Quadratic autocorrelation and photocurrent saturation study in two-photon QWIPs

H. Schneider, O. Drachenko, S. Winnerl, M. Helm, and M. Walther

***Abstract*— Using the free-electron laser facility FELBE, we have studied the influence of the intensity on the quadratic autocorrelation measured with two-photon quantum well infrared photodetectors (QWIP). At high illumination powers, the shape of the autocorrelation trace is affected by photocurrent saturation of the two-photon QWIP. We describe the saturation mechanism by different analytical models taking account of the photocurrent nonlinearity in analogy to linear QWIPs and give conditions where true quadratic behavior can be observed.**

***Index Terms*— free-electron laser, GaAs/AlGaAs, quantum well infrared photodetector, QWIP, two-photon absorption, photocurrent saturation**

I. Introduction

The two-photon QWIP comprises three equidistant subbands, two of which are bound in the quantum well, and the third state in the continuum. The intermediate subband causes a resonantly enhanced optical nonlinearity, which is about six orders of magnitude stronger as compared to usual semiconductors [1]. In addition, temporal resolution is only limited by the sub-ps intrinsic time constants of the quantum wells, namely the intersubband relaxation time and the dephasing time of the intersubband polarization. Both properties make this device very promising for quadratic autocorrelation measurements of pulsed mid-infrared lasers.

We report here on autocorrelation measurements of ps optical pulses from the free-electron laser (FEL) facility FELBE at the Forschungszentrum Dresden Rossendorf. Using a rapid-scan autocorrelation scheme, high-quality quadratic autocorrelation traces are obtained, yielding ratios close to the theoretically expected value of 8:1 between zero delay and large delay for interferometric autocorrelation, and 3:1 for intensity autocorrelation. Thus, two-photon QWIPs provide an excellent new technique for online pulse monitoring of the FEL. In addition, we have investigated the saturation mechanism of the photocurrent signal, which is due to internal space charges generated in the detector.

Manuscript received March 15, 2007. This work has partially been supported by EuroMagNET under the EU contract RII3-CT-2004-506239 of the 6th Framework 'Structuring the European Research Area, Research Infrastructures Action'.

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II. Experimental

The FEL is operated in quasi-continuous mode, providing a continuous train of infrared pulses with a repetition rate of 13 MHz. Both the pulse duration and pulse energy depend on the emitted wavelength, with typical values of 0.7 – 5 ps and 0.01 – 2 µJ, respectively. Due to a recent extension [2], a wavelength range of $\lambda = 4 - 200$ µm is now available.

Our two-photon QWIP structures were grown by molecular beam epitaxy on semi-insulating GaAs substrates. The active region contains 20 quantum wells, n-doped to a concentration of 4×10^{11}cm^{-2} electrons per well. Mesa detectors of 120×120 µm^2 and 240×240 µm^2 area were processed by optical lithography and wet-chemical etching. Sample X1649 contains 7.6 nm wide GaAs quantum wells and 47 nm $Al_{0.33}Ga_{0.67}As$ barriers, which results in a peak detection wavelength of 10.4 µm. Sample X1654) uses 6.8 nm $In_{0.10}Ga_{0.90}As$ wells and 47 nm $Al_{0.38}Ga_{0.62}As$ barriers, with an observed peak wavelength of 8 µm. Standard 45°-facets were realized for optical coupling.

III. FEL Pulse Diagnostics

In order to demonstrate FEL pulse diagnostics, we have performed measurements at different FEL pulsewidths. By changing the length l of the FEL cavity, it is possible to vary the optical pulse width to a certain extent. Interferometric autocorrelation traces at an operation wavelength of $\lambda = 10.5$ µm are shown in Fig. 3. The autocorrelation trace of Fig. 3a refers to a non-detuned FEL cavity (i.e., $\Delta l = 0$) where the pulse width is at its minimum. The data are normalized to the signal at large delay and contain over 100 interference fringes which are not resolved in the figure. In addition, an intensity autocorrelation is shown where these fringes have been filtered out numerically. For (quadratic) interferometric autocorrelation, the expected ratio between the signal at zero time delay and at large delay amounts to 8:1 (and 3:1 for intensity autocorrelation) [1]. Slightly smaller ratios are present in the figure, which we attribute to saturation as discussed below. According to Fig. 1a, the autocorrelation width amounts to 2.2 ps. This corresponds to a pulse duration of $\tau = 1.6$ ps full-width at half maximum (FWHM), resulting in a FEL duty cycle of 2×10^{-5}.

As shown in the inset, the simultaneously measured spectral dependence reveals a FEL linewidth of $\Delta\lambda = 95$ nm FWHM, or $\Delta\lambda/\lambda = 0.009$. Since the operation wavelength corresponds to a frequency of $\nu = 29$ THz, we obtain $\Delta\nu = 0.26$ THz,

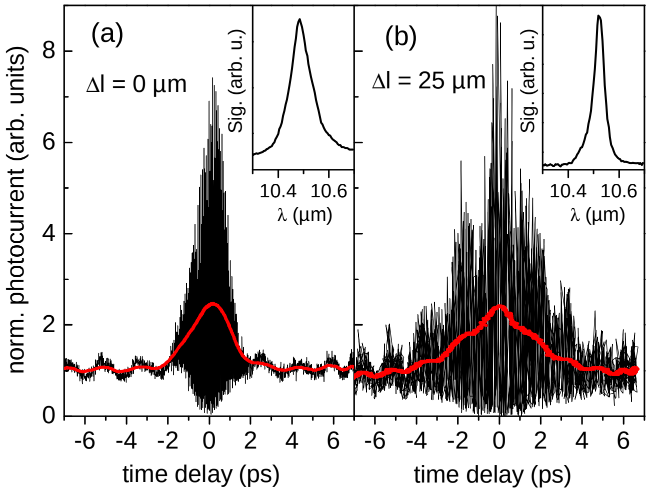

Fig. 1. Interferometric autocorrelation traces (black curves) and intensity autocorrelation (red/grey) of FEL radiation using two-photon QWIP #X1649 at 77 K, 2 V applied bias, and 0.3 mW incident power (1.3 kW/cm^2). Figs. (a) and (b) refer to different FEL pulse widths. Respective FEL spectra are shown in the insets.

which yields $\tau\Delta\nu = 0.42$. This value is in between the value of $\tau\Delta\nu = 2\ln 2/\pi = 0.441$ for Gaussian and $\tau\Delta\nu = 0.315$ for sech^2 pulses. Similarly, Fig. 3b displays autocorrelation measurements where the cavity length of FELBE has been detuned by $\Delta l = 25$ µm. Here the FEL pulse measures 3 ps, roughly twice as much as for $\Delta l = 0$, and the inset indicates a measured spectral width of 45 nm.

The shape of the interference fringes, which are not resolved in Fig. 1, provides additional evidence for the quadratic nature of the photocurrent. In fact, these fringes show perfect sinusoidal shape if the square root of the signal is plotted [3].

IV. Photocurrent Saturation

The intensity dependence of the two-photon QWIP signal provides valuable information on the device operation. Photocurrent saturation influences the precise shape of the autocorrelation trace and may thus have some impact on the apparent pulse properties.

Fig. 2 shows the photocurrent density of a two-photon QWIP as a function of power density. The data refer to FEL pulse pairs at zero delay and at large delay ($\Delta t = 50$ ps). The horizontal scale relates to a duty cycle of 4×10^{-5} which corresponds to pairs of time-delayed 1.6 ps FEL pulses at a repetition rate of 13 MHz. While the signal exhibits truly quadratic power dependence at low power, saturation occurs at around 100 kW/cm^2 peak power density.

The observed saturation behavior allows us to draw some conclusions concerning the saturation mechanism of the photocurrent. A simple saturation model (“linear screening”) is obtained by assuming that electric field screening inside the QWIP occurs in analogy to a capacitor which is discharged by a photocurrent [3], leading to the dashed curves in Fig. 2.

Another approach for space charge saturation is based on a low-power screening mechanism which is well known from linear QWIPs [4,5]. Under static illumination, this low-power photocurrent nonlinearity is caused since the “first” barrier on the emitter side of the QWIP only bears a thermal current

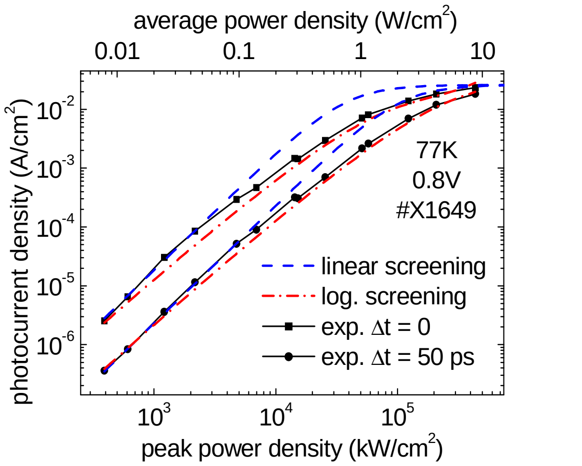

Fig. 2. Photocurrent of two-photon QWIP #X1649 and simulations for linear and logarithmic screening at zero delay and large delay of 50 ps, vs. power density.

while the remaining barriers also carry a photoexcited current. To maintain the total current constant, the electric field at the emitter barrier thus has to be higher than in the rest of the active region. Assuming that the thermal current obeys an exponential dependence $I \sim \exp(\alpha F)$ on the electric field F (with prefactor α) and that the photocurrent is proportional to F, this “logarithmic screening” model [3] reproduces the observed power dependence reasonably well.

V. Conclusion

Two-photon QWIPs have been exploited for interferometric autocorrelation measurements of free-electron laser radiation. Special emphasis has been given to study the saturation behavior of the two-photon QWIP signal, which is limited by the generation of internal space charges rather than capacitive discharging or absorption saturation. At 77 K, almost truly quadratic behavior has been achieved, with enhancement factors close to the theoretically expected value of 8:1 between zero time delay and large time delay.

Acknowledgment

The authors are grateful to P. Michel and the whole ELBE team for their dedicated support.

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