Ultrafast Optical Thresholding based on Two-Photon Absorption GaAs Waveguide Photodetectors

Z. Zheng, A. M. Weiner, J. H. Marsh, and M. M. Karkhanehchi

***Abstract*—We report measurements of the pulsewidth dependence of the two-photon absorption photocurrent in GaAs p-i-n waveguide photodetectors using subpicosecond optical pulses at 1.5 μm. For fixed pulse energy, the photocurrent is observed to depend linearly on the inverse of the optical pulsewidth. A subnanosecond electrical response is also observed. Our results show the feasibility of applying such devices for nonlinear processing in ultrafast optical code-division multiple-access and other ultra high-speed optical network applications.**

***Index Terms*—Code division multiaccess, nonlinear optics, optical pulse shaping, photodetectors, semiconductor waveguides, threshold decoding, two-photon absorption, ultrafast optics.**

ALL-OPTICAL signal processing can potentially be used for pattern matching applications in broad-band optical networks. For example, in proposed coherent ultrashort pulse code-division multiple-access (CDMA) systems [1], multiplexing would be achieved by assigning different, minimally interfering spectral phase codes to different transmitter-receiver pairs. The spectral coding process would stretch coherent femtosecond input pulses into picosecond duration pseudonoise bursts by using a pulse shaper to transfer a pseudorandom phase pattern from a spatial mask onto the spatially dispersed spectrum [6]. The receiver must then detect waveforms corresponding to the desired code while rejecting unwanted multiple-access interference. Code recognition could be accomplished by optical matched filtering followed by a nonlinear optical thresholder. The decoding process could be realized by using a pulse shaper containing a phase mask conjugate to that used in the encoder. Correctly coded waveforms would be decoded into short and intense femtosecond pulses, while incorrectly coded waveforms would remain low intensity picosecond pseudonoise bursts (but with the same energy per pulse). The thresholder would then distinguish between properly and improperly decoded signals using the contrast in their peak intensity. Although the nonlinear optical response would need to be very fast, the electrical response of these devices could be as slow as the data rate per channel (~Gb/s). A similar scheme could potentially be applied for header recognition in ultrafast time-division networks.

In this letter, we report experiments which demonstrate the feasibility of using two-photon absorption (TPA) in semiconductor waveguides as the nonlinear detector mechanism for such applications. As is well known, TPA is an instantaneous effect in which two photons (usually with energies below the bandgap) are absorbed simultaneously to generate a single electron-hole pair. In recent years, TPA has begun to play an important role in ultrafast guided-wave nonlinear optics. Nonlinear absorption induced by TPA has been recognized as one of the chief limiting factors in all-optical switching in semiconductor waveguides [2] and has also led to break-up of spatial solitons in glass waveguides [3]. In contrast to these deleterious effects, the nonlinear photoconductivity associated with TPA has been applied for autocorrelation measurements of ultrashort pulses [4], [5]. Experiments using 1.06- and 1.3-μm pulses tens of picoseconds in duration demonstrated that GaAs waveguide photodetectors could be used as high-sensitivity TPA autocorrelators [5]. Here, we investigate the TPA-induced photocurrent in GaAs waveguides as a function of optical pulsewidth for pulses ranging from a few picoseconds down to ~150 fs. Our experiments reveal a strong pulsewidth dependence of the photocurrent which can be used to approximate the desired ultrafast thresholding function. Furthermore, we demonstrate for the first time to our knowledge that these nonlinear waveguide photodetectors can have subnanosecond electrical response times suitable for Gb/s communications applications.

The TPA waveguide detector used here was similar to those used in earlier autocorrelation experiments [5]. The MBE-grown GaAs ridge waveguide was 1-mm long and 3-μm wide. It consisted of a p-i-n structure with a 0.6-μm-thick GaAs (870-nm bandgap) layer sandwiched between $Al_{0.15}Ga_{0.85}As$ layers. For photons at 1.5 μm, there was little linear absorption but strong two-photon absorption. The dark current at a typical −5 V bias was about 90 pA, which was negligible for our experiments.

The experimental setup is shown in Fig. 1. Our experiments used 150-fs pulses at 1.5-μm wavelength and 80-MHz repetition rate from a Spectra Physics femtosecond optical parametric oscillator synchronously pumped by a mode-locked Ti:Sapphire laser. A polarizer was used to set a horizontal input polarization, and a stepper motor driven variable attenuator wheel was used to adjust the optical power. For some measurements, a mechanical chopper was used to enable lock-in detection. Light was coupled into the waveguide by using a 40 × microscope objective. Fresnel reflection from the uncoated front facet introduced 30% reflection loss of the input light.

For pulsewidth dependent measurements, the beam was sent into a double-pass pulse shaper [6] before it was coupled into the waveguide. The pulse shaper consisted of a 600 line/mm

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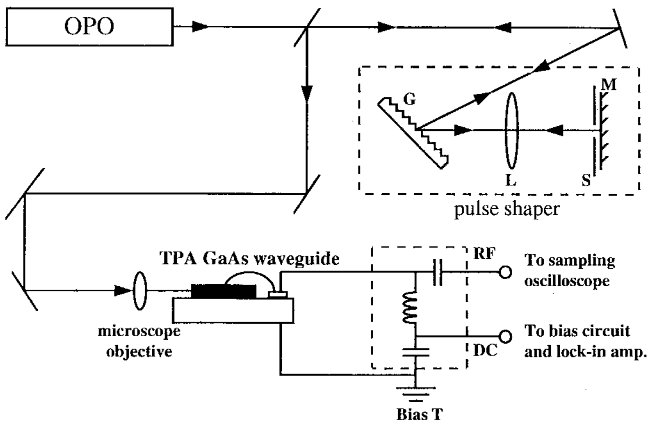

Fig. 1. Scheme of two-photon absorption thresholding experiment. OPO: Ti:Sapphire laser pumped femtosecond optical parametric oscillator; G: 600 line/mm grating; L: achromatic lens; S: slit; M: flat mirror.

grating, an achromatic lens ($f = 190$ mm) and a planar mirror placed in the focal plane of the lens. With the pulse shaper adjusted to the zero-dispersion point and a variable slit placed just before the mirror, this worked as an adjustable pulse stretcher [6]. The slit acted as a spectral window, and its width was adjusted to change the width of spectrum and, hence, the pulsewidth. Pulsewidth adjustment was accomplished with no spatial movement of the beam. Since the experimental results were very sensitive to any changes of coupling condition, this was crucial to get reliable data. The pulsewidth was measured by an autocorrelator.

The waveguide was reverse biased by a dc power supply connected through a bias tee. A home made metal finger probe was used to provide the electrical contact to the wire-bonded waveguide. A sampling oscilloscope and a lock-in amplifier were connected to the bias tee to measure the photocurrent time response and the average photocurrent, respectively.

The evolution of the carrier density N is given as [5]

$$\frac{dN}{dt} = \frac{\alpha}{h\nu} I + \frac{\beta}{2h\nu} I^2 \tag{1}$$

where I is the intensity of the beam, β is the two-photon absorption coefficient and α is the one-photon absorption coefficient. We assume that the light remains undepleted so that I and N are nearly constant throughout the length of the waveguide. We also assume the pulses have a Gaussian shape:

$$I(t) = I_{\text{ave}} \sqrt{\frac{2}{\pi}} \frac{T}{\tau} \exp \frac{-2t^2}{\tau^2} \tag{2}$$

where I_{ave} is the average intensity, τ is a pulsewidth parameter, and T is the period of the modelocked pulse stream. The average photocurrent i_{ave} is

$$i_{\text{ave}} = \frac{e\Omega}{T} \int_{-T/2}^{T/2} \frac{dN}{dt} dt = e\Omega \left(\frac{\alpha}{h\nu} I_{\text{ave}} + \frac{\beta T}{2\sqrt{\pi} h\nu\tau} (I_{\text{ave}})^2 \right) \tag{3}$$

when T is much larger than τ. Ω is the volume in which carriers are generated.

When two-photon absorption is the dominant effect and linear absorption is negligible, TPA photocurrent is expected to vary quadratically as the input average power changes. The equation also predicts that the current linearly depends on the inverse pulsewidth $(1/\tau)$.

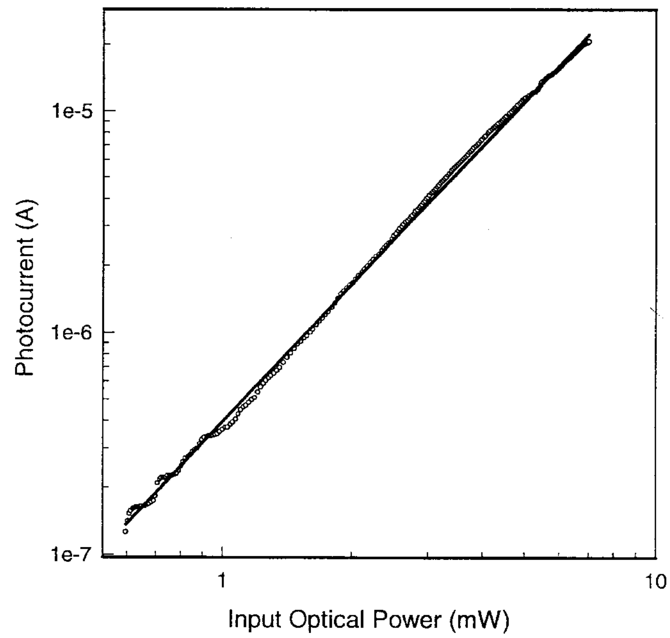

Fig. 2. Intensity dependence of TPA photocurrent of GaAs waveguide. o: experimental data for 150 fs OPO. —: straight line fitted to experimental points with a slope of 2.02. The precision in the slope measurement, based on several data sets, is $\sim \pm 0.12$. Optical power was measured before the coupling optics.

Fig. 2 shows a plot of the measured photocurrent as a function of average optical intensity, for a fixed 150 fs pulsewidth. The data clearly showed a quadratic dependence of the photocurrent to the optical average power, which is consistent both with the theoretical prediction above and with previous experimental results at 1.06 μm [5] using ~100 ps pulses. Assuming that roughly 10% of the light was coupled into the waveguide, the corresponding average intensity in waveguide ranges from $9 \cdot 10^6$ to $1.2 \cdot 10^8$ Wm^{-2}, using $\Omega = 5.6 \cdot 10^{-15}$ m^3. From the magnitude of the measured photocurrent, we estimate β is ~1 cm/GW (assuming 100% collection efficiency for the photogenerated carriers). This is significantly lower than the value $\beta = 24$ cm/GW measured in [7] for a GaAs waveguide at 1.5 μm and $\beta = 20$ cm/GW measured at 1.06 μm [5], but is close to the value measured for $Al_{0.18}Ga_{0.82}As$ at 1.5 μm [8]. Since our waveguide consists of a sandwich of GaAs and $Al_{0.15}Ga_{0.85}As$ layers, our results are in reasonable agreement with previous measurements. We note that there is some uncertainty in our estimation of β due to the difficulty in accurately measuring the power coupled into the waveguide. We also note that for a fixed material, β is expected to vary with photon energy according to the theoretical formula $\beta \sim E_g^{-3}(2h\nu/E_g - 1)^{3/2}/(2h\nu/E_g)^5$ [9]. Experiments with InGaAs waveguides at 1.5 μm have indicated a substantially larger β compared to our current devices, presumably due to the lower bandgap of InGaAs [10]. Such an enhancement in β would provide good signal levels at low optical power and for higher pulse repetition rates of ~1 Gb/s and beyond, and would also allow the use of shorter waveguide to reduce the *RC* time and increase the speed.

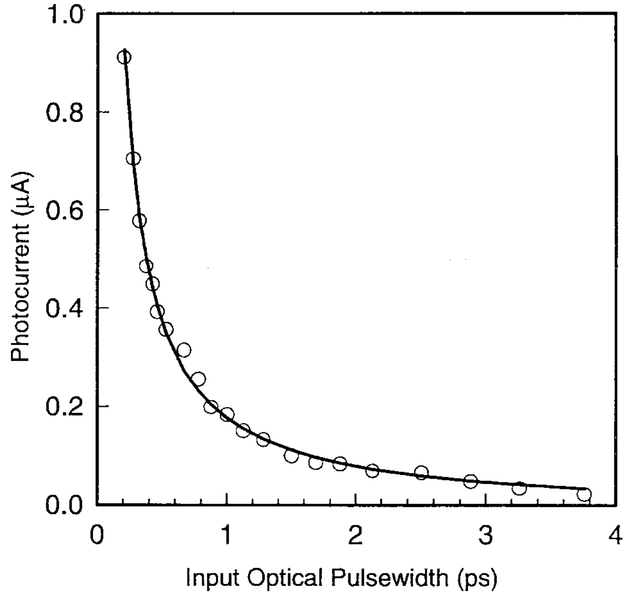

Fig. 3. Pulsewidth dependence of TPA photocurrent. o: experimental data measured for different pulsewidths, with average input power held constant at 1.4 mW. —: $a\tau^{-1}$ curve fitted to the data.

We also performed pulsewidth dependent measurements to assess the suitability of the TPA GaAs waveguide detector for ultrafast thresholder operation. The idea is that according to (3), two pulses with equal energies but very different pulsewidths (hence different peak intensities) should give correspondingly different photocurrents. A strong contrast in photocurrent as a function of peak intensity would approximate the desired ultrafast thresholding function. Fig. 3 shows data obtained by using the pulse stretcher setup to broaden the pulses over the range from ~180 fs to ~4 ps. The average optical power was held constant at 1.4 mW. The average photocurrent decreases by about twenty times as the pulsewidth increases from ~180 fs to ~4 ps. The data are well fitted by a τ^{-1} curve in good agreement with theoretical prediction. There are some small deviations from the fitted curve, which may be caused by changes in the pulseshape itself (not just the pulsewidth) as the slit width is varied. To our knowledge, this is the first experimental verification of the pulsewidth dependence of TPA on femtosecond time scale.

To show the feasibility of utilizing these devices as nonlinear detectors for communication applications, the electrical response of the waveguide photodetectors was observed in the time domain by using a sampling oscilloscope. The trace obtained using the 80 MHz modelocked pulse train is shown in Fig. 4. The FWHM width of the current pulse was ~400 ps. The extra bumps in the data are reflections due to impedance mismatches in the external circuit. The peak voltage response on the 50-Ω oscilloscope was >50 mV at 10 mW avearge optical input. The nonlinear photocurrent observed in the current experiments already shows a sufficiently fast response for applications up to ~1 Gb/s. The response time is most likely limited either by the *RC* time of the waveguide photodetector itself or by parasitics associated with our rather crude external contacting scheme. It should be possible to obtain

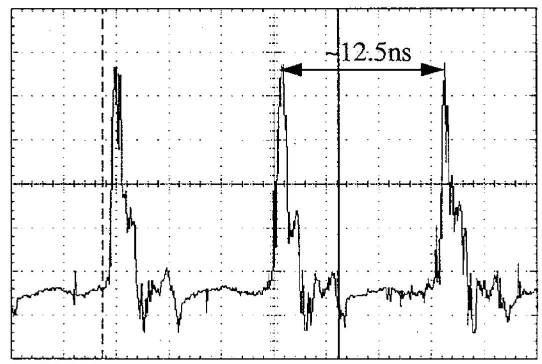

Fig. 4. Measured electrical impulse response of the waveguide on sampling oscilloscope. The waveguide was illuminated by 150-fs optical pulses at 80-MHz repetition rate. The FWHM of the electrical pulses is ~400 ps.

faster electrical response by reducing the waveguide length and improving the electrical packaging.

In summary, we have characterized the TPA-induced photocurrent in a bulk GaAs waveguide photodetector in response to femtosecond pulses at 1.5 μm. Our measurements verify that the photocurrent varies inversely with optical pulsewidth for a twenty-fold variation in pulsewidth. The device also demonstrated a subnanosecond electrical response time. These experiments demonstrate the possibility of applying such devices as nonlinear detectors at to retrieve peak intensity and pulsewidth related information communications wavelengths at high speed.

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