Ultrashort Pulse Measurement Using High Sensitivity Two Photon Absorption Waveguide Semiconductor

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Abstract: Two photon absorption in a reverse-biased *pin* AlGaAs optical waveguide is observed. This waveguide was used as a combined nonlinear mixer and detector of an autocorrelator for measuring the pulse width of 1.3μm wavelength optical pulses. The autocorrelation trace gives the FWHM of a 1.3μm Q-switched semiconductor laser to be approximately 13 ps.

Keywords: Two photon absorption, autocorrelator, semiconductor laser, Q-switching, optical waveguide

1 Introduction

The accurate measurement and a reliable knowledge of the optical pulse structure are very essential in both basic research and applications of lasers.

All the techniques for determining the temporal profile I(t) of a laser pulse can be generally classified into direct and indirect methods of diagnostics [1]. The direct method consists of measurements of I(t) taken with a photodetector-oscilloscope combination or an electron-optical camera. The indirect method deals with the correlation functions of I(t) of different orders [2].

Optical autocorrelation is perhaps the most commonly used technique for the measurement of the pulse width of ultrashort optical pulses which are beyond the resolution of the fastest photodiodes [2]. In order to measure the duration of ultra short laser pulses, various autocorrelation techniques have been developed [3, 4]. A conventional autocorrelator consists of a Michelson interferometer, which splits an incident train of laser pulses into two paths. Both beams are then combined in a second harmonic generating crystal and the pulse width is obtained by measuring the intensity of the second harmonic generated (SHG) light as a function of the time delay between the two beams [5, 6]. And, also, two-photon-induced photoconductivity (TPC) in commercial photodiodes [7-9]. Using TPC is relativity wavelength insensitive, so that photons of energy between Eg/2 and Eg can be used to obtain an autocorrelation trace, where as a SHG crystal has to be phase match at the appropriate wavelength. Also, due to the increases nonlinear interaction length, using the waveguide geometry for the photodiode increases the sensitivity of the measurement and allows greater opportunity for integration. However, it has the disadvantage that some temporal resolution is lost due to dispersion.

2 Waveguide design and fabrication

A ridge p-i-n waveguide structure which consisted of a $Al_{0.2}Ga_{o.8}As$ waveguide core surrounded by $Al_{0.3}Ga_{0.7}As$ cladding regions, was grown by molecular beam epitaxy (MBE). The upper and lower cladding layer thicknesses were 1μm and 4 μm respectively, both sufficiently thick to ensure only a small optical leakage into the cap and substrate. In order to reduce losses due to free carrier absorption, those parts of the cladding which were expected to have significant overlap with the optical mode were left undoped. This device was designed to measure pulse widths with a wavelength greater than 840 nm. Ridge waveguide 3µm wide, 1 mm long, and separated by about 100µm were fabricated by dry etching; wet etching was then used to mesa between the ribs to isolate individual devices, Fig. 1. The reverse breakdown voltage was at least -25 V, and the dark current of the devices at 5V was measured to be -50 pA. It is very important that this dark current is as small as possible in order to increase the autocorrelator's sensitivity.

3 Experiments

To test the correct operation of the device, single beam measurements were carried out initially. Mode-locked pulses from the YAG laser were end fire coupled into the ridge waveguide, which was reversed biased by 4.5 V. A 1kΩ resistor was placed in series with the waveguide, and the photocurrent was found by measuring the voltage across the resistor using a lock-in amplifier. The photocurrent was found to be extremely sensitive to the degree of coupling of the laser beam into the guided mode, and also to the quality of mode-locking of the laser. Using both mode-locked and CW laser beams in turn, the average photocurrent was then measured as a function of the average input intensity of the beam, and the resulting graph is shown in Fig. 2.

The shape of these plots can be easily explained. For a single CW beam, the average photocurrent is given by [10]:

$$\left(J_{ph}\right)_{CW} = e\Omega\left(\frac{\alpha}{h\nu} I_{ave} + \frac{\beta}{2h\nu} I_{ave}^{2}\right) \quad (1)$$

where e is the electron charge, Ω is the volume in which the photo-generated carriers are created, hν is the photon energy, I_{ave} is the intensity of the beam, β is the two photon absorption coefficient, and α is the one photon absorption coefficient.

Also, the average photocurrent for the mode-locked beam is given by:

$$\left(J_{ph}\right)_{ml} = e\Omega\left(\frac{\alpha}{h\nu} I_{ave} + \frac{\beta t_p}{2\sqrt{\pi} h\nu T} I_{ave}^{2}\right) \quad (2)$$

where t_p is the time between mode-locked pulses, and T is the duration of the laser pulses.

It may be seen that the linear term in the expressions for the photocurrent is identical for a CW and a mode-locked laser beam, as expected, while the quadratic terms vary only by a constant factor.

The fit to the experimental points was obtained from (1) and (2). For the CW case, the photocurrent is directly proportional to the input intensity, as seen from the fit to the solid straight line. This is because there is still some residual one photon absorption. The photocurrent for the mode-locked case is, however, substantially greater. This is because the peak intensity in the waveguide is now higher, so that TPC becomes the dominant effect. Because the conductivity is governed by a two photon effect, there is now a quadratic relationship between the photocurrent and the average intensity in the waveguide, as seen from the fit to the parabola in Fig. 2.

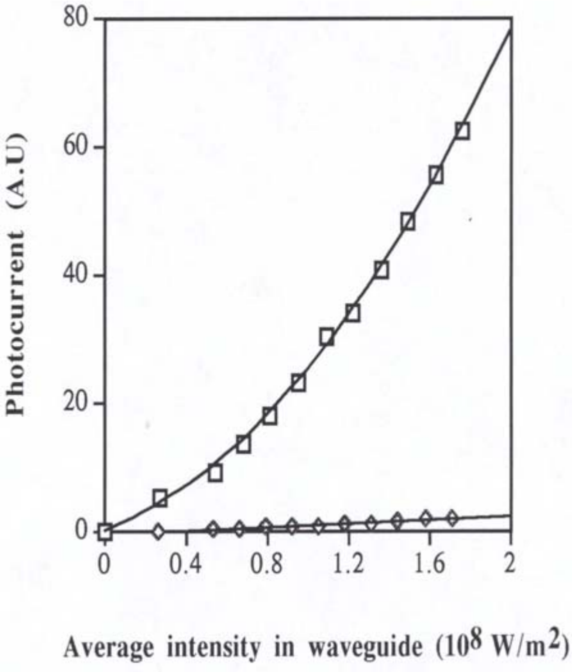

Fig.2: Intensity-dependence of the conductivity of the waveguide. The solid line and a parabola fitted to the experimental points for CW and mode-locked case, respectively.

The experimental set up for the autocorrelation measurements is shown in Fig. 3.

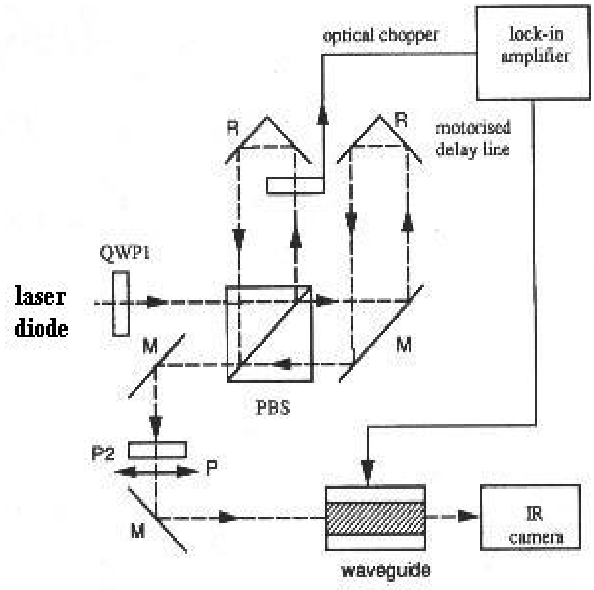

Fig. 3: Experimental set-up
Keys: M: mirror, R: retroreflector, PBS: polarizing beam splitter, QWP: quarter wave plate, P: polarizer

Optical pulse were generated by a Q-switched diode operating at 1.3μm. the full width half maximum (FWHM) duration of the optical pulses was measured using a conventional SHG autocorrelation to be 12.6 ps (assuming a Gaussian intensity profile). It is noted that for Gaussion pulses, the width of the autocorrelation trace was divided by $\sqrt{2}$ to obtain the true pulse width. The average power incident on the waveguide was 0.6 μW. The quarter wave plate in Fig. 3 made the pulses circularly polarized, thus enabling the polarizing beam-splitter to divide the pulse equally into two orthogonal polarizations. The two orthogonally polarized pulses were recombined after one was delayed with respect to the other by the motorized variable delay line. The beam was the end-fire coupled into a reverse biased p-i-n waveguide, where the corresponding photocurrent was measured by lock-in amplifier and hence the pulse width measured. An infra-red camera was placed at the end of the waveguide to aid alignment and to ensure that the light guided through the waveguide was in zeroth order mode. A piezo-electric translator (PZT) was placed in stationary arm of the autocorrelator to eliminate the coherence spikes.

The intensity autocorrelation trace is shown in Fig. 4. The average autocorrelation photocurrent as a function of time delay between pulses is given by [9]:

$$J_{ph}(t_d) = e\Omega\left\{\frac{2\alpha}{h\nu}I_{ave} + \frac{\beta t_p I_{ave}^2}{\sqrt{\pi}h\nu T}\left[1+\exp\left(-\frac{t_d^2}{T^2}\right)\right]\right\} \tag{3}$$

Where td is the time delay between the two pulses in the waveguide. It can be seen from the expression that, for Gaussian pulses, the average photocurrent has the same Gaussian dependence on the time delay between the two beams as a conventional SHG autocorrelator. Therefore any autocorrelation trace obtained from this method should be divided by $\sqrt{2}$ to obtain the true pulse width.

From the intensity autocorrelation trace shown in Fig. 4, the FWHM of the Q-switched semiconductor laser pulses was calculated to be 13 ps (assuming a Gaussion intensity profile). This result is in close agreement with SHG autocorrelation measurement of the optical pulse of this laser (12.2 ps), the discrepancy being 6% which is within the experimental accuracy (± 10%). Because of high efficiency of the waveguide autocorrelator than the TPC in the waveguide [8,9], a waveguide autocorrelator is therefore much more suitable for applications where optical power levels are lower, such as for semiconductor lasers.

Also the ratio of the correlation peak to the background was not 2:1 as would be expected theoretically [6], but was only 1.5:1. This is attributed to the effect of single photon absorption on the contrast ratio of the two photon waveguide autocorretor [11]. The peak power level in the waveguide was approximately 50 mW, corresponding to an insertion loss of approximately 20dB. The dispersion in the waveguide was negligible because the dispersion length is much more than the length of the laser pulses.

Interferometricautocorrelation measurements may be observed by this device.

4 Conclusions

We have characterized the nonlinear intensity dependence of the photocurrent for both a CW and mode-locked laser beam in a AlGaAs waveguide detector. Then, we have used two photon absorption (TPA) in an AlGaAs waveguide for a high sensitivity autocorrelator suitable for measuring the pulse width of low power 1.3μm wavelength optical pulses. The autocorrelation pulse widths are consistent with that expected from a conventional SHG autocorrelation.

The use of TPA in a semiconductor waveguide was found to be a practical and sensitive alternative to the use of SHG for autocorrelation measurements. Furthermore, the device is sensitive and, being waveguide-based, has the potential both for integration and for simple coupling into a fiber-based interferometer.

5 Acknowledgements

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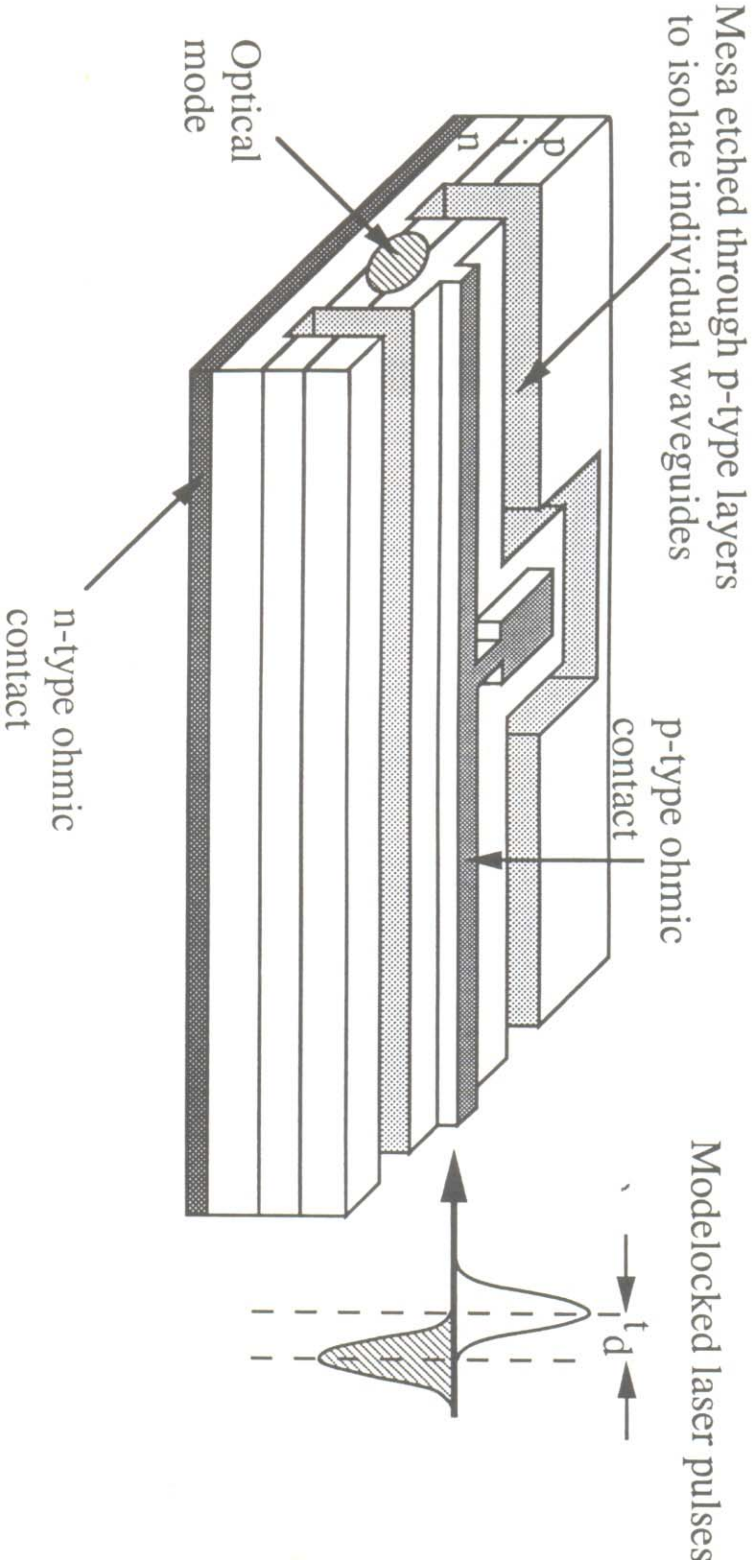

Fig. 1 Schematic of a p-i-n waveguide autocorrelator

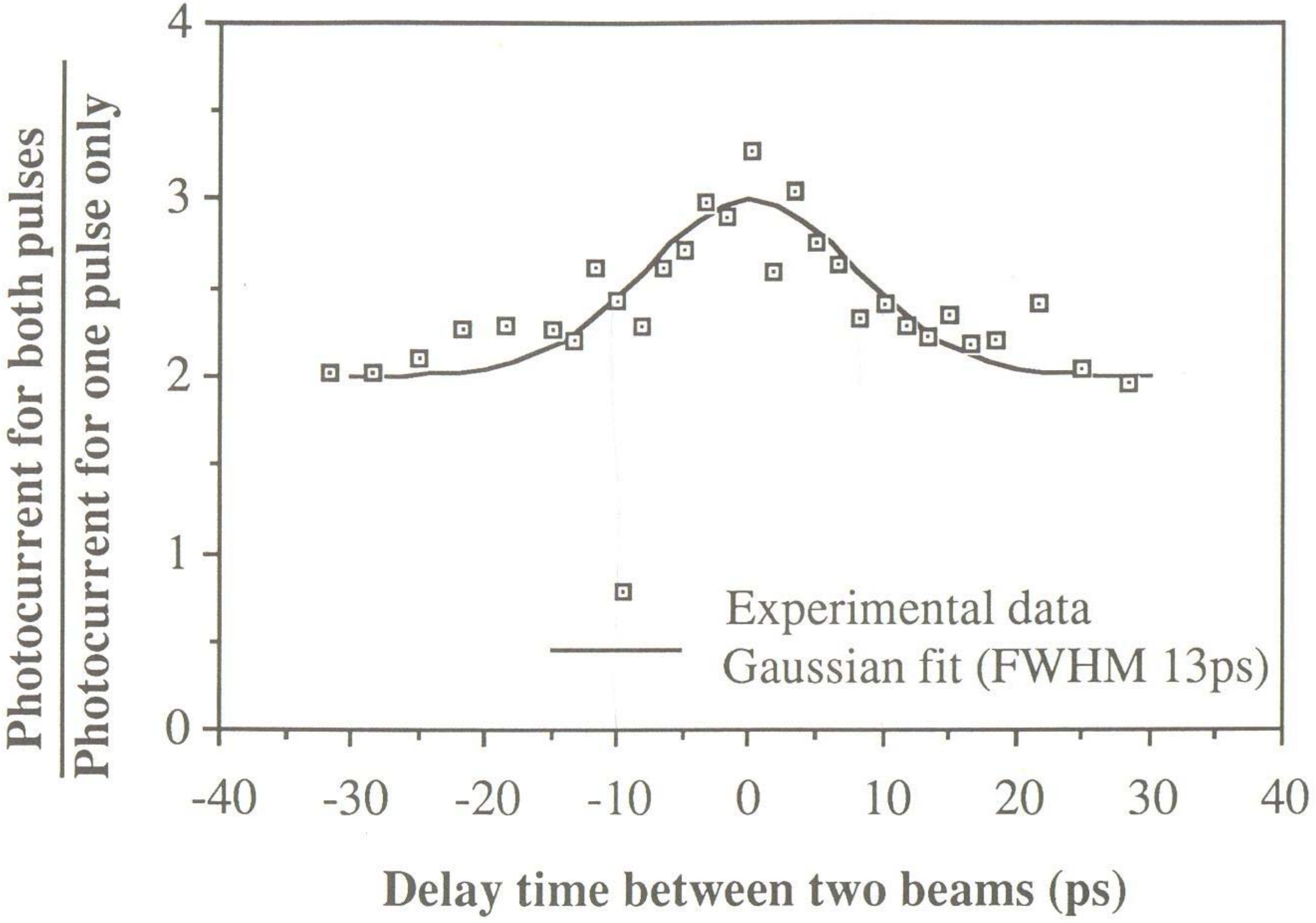

Fig. 4 Autocorrelation trace of a 1.3 μm Q-switched semiconductor laser