrelation recorded from the femtosecond Ti:sapphire laser by a conventional autocorrelator based on a Michelson interferometer and a nonlinear crystal is shown in Fig. 3(a). The results in Fig. 3(b) were obtained with a Michelson interferometer and a LED, and the inset shows the intensity autocorrelation, which was recorded with an average power of only 350 μW incident upon the LED detector. The similarities between Figs. 3(a) and 3(b) confirm that, in the femtosecond domain, the LED can be used to measure genuine second-order autocorrelations. The results presented in Fig. 1 imply that this will also be true in the picosecond case. Figure 3(c) shows the autocorrelation measured with the Wollaston prism

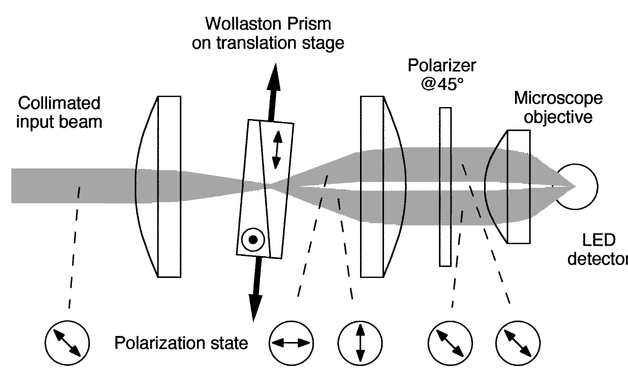

Fig. 2. Wollaston-prism-based autocorrelator.

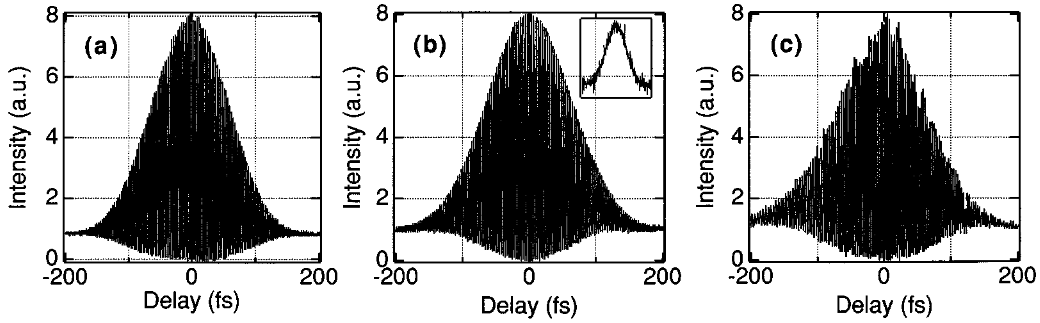

Fig. 3. Interferometric autocorrelators obtained (a) with a Michelson interferometer, a nonlinear crystal, and a photomultiplier; (b) a Michelson interferometer and a LED; and (c) a Wollaston prism and a LED. The respective pulse durations inferred from the profiles are 81, 85, and 88 fs.

Table 1. Comparison of Common Wollaston-Prism Materials for Autocorrelator Applications[a]

Material	$t_{1\text{ ps}}$ (mm)	Broadening of 100-fs Pulse After $t_{1\text{ ps}}$ (%) At $\lambda =$ 800 nm	At $\lambda =$ 1000 nm	At $\lambda =$ 1200 nm
Quartz	~33	8	2.7	0.6
Calcite	~2	1.6	0.04	0.01
MgF_2	~30	1.1	0.27	44

[a]The distance $t_{1\text{ ps}}$ is defined as the prism thickness required for a maximum delay of ± 1 ps between the orthogonal polarization components of the transmitted pulse. Pulse-broadening values are derived for the mean refractive index of the prism.

interferometer and the LED. For technical reasons the measurement given in Fig. 3(a) was made with an output from the opposite end of the laser cavity to that used for measurements in Figs. 3(b) and 3(c). Consequently, the autocorrelations of Figs. 3(b) and 3(c) appear slightly chirped, as the pulse has made a further pass through the intracavity optics before measurement. A small amount of additional chirp resulting from the thickness of quartz (10 mm) encountered by the pulse during its transit through the prism is responsible for the longer pulse duration determined from Fig. 3(c). The additional noise that is apparent in Fig. 3(c) may be related to the mechanical mechanism that was used to translate the prism, or it might be caused by inhomogeneities in the prism material or at the optical interface between the two prism components. Wollaston prisms are available in other materials that permit optimization for low dispersion at particular laser wavelengths. Table 1 shows a selection of available materials and their associated dispersion parameters. For a typical Ti:sapphire wavelength of 800 nm we expect MgF_2 or calcite to be the most suitable material. For applications at wavelengths greater than 1 μm calcite or quartz would be an appropriate choice.

The autocorrelation technique presented here can be compared with other techniques that also use only electronics to perform ultrafast-pulse measurement. The first of these used a microwave mixer circuit as a nonlinear element and achieved a temporal resolution of 2 ps,[7] and recent research extended this technique to the femtosecond domain with a resolution of 50 fs.[8] In contrast, the nonlinearity in a LED is instantaneous and so has a temporal resolution suitable for measuring even extremely short femtosecond pulses.

In summary, we have demonstrated a new and useful effect in a light-emitting diode that can be used for sensitive detection and characterization of picosecond and femtosecond pulses over a wide wavelength range. Recent results in which high-quality fringe-resolved femtosecond autocorrelations at 1300 nm were obtained confirmed that the bandwidth of the LED extends to wavelengths approaching the half-band-gap energy. The broad bandwidth and small substrate thickness of the LED suggest a possible application in the measurement of sub-10-fs Ti:sapphire pulses, and research is currently under way to determine whether this is indeed the case.

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