Nonlinear pulse-shaping phenomena of semiconductor saturable absorber mirror

Jiun-Cheng Wang, Chi-Kuang Sun, and Juen-Kai Wang

Citation: Applied Physics Letters **89**, 231106 (2006); doi: 10.1063/1.2400396
View online: http://dx.doi.org/10.1063/1.2400396
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/89/23?ver=pdfcov
Published by the AIP Publishing

Nonlinear pulse-shaping phenomena of semiconductor saturable absorber mirror

Jiun-Cheng Wang and Chi-Kuang Sun
Graduate Institute of Electro-Optical Engineering, National Taiwan University, Taipei 106, Taiwan and Department of Electrical Engineering, National Taiwan University, Taipei 106, Taiwan

Juen-Kai Wang[a)]
Center for Condensed Matter Sciences, National Taiwan University, Taipei 106, Taiwan and Institute of Atomic and Molecular Sciences, Academia Sinica, Taipei 106, Taiwan

(Received 3 September 2006; accepted 22 October 2006; published online 5 December 2006)

The authors report the experimental investigation of pulse-shaping effects of a semiconductor saturable absorber mirror (SESAM). The induced pulse shortening and phase variation exhibit fluence dependences which follow the saturation behavior of nonlinear reflectivity. The experimental results have been compared with the prediction based on saturable population relaxation model. The study provides an unprecedented opportunity to investigate the role of SESAM in ultrafast mode-locked lasers. © *2006 American Institute of Physics*.
[DOI: 10.1063/1.2400396]

Semiconductor saturable absorber mirrors (SESAMs) have been used to initialize and stabilize mode-locking operation in many ultrafast solid-state laser resonators.[1,2] Their properties are usually described by several phenomenological parameters such as saturation fluence and relaxation time which greatly influence the usage of SESAMs in the laser resonators. Many experimental and theoretical efforts have been devoted to investigate the role of SESAMs in the laser operation.[3–5] For example, the dynamical response of SESAMs had been incorporated into laser master equation to calculate their influence upon the output characteristics of the laser resonators.[4] In these theoretical investigations, the phase change induced by SESAMs was described by linewidth enhancement factor.[4,5] This parameter was demonstrated theoretically to be very influential on the laser output pulse duration and the stability of the mode-locking operation. There is, however, no experimental measurement on the actual phase change induced by SESAMs and therefore no direct identification of its role in the mode-locking operation. In this letter, we present the measurements of pulse-shaping effects of a SESAM with frequency-resolved optical gating based on two-beam coupling (TBC-FROG).[6,7] This technique has been demonstrated to be highly phase sensitive.[8] The measured results are compared with theoretical prediction based on a saturable population relaxation model which has been used previously to describe the function of slow saturable absorbers in soliton mode-locking operation.[4,5]

The sample under study is a commercially available semiconductor saturable absorber mirror (SESAM, SAM-800-8, BATOP GmbH) designed for mode-locked Ti:sapphire oscillators, which consists of a low-temperature-grown GaAs (LT-GaAs) quantum well and a 27-pair $Al_{0.3}Ga_{0.7}As/AlAs$ Bragg reflector underneath. Its low-intensity reflectance spectrum exhibits a reflectivity of >80% from 775 to 825 nm and a peak reflectivity of 88% at 800 nm. A single peak at 800 nm appears in the photoluminescence spectrum. A femtosecond mode-locked Ti:sapphire laser centered at 800 nm serves as the light source for the rest of experiments. Its full width at half maximum (FWHM) spectral width is 10 nm, making its full spectrum being well within the high-reflectivity range. The saturation energy density (fluence) and the modulation depth were determined by nonlinear reflectivity measurement in which the reflectivity of the femtosecond laser pulses was measured as a function of laser fluence. Its saturation dynamics was investigated by a pump-probe transient reflectance measurement. For the pulse-shaping measurements, the output from the femtosecond laser source is split into two beams with different pulse energies. The more intense beam is sent through a prism pair for chirp adjustment. It then impinges normally onto the SESAM with different fluences at three chirp conditions: $B_2=0.5(\partial^2\phi/\partial\omega^2)=870$, 0, and $-870\ \mathrm{fs}^2$, where ϕ is the phase of the laser pulses.[9] The reflected beam is then sent to a 2 mm ZnSe plate to spatially overlap with the less intense beam which is characterized in advance. A mechanical scanner provides fast temporal-delay scan between the two beams with a time resolution of 4 fs. After transmitting through the ZnSe plate, the more intense beam is then dispersed in a 30 cm monochromator for spectrally resolved measurements. A TBC-FROG trace, constructed by a series of averaged transient signals at continuously scanned wavelengths, is then used for phase-retrieval calculation. Both electric field amplitude and phase are retrieved. The precision and accuracy of this method have been carefully examined on a CaF_2 plate which has well-characterized dispersion property.

Figure 1 shows the reflectivity as a function of the incident laser fluence (F). The unsaturated reflectivity at low fluence is 88% and the saturated reflectivity at high fluences is 95%. The fit with a carrier population relaxation model[2] yields saturation fluences F_{sat} of 30, 36, and 28 $\mu\mathrm{J/cm}^2$ for positive-chirp, chirpless, and negative-chirp pulses, respectively. The inset of Fig. 1 shows the transient differential reflectivity measured with 90 fs pulses. The instantaneous rise at the time zero is followed by a fast decay to a negative reflectivity variation (ΔR). It then recovers slowly to zero. This transient reflectance behavior agrees with the previous works on LT-GaAs samples[10,11] and represents fast trapping

[a)]Author to whom correspondence should be addressed; electronic mail: jkwang@ntu.edu.tw

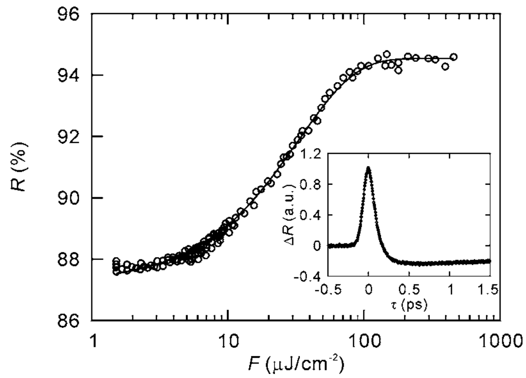

FIG. 1. Nonlinear reflectivity of semiconductor saturable absorber mirror (SESAM) measured with positively chirped pulses. The open circles are data points and the solid curve is a fit to a gain-saturation model. The inset shows transient differential reflectivity of the SESAM. The solid curve is a fit to a population relaxation model.

of the photoexcited carriers followed by slow recombination of trapped carriers. After fitting by the rate equation model by Grenier and Whitaker,[12] the extracted trapping time is 85 fs. The electron trapping process is expected to be much faster than the electron energy relaxation process which is merely due to acoustic phonon emission because the kinetic energy of free electrons produced by the 800 nm photoexcitation is smaller than the optical phonon energy of GaAs. The electrons excited by the leading edge of the 90 fs pulse therefore may not influence the photoexcitation process during the tailing edge of the pulse. Any chirp dependence of the saturation fluence is expected to be insignificant. Finally, two extracted time constants for carrier recombination are 4 and 100 ps, which are originated from two different traps (As antisites and As complex).[12] Since the carrier recombination processes occur in a time scale much longer than the pulse duration, they likely play only a negligible role in the pulse-shaping effects.

In all of the retrieved pulse characteristics, the pulse envelope remains in all measurements. The FWHM pulse duration, τ_p, and the second derivatives of the phase in frequency domain, B_2, are therefore used to represent the main characteristics of the resultant pulses. Figure 2 shows the extracted τ_p and B_2 as a function of normalized fluence (F/F_{sat}) for positive-chirp pulses. Each error bar of the experimental result represents the standard deviation of six repetitive measurements. τ_p first decreases with F and then reaches a plateau value at $F = \sim 4F_{\mathrm{sat}}$, while B_2 simultaneously decreases from $1020\ \mathrm{fs}^2$ to a plateau value of $960\ \mathrm{fs}^2$. Notice that the saturation behavior of τ_p and B_2 is quantitatively coincident with that of the nonlinear reflectivity, suggesting that the origin of this saturation behavior is strongly related to the saturation of the photoexcited carriers in the SESAM. The photoexcitation by the femtosecond laser pulses varies the amount ratio between the free carriers in the conduction band and the unexcited electrons in the valence band in the LT-GaAs layer of the SESAM, which determines the dispersion contributions from both parts. Since the photoexcited free carriers can be approximated by the Drude model, their negative dispersion contribution may compensate the positive dispersion by the unexcited electrons, resulting in the observed decrease of B_2.[13] The resultant variation of B_2 is thus expected to be synchronous with the variation of this ratio which is caused by the different incident laser

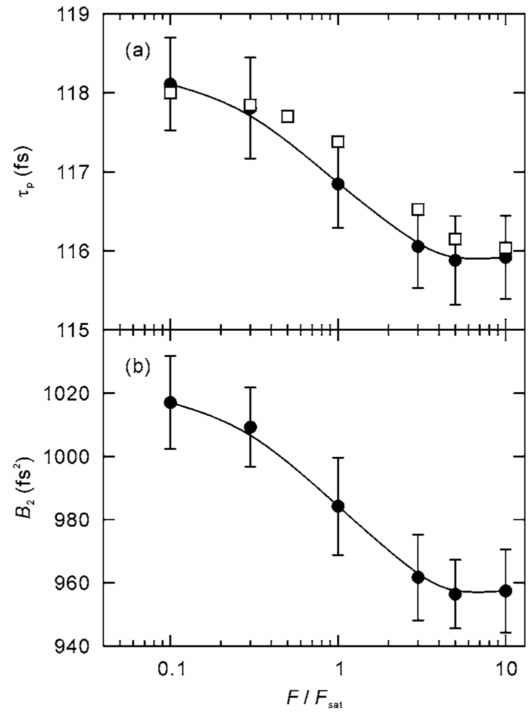

FIG. 2. (a) τ_p and (b) B_2 as a function of normalized fluence (F/F_{sat}) for positive-chirp laser pulses. τ_p is the full width at half maximum pulse duration, $B_2 = 0.5(\partial^2\phi/\partial\omega^2)$, and F_{sat} is saturation fluence. The filled circles are experimental data and the solid curves are guides for the eyes. The open squares are calculation results.

fluences. In the cases of chirpless and negative-chirp pulses (not shown here), B_2 exhibits similar saturation behavior and the amount of variation is almost identical to that for the positive-chirp pulse, suggesting that the dynamical behavior of the excited carriers within the pulse duration is approximately the same under the three chirp conditions and is supported by the transient reflectivity result described above.

In previous works, the refractive index change caused by the photoexcited carriers in the SESAM was approximated by the linewidth enhancement factor which has been used to describe the linewidth increase in semiconductor lasers.[14,15] The induced phase change, $\Delta\phi_{\mathrm{sa}}$, is proportional to the loss function of the saturable absorber:[5]

$$\Delta\phi_{\mathrm{sa}}(t) = \alpha q(t)/2, \tag{1}$$

where α is the linewidth enhancement factor and $q(t)$ is the response of the loss coefficient of the saturable absorber. α is usually positive for SESAMs and Paschotta and Keller suggested a value between 0 and 3.[5] The resultant electric field after interacting with a saturable absorber is expressed as

$$E_{\mathrm{out}}(t) = E_{\mathrm{in}}(t)\exp\{-q(t)\exp[i\Delta\phi_{\mathrm{sa}}(t)]\}. \tag{2}$$

Based on rate equation[4] for $q(t)$ which accounts for the saturation relaxation behavior of the excited carriers and Eq. (1), we have calculated $E_{\mathrm{out}}(t)$ as a function of the incident laser fluence for the positive-chirp pulse with the following parameters: the extracted relaxation time (85 fs), the saturation fluence ($30\ \mu\mathrm{J/cm}^2$), the unsaturated reflectivity (88%), and $\alpha = 2$. For each fluence, the FWHM pulse duration and the second derivative of the phase in time domain, $b_2 = 0.5(\partial^2\phi/\partial t^2)$, are extracted from the obtained electric field. The calculated pulse duration follows the measured value well within the error bar, as shown in Fig. 2(a), indicating

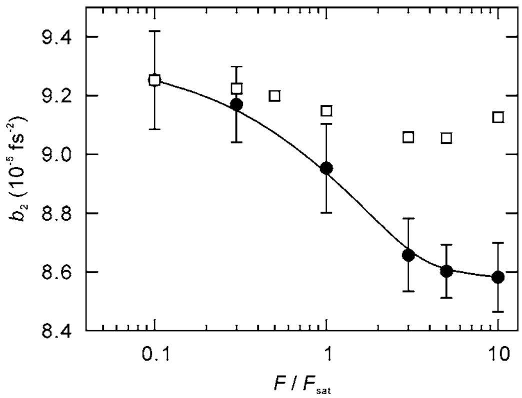

FIG. 3. b_2 as a function of normalized fluence (F/F_{sat}) for positive-chirp laser pulses. $b_2=(1/2)(\partial^2\phi/\partial t^2)$ and F_{sat} is saturation fluence. The filled circles are experimental data and the solid curves are guides for the eyes. The open squares are calculation results multiplied by 20.

that the pulse shortening behavior can be well described by the saturable population relaxation model. In contrast, the measured b_2 is about 60 times of the measured one at high fluences (Fig. 3). Even for choosing α to be an unphysical value of 20, the calculated b_2 at high fluences is still one-sixth of the measured value. This discrepancy suggests that the combination of the simple saturable population relaxation model and the linewidth enhancement factor cannot fully describe the phase change induced by the nonequilibrated carriers in the SESAM. In fact, the excitation induced absorption and refractive index changes in GaAs-based materials have been studied experimentally and theoretically.[16–19] In general, the linewidth enhancement factor should be considered as a function and not a constant, as reported by many previous studies.[20–24] A question is thus raised about how the observed pulse-shaping effects of SESAM influence soliton mode locking.[4] Three inferences can be drawn based on our observations. First, the finding that the pulse duration variation at different fluences can be described by the loss function based on the saturation population relaxation model supports the role of initialization and stabilization in the mode-locked lasers where the dispersion consideration is not important. Second, the non-negligible negative dispersion introduced by the SESAM may greatly shift the balance between intracavity group-velocity dispersion and self-phase modulation in the case of soliton mode locking and thus alter the stable laser operation regime. Third, since B_2 depends only on the laser fluence, incorporating the effects of slow saturable absorbers in the mode-locking calculation may need to be considered accordingly.[4]

In conclusion, we have experimentally investigated the fluence-dependent pulse-shaping effects of a semiconductor saturable absorber mirror. The phase variation introduced by a semiconductor saturable absorber was measured. The induced dispersion exhibits identical saturation behavior as the nonlinear reflectivity and it is insensitive to the chirp condition of the incident laser pulse. This behavior is interpreted by the dynamics of photoexcited carriers. Disagreement between the finding and the calculation results based on saturable population relaxation model urges revisiting the role of slow semiconductor saturable absorbers in soliton mode-locking theory.

The authors thank the financial support from the National Science Council (Grant No. 95-2745-M-002-010) and Academia Sinica in Taiwan.

[1]U. Keller, K. J. Weinggarten, F. X. Kärtner, D. Kopf, B. Braun, I. D. Jung, R. Fluck, C. Hönninger, N. Matuschek, and J. Aus der Au, IEEE J. Sel. Top. Quantum Electron. **2**, 435 (1996).
[2]U. Keller, in *Nonlinear Optics in Semiconductors II*, edited by E. Garmire and A. Kost (Academic, San Diego, 1999), Chap. 4, p. 211.
[3]S. Tsuda, W. H. Knox, S. T. Cundiff, W. Y. Jan, and J. E. Cunningham, IEEE J. Sel. Top. Quantum Electron. **2**, 454 (1996).
[4]F. X. Kärtner, I. D. Jung, and U. Keller, IEEE J. Sel. Top. Quantum Electron. **2**, 540 (1996).
[5]R. Paschotta and U. Keller, Appl. Phys. B: Lasers Opt. **73**, 653 (2001).
[6]R. Trebino, *Frequency-resolved Optical Gating: The Measurement of Ultrashort Laser Pulses* (Kluwer, Norwell, 2000).
[7]S. Yeremenko, A. Baltuška, F. de Hann, M. S. Pshenichnikov, and D. A. Wiersma, Opt. Lett. **27**, 1171 (2002).
[8]J.-K. Wang, T.-L. Chiu, C.-H. Chi, and C.-K. Sun, J. Opt. Soc. Am. B **16**, 651 (1999).
[9]A 15 mm Ti:sapphire laser crystal which is typically used in mode-locked Ti:sapphire laser resonators has a B_2 of 870 fs^2. The chirp conditions ($B_2=+870$, 0, and -870 fs^2) thus occur in between three optical components inside a stable mode-locked laser resonator (laser crystal, output coupler, and prism pair).
[10]U. Siegner, R. Fluck, G. Zhang, and U. Keller, Appl. Phys. Lett. **69**, 2566 (1996).
[11]H. S. Loka, S. D. Benjamin, and P. W. E. Smith, IEEE J. Quantum Electron. **34**, 1426 (1998).
[12]P. Grenier and J. F. Whitaker, Appl. Phys. Lett. **70**, 1998 (1997).
[13]The dielectric function of free carriers can be described as $\varepsilon(\omega)=\varepsilon_\infty-\omega_p^2/(\omega^2+i\omega\omega_\tau)$, where ε_∞ is the dielectric constant at high frequency, ω_p is the plasma frequency, and $\omega_\tau=1/2\pi c\tau$. Since the photoexcited carrier density is estimated to be less than 10^{18} cm^{-3}, the corresponding ω_p is much smaller than the corresponding frequency of the laser spectrum and the resultant $\varepsilon(\omega)$ exhibits negative dispersion. This is in contrast to the positive dispersion of unexcited electrons in the valence bands.
[14]C. H. Henry, IEEE J. Quantum Electron. **18**, 259 (1982).
[15]M. Osiński and J. Buus, IEEE J. Quantum Electron. **23**, 9 (1987).
[16]Y. H. Lee, A. Chavez-Pirson, S. W. Koch, H. M. Gibbs, S. H. Park, J. Morhange, A. Jeffery, N. Peyghambarian, L. Banyai, A. C. Gossard, and W. Wiegmann, Phys. Rev. Lett. **57**, 2446 (1986).
[17]S. W. Koch, N. Peyghambarian, and H. M. Gibbs, J. Appl. Phys. **63**, R1 (1986).
[18]S. H. Park, J. F. Morhange, A. D. Jeffery, R. A. Morgan, A. Chavez-Pirson, H. M. Gibbs, S. W. Koch, N. Peyghambarian, M. Derstine, A. C. Gossard, J. H. English, and W. Weigmann, Appl. Phys. Lett. **52**, 1201 (1988).
[19]E. Gehrig, O. Hess, A. Volland, G. Jennemann, I. Fischer, and W. Elsäßer, J. Opt. Soc. Am. B **21**, 1638 (2004).
[20]W. W. Chow, S. W. Koch, M. Sargent III, and C. Eli, Appl. Phys. Lett. **58**, 328 (1991).
[21]M. F. Pereira, Jr., S. W. Koch, and W. W. Chow, J. Opt. Soc. Am. B **10**, 765 (1993).
[22]R. Jin, D. Bobbavarapu, G. Khitrova, H. M. Gibbs, Y. Z. Hu, S. W. Koch, and N. Peyghambarian, Appl. Phys. Lett. **61**, 1883 (1992).
[23]W. W. Chow and S. W. Koch, *Semiconductor Laser Fundamentals: Physics of the Gain Materials* (Springer, Berlin, 1999).
[24]H. Haug and S. W. Koch, *Quantum Theory of the Optical and Electronic Properties of Semiconductors*, 4th ed. (World Scientific, Singapore, 2004), p. 335.