Autocorrelation measurement of 6-fs pulses based on the two-photon-induced photocurrent in a GaAsP photodiode

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We experimentally characterize the two-photon response of a GaAsP photodiode by use of a femtosecond Ti:sapphire laser tuned below the diode bandgap. The photodiode is shown to be highly suitable for real-time second-order autocorrelation measurements of pulses as short as 6 fs in duration and with energies as small as a few picojoules. © 1997 Optical Society of America

Conventional pulse-width measurement techniques for ultrashort optical pulses have relied on the detection of light generated by either a $\chi^{(2)}$ or a $\chi^{(3)}$ process.[1-3] The most common method used to infer the temporal width of a pulse is based on a Michelson-type autocorrelator and the generation of a phase-matched second-harmonic signal. For sub-10-fs optical pulses[4-6] the use of a thin (<25-μm) frequency-doubling crystal is necessary to minimize the added dispersion and phase mismatch between the fundamental and the second-harmonic frequencies. Phase mismatch, in particular, can lead to a spectral-filtering effect that can significantly distort the measured autocorrelation function.[7] The polishing of such thin crystals can be difficult and costly, and the small conversion efficiency over the short path length requires that one use a photomultiplier tube (PMT) to detect the generated second-harmonic signal.

Aside from second-harmonic generation, one can use other nonlinear-optical processes that do not require phase matching for second-order autocorrelation measurements.[8-13] By use of two-photon-induced free-carrier generation in semiconductors, second-order autocorrelation measurements of picosecond[10,11] and 100-fs pulses[12,13] were obtained. A significant advantage of incorporating a semiconductor photodiode into autocorrelation measurements is that the desired two-photon response and the transformation of light into electric current are combined into a single solid-state device.

For an autocorrelator device to gain wide acceptance, it is critical that one completely characterize its properties, including the pulse width and the spectral dependence of the two-photon-induced photocurrent, the lower limit of the pulse duration owing to the inherent dispersion of the device, and the dynamic range over which the quadratic intensity dependence is maintained. To date, only the last measurement has been made on solid-state semiconductor devices. Although the quadratic response is a necessary prerequisite for a second-order autocorrelation, it is by no means a sufficient condition. For example, the reliability of an autocorrelation measurement is greatly determined by the uniformity of the spectral response.[7] Furthermore, it remains unclear whether the dispersion and the response time of the nonlinearity of the device allow for the measurement of sub-10-fs optical pulses generated by state-of-the-art lasers.

In this Letter we report on the characterization of a GaAsP photodiode for use in measuring pulses ranging from 6 fs to 1 ps in duration produced by a mode-locked Ti:sapphire laser at various repetition rates in the range of 1 kHz to 80 MHz. The current generated by two-photon absorption is measured as a function of pulse width, pulse energy, and wavelength. Our results demonstrate that an ordinary off-the-shelf GaAsP photodiode is more sensitive, has a broader spectral response, is easier to implement, and is far cheaper than a conventional second-harmonic crystal–PMT combination.

For our measurements we used a large-area (5.6 mm × 5.6 mm) GaAsP diffusion diode (Hamamatsu G1117). The spectral bandwidth of the linear response ranged from 300 to 680 nm, with a peak response at 660 nm, allowing for a two-photon response in the region of 680–1360 nm. The thickness of the active region was of the order of a few micrometers, and the response time of the diode was measured to be approximately 5 μs. We used a low-impedance current preamplifier to produce a voltage output proportional to the generated diode current.

The output of a 100-fs, 80-MHz Ti:sapphire laser tuned to 800 nm was focused onto the diode, and the induced current was measured as a function of average power P. In Fig. 1 we plot the diode response for two values of spot size ω_0. In the tighter focusing case ($\omega_0 = 25$ μm), a two-photon signal could be measured for pulse energies as small as 2 pJ. The diode response remained nearly quadratic as the intensity was increased to 1 GW/cm^2, at which point higher-order nonlinear processes, possibly three-photon absorption or excited-state absorption, contribute to the signal. At intensities near 4 GW/cm^2, saturation of the output was observed. For the 80-μm

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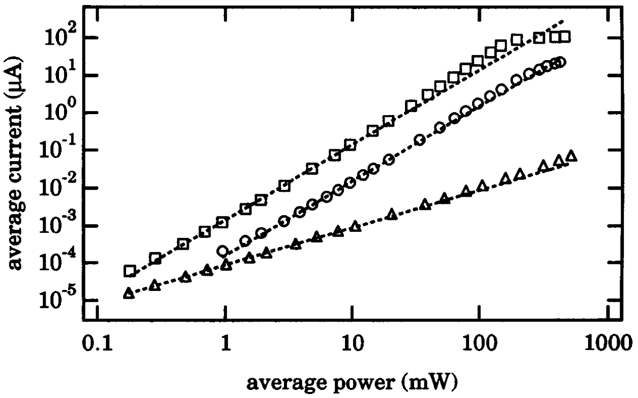

Fig. 1. Observed diode current as a function of average incident power for an 80-MHz train of 100-fs pulses from a Ti:sapphire laser tuned to 800 nm and focused to 80 μm (circles) and 25 μm (squares) and for a cw laser tuned to 800 nm and focused to 80 μm (triangles). The dotted curves represent the respective quadratic and linear fits to the data.

spot size, saturation was seen to occur at intensities approximately three times smaller than at 25 μm. We fitted the measured current data to $i_d = qP^2$, with $q = 1.52 \times 10^{-4}$ μA/mW^2 for $\omega_0 = 80$ μm and $q = 1.42 \times 10^{-3}$ μA/mW^2 for $\omega_0 = 25$ μm. From these data we find that at 1 GW/cm^2 the quantum efficiency of the two-photon response, defined as the number of photoelectrons per incident photon, of $\sim 2 \times 10^{-4}$ is comparable with that of a 100-μm β-barium borate (BBO) crystal–PMT combination.

We measured the response of the diode to a cw Ti:sapphire laser tuned to 800 nm to examine the effects of one-photon absorption and thermal heating. The generated photocurrent that was due to linear absorption was significantly smaller than the nonlinear response. At >100 mW of average power, a deviation in the linearity that could be a result of heating of the diode case was observed. The linear absorption at the low-intensity side and the higher-order nonlinearity at the high-intensity side limited the dynamic range of the two-photon response to approximately 4 decades for real-time autocorrelation measurements.

The diode response to a single pulse was measured with a 1-kHz Ti:sapphire regenerative amplifier (Clark-MXR), which produced 1-mJ, 95-fs pulses. Shot-to-shot fluctuations in the pulse energy were less than 4%. A fraction of the amplifier output was spatially filtered and focused onto the diode. The peak diode current was measured for focused spot sizes of 850 and 200 μm as a function of incident pulse energy (Fig. 2). As with the mode-locked oscillator, the response of the diode is nearly quadratic for intensities as high as 1 GW/cm^2, at which point higher-order effects appear. At slightly higher intensities, saturation of the output was observed. By adjusting the dispersion compensation in the compressor of the chirped-pulse-amplification system, we varied the pulse duration τ of the output from 95 to 900 fs. In Fig. 3 we plot the measured peak diode current as a function of pulse duration for a 400-nJ pulse focused to $\omega_0 = 850$ μm. The data closely fit the expected dependence τ^{-1}, which is characteristic of the time-integrated response of a photodiode. Note that this result is different from the observations of Reid *et al.*[12]

To characterize the wavelength dependence of the two-photon response, we measured the generated photocurrent that was due to an incident ~100-fs pulse as the center wavelength of the pulse was varied (Fig. 4). We normalized the generated current ($i_d \tau \lambda^2 / P^2$) to account for variations in power, pulse width, and focused spot size as the wavelength was changed. The data were taken at various incident powers, which yielded a range of values represented by the error bar in Fig. 4. The response can be seen to be relatively uniform in the range 720–950 nm. For comparison, in the same figure we also depict the spectral response of a 100-μm-thick BBO crystal for type I phase matching calculated according to Ref. 7. The appreciably narrower frequency-acceptance range of the crystal becomes significant in the characterization of pulses with irregular spectra and arbitrary spectral phases. Furthermore, the spectral response of the detector and filter used in conjunction with the second-harmonic crystal may narrow the useful bandwidth even further.

In Fig. 5 we show the interferometric autocorrelation trace of an ~6-fs pulse measured with a 15-μm BBO crystal (solid curve) and the photodiode

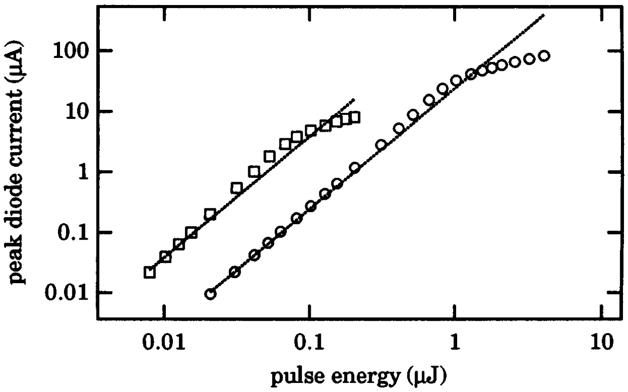

Fig. 2. Peak diode current as a function of incident pulse energy for a 1-kHz train of 100-fs pulses produced by a Ti:sapphire regenerative laser amplifier. The circles (squares) are for a spot size of 850 μm (200 μm) at the diode. The dotted lines represent the quadratic fits to the data.

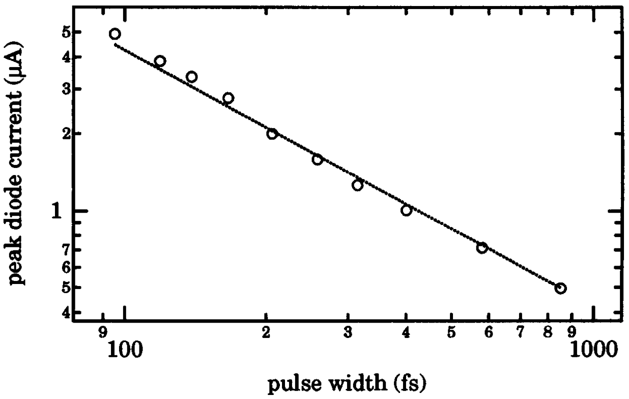

Fig. 3. Peak diode current as a function of pulse duration for a 1-kHz train of 400-nJ pulses focused to 850 μm (circles). The dotted line represents a τ^{-1} fit to the data.

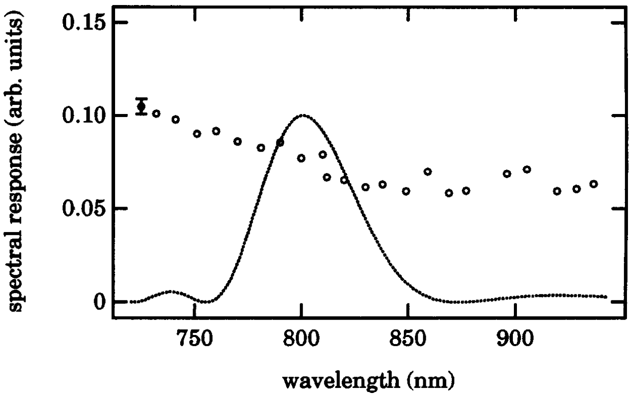

Fig. 4. Spectral dependence of the generated two-photon current for a GaAsP photodiode measured with an 80-MHz train of 100-fs pulses (circles). The calculated spectral response of a 100-μm BBO crystal is shown by the curve.

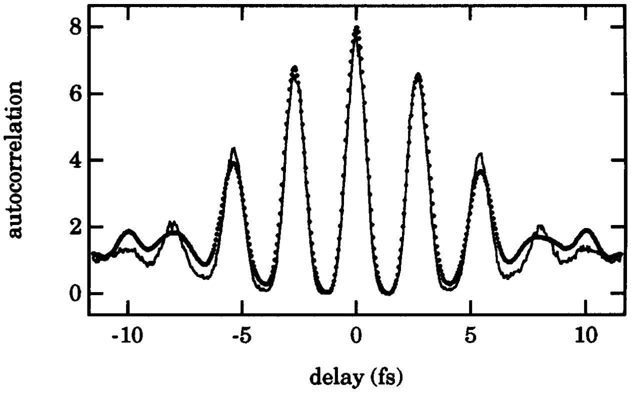

Fig. 5. Interferometric autocorrelation measurement of a 6-fs pulse with a GaAsP photodiode (circles) and a 15-μm BBO crystal (curve).

(circles). The pulses were obtained from a system capable of producing 5-fs pulses[4]; however, we filtered out the spectral components of the white-light continuum below ~680 nm in the compressor to avoid the one-photon response of the photodiode. We carefully removed the resin coating covering the diode's surface to eliminate unwanted material dispersion.[14] Although the two traces displayed in Fig. 5 exhibit close similarity, the autocorrelation measured with the photodiode is noticeably less noisy than that obtained with the thin BBO crystal and PMT. This measurement clearly proves that the dispersive pulse broadening in the active region and the finite response time of the nonlinearity are negligibly small. Furthermore, in the case of broadband ultrashort pulses, the autocorrelation measured with a photodiode might yield a better estimate of the pulse duration than that obtained with a frequency-doubling crystal, in which both material dispersion and spectral filtering are present.[7] We also measured the autocorrelation of 5-fs pulses with a GaP photodiode (Hamamatsu G1962); however, to obtain reliable interferometric autocorrelation traces one needs to subtract the relatively large linear response that results from doping impurities in the wafer.

In conclusion, the two-photon response of a GaAsP diffusion diode was characterized for use in the measurement of femtosecond pulses at 800 nm. The diode current was observed to vary quadratically with pulse energy and inversely with pulse duration. The spectral dependence of the two-photon response of the diode was shown to be relatively uniform in the 720–950-nm range. Pulse broadening owing to material dispersion was sufficiently small for measurement of the autocorrelation of pulses as short as 6 fs. In addition, the sensitivity of the diode allowed for real-time second-order interferometric autocorrelation measurement of femtosecond pulses with only a few picojoules of energy. At present, commercially available photodiodes should allow for autocorrelation measurements of pulses with wavelengths ranging from 500 nm to 10 μm. Replacement of the second-harmonic crystal with a photodiode provides numerous advantages, from ease of alignment and the elimination of phase-matching requirements to an increase in sensitivity and a significant reduction in cost. Furthermore, one can use a photodiode-based autocorrelator to characterize the temporal amplitudes and phases of sub-10-fs pulses.[15,16] Single-shot autocorrelations of unamplified femtosecond pulses should also be feasible with a photodiode array.[10,13]

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