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Double pulse generation in a highly nonlinear GaAs optical waveguide

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Abstract: This paper presents a simulation and investigation about the nonlinear interplay between an optical pulse and GaAs waveguide. The results obtained show that the nonlinear processes including self-phase modulation, 2-photon absorption, and free carrier related effects will have significant influences on the temporal shape and frequency spectrum of a propagating pulse in the GaAs waveguide with the result that 2-photon absorption can extend the pulse duration that can be again compressed by the free carrier absorption. The outcome spectrum is also asymmetrical due to the free carrier related effects, which takes on a complicated oscillation structure resulting from the interference. In addition, an interesting phenomenon is that the input pulse will eventually evolve into a double pulse along the GaAs waveguide by means of judiciously adjusting the intensity, waveform, and time duration of the input pulse, i.e. when the time duration of the input pulse is larger than the carrier lifetime, the input pulse with high enough intensity can develop into a double pulse at the end of the waveguide.

Key words: Integrated optics, GaAs waveguides, nonlinear optics, double pulse generation

1. Introduction

It is well known that highly nonlinear materials have always attracted much attention in optical communications because of the urgent requirement of signal processing and logic operation in integration optoelectronics. Undoubtedly, during the last decade, semiconductor waveguides with strong nonlinear effects, such as the silicon and chalcogenide waveguide, have attracted tremendous attention [1,2], and have been considerably investigated and demonstrated to realize compactly optoelectronic devices for wavelength conversion [3,4], optical switching [5,6], modulation [7,8], and light propagation [9,10]. Compared to the significant previous reports, the passive GaAs semiconductor waveguide has stronger third order nonlinearity and 2-photon absorption coefficients [11,12] and so it can be considered another highly nonlinear medium, and has already been investigated in wavelength conversion, optical switching, and other potential applications [13–16]. In general, it is thought that the GaAs based waveguide is strictly limited in signal processing due to its enhanced free carrier related effects. In reality, by utilizing the corresponding nonlinear optical properties such as decreased carrier lifetime determined by the inherent mechanisms and waveguide properties of media [17], the GaAs material should have some potential applications such as ultrafast optical modulators and logic gates. Based on these ideas, a novel project to generate a double pulse will be presented and analyzed in the GaAs waveguide by suitably selecting the shape, temporal width, and intensity of an initial pulse. To date, various techniques have been proposed and effectively demonstrated to generate a double pulse in the time domain regime, whose main components usually consist of fiber [18,19] and grating [20,21]. In these investigations, it is necessary to strictly control the fiber dispersion

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and grating position for generating the double pulse. Moreover, some additional elements are also required that are limited for integration technology. Compared to previous reports, the GaAs waveguide based double pulse generator in this study should have more remarkable advantages including a compact structure, simple operation, and tunable pulse separation between 2 pulses with the result that the double pulse required can easily be obtained by means of controlling the properties of the input pulse. The generated double pulse, which has short time duration, can be used in the Brillouin optical time domain analysis (BOTDA) technology to improve the spatial resolution of sensor measurement [22]. Through this research and discussion, one can see that the properties of the output pulse are strongly dependent on the characteristics of the input pulse, and another main goal of this paper is to again open up a peculiar application (double pulse generation) in optical signal processing for the highly nonlinear GaAs optical waveguide.

2. Theory

The schematic cross-section adopted GaAs strip waveguide is depicted in Figure 1, in which the GaAs (n= 3.43) guiding layer is surrounded by the AlGaAs (n= 3.33) upper cladding and lower cladding, and the substrate is still GaAs material. The presented waveguide structure is similar to that in a previous report [14].

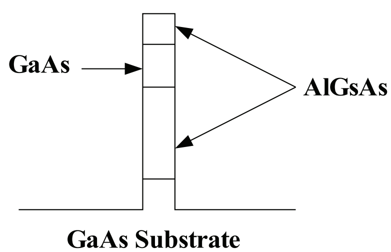

Figure 1. Cross-sectional view of strip GaAs optical waveguide.

When the optical beam is passing through the GaAs guiding region, the nonlinear interaction can be modeled by the following propagation equations [23,24]:

$$\frac{\partial \mathrm{A}}{\partial z} = -\frac{\alpha}{2}A - \frac{\beta}{2A_{eff}}\left|A\right|^2 A + i\gamma\left|A\right|^2 A - \frac{\sigma_\alpha N}{2}A + i\frac{\omega\sigma_r N}{c}A \tag{1}$$

where N is the time-dependent free carrier concentration written as

$$\frac{\partial N}{\partial t} = \frac{\beta}{2\hbar\omega A_{eff}^2}\left|A\right|^4 - \frac{N}{\tau} \tag{2}$$

In these equations, A is the slowly varying envelope of the optical beam, z is the propagation distance, α is the linear loss parameter (mainly caused by the light scattering), β denotes the 2-photon absorption coefficient (which will generate a large amount of free carrier), A_{eff} is the effective core area, γ $(= n_2\omega_i/cA_{eff})$ represents the nonlinear parameter with n_2 being the nonlinear Kerr coefficient, both σ_α and σ_r are, respectively, free carrier absorption cross section and refractive index change per carrier pair density, t is the time, $\hbar$ is the reduced Plank constant, and τ is the carrier recovery time, which can effectively be shortened to as low as several tens of picoseconds in the GaAs media. Another noticeable issue is that the linear dispersion terms are not considered in Eq. (1) because the corresponding dispersion length is longer than the adopted waveguide length in this study. In addition, other nonlinear processes such as the cross-phase modulation and 4-wave mixing are not considered in the presented equation because only a single optical field is adopted in this model.

3. Results and discussion

In this investigation, a Gaussian optical pulse is introduced before entering the GaAs waveguide, whose envelopment can be described by

$$A(0,t)=\sqrt{P_{in}}\exp[-\frac{1}{2}(\frac{t}{t_0})^2]. \tag{3}$$

Here, P_{in} and t_0 are the initial peak power and half width at 1/e intensity point of the input pulse. To characterize the output pulse, the waveguide parameters can effectively be assumed by: $\alpha = 0.5$ cm^{-1}, $n_2 = 1.3 \times 10^{-17}$ m$^2 \cdot$W^{-1}, $\beta = 24$ cm$\cdot$GW^{-1}, $A_{eff} = 0.5$ μm^2, $\sigma_\alpha = 1.5 \times 10^{-16}$ cm^2, $\sigma_r = -4.76 \times 10^{-21}$ cm^3, $\tau = 20$ ps [13,14,23], waveguide length $L = 1$ mm.

The outputted temporal shapes and corresponding frequency spectra for 3 input peak intensity cases of $I_{in} = 2$ W/μm^2, 20 W/μm^2, and 200 W/μm^2 are, respectively, shown in Figures 2a and 2b, in which we can see that, compared to the input pulse, both the output temporal shapes and frequency spectra are distorted as a result of the enhanced free carrier absorption induced by the 2-photon absorption at high initial peak level. The optical intensity is also experiencing serious decay due to the strong losses including 2-photon absorption, free carrier absorption, and linear loss. The physical mechanism in Figure 2a can be explained by the nonlinear process in which the front end of the pulse will rapidly generate a great deal of free carrier induced by the strong 2-photon absorption while the high intensity pulse is propagating along the GaAs waveguide. As a consequence, those excessive carriers will absorb the trailing pulse energy and result in the obvious reduction in pulse intensity of the following part so that the output intensity is very low compared with the initial case. In addition, some noticeable issues are that 2-photon absorption can induce the pulse symmetrically broadened, and the free carrier absorption will distort the waveforms. Therefore, it is obvious that, when input power is at a low level (e.g., $I_{in} = 2$ W/μm^2), the 2-photon absorption process will dominate, and the free carrier absorption effect is gentle so that the full-width at half maximum (FWHM) of the output pulse is extended to about 20 ps as a result of 2-photon absorption. On the other hand, when the input intensity is increased to 20 W/μm^2, the related free carrier absorption will be remarkably enhanced so that the time duration of the output pulse is significantly shortened owing to the strong free carrier absorption. Through the calculation, it is known that the FWHM of the output pulse can be compressed to $\sim$10 ps at 200 W/μm^2 input peak level. In the investigation, some phenomena should be noted and observed, i.e. as the input intensity is increased, the intensity constant ratio of the signal pulse (output intensity to input intensity) is quickly decayed resulting from the rapidly enhanced nonlinear absorption. In addition, the corresponding peak intensity and temporal width of the output pulse will also arrive at the quasi-steady level. The intensity change will also influence the spectral property of the output pulse illustrated in Figure 2b, where the spectrum bandwidth is significantly broadened, and a majority of pulse energy is blue-shifted as a result of enhanced free carrier related effects under the condition of high input peak level. The spectrum property shown is similar to the reported experiment result as the initial intensity is gradually enhanced [12,24].

Now, let us focus on the influence of changed time duration on the output pulse at the end of a 1-mm long waveguide, where the output pulse shapes and frequency spectra are, respectively, depicted for 3 cases of $t_0 = 10$ ps, 30 ps, and 50 ps in Figures 3a and 3b. As can be seen from the figure, the output pulse has a steep leading edge, and very long trailing that should be attributed to the free carrier related effects. In addition, the corresponding frequency spectrum is gradually shortened with the increase in initial time duration, which also takes on an oscillation structure resulting from the interference effect. Another interesting phenomenon from Figure 3a is that the output pulses exhibit 2 peaks in the cases of $t_0 = 20$ ps and 30 ps, i.e. a significant

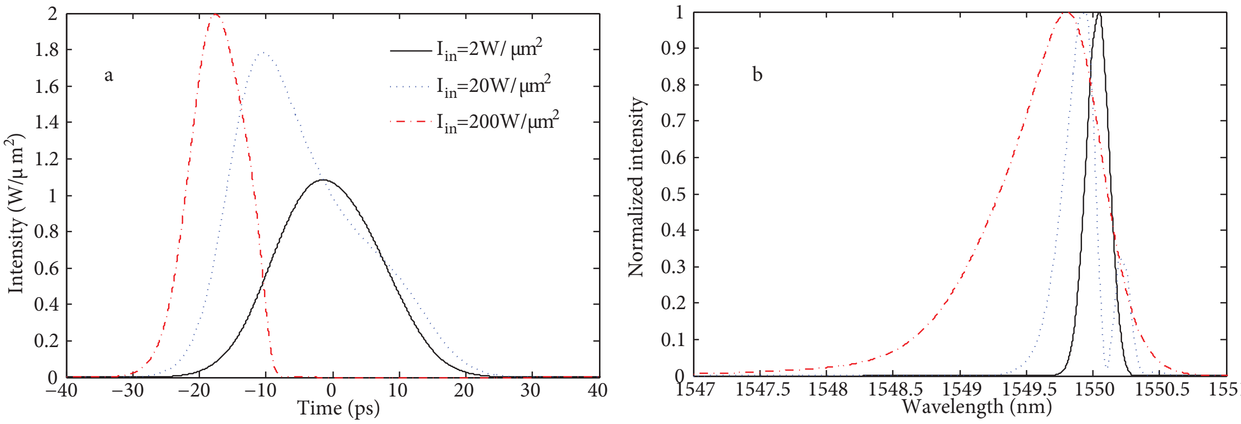

Figure 2. Output pulses for different input intensity cases with $t_0 = 10$ ps, (a) temporal shapes, (b) normalized frequency spectra. Here, same line styles in temporal and spectral shapes with identical input intensity.

dip appears in the center region of the output pulse. It can be explained that the input Gaussian pulse has a long rising (falling) time that is further extended due to the increased time duration. However, the free carrier concentration will gradually be decayed due to the combined effects of the decreased intensity in the region of long falling time and short carrier recovery time. As a consequence, the corresponding free carrier absorption effect is also reduced. Therefore, we can conclude that an output pulse with 2 peaks may be generated, if the time duration of the input pulse is longer than the carrier recovery time. Of course, the corresponding frequency spectra shown in Figure 3b have remarkable distinction for various input pulse duration. Based on the output pulse properties, if both the intensity and time duration are further increased, how is the output pulse? We can expect that a single pulse with high intensity and long time duration will evolve into a double pulse at the end of the waveguide, which is numerically demonstrated in the following analysis.

The temporal shapes and spectra of outputted double pulse are, respectively, shown in Figures 4a and 4b, in which the input pulse width is, respectively, 100 ps, 300 ps, and 500 ps, which are much longer than the carrier recovery time, and the input peak intensity is also as high as 20 W/μm^2, which will lead to a great deal of free carrier. The generated free carrier will thoroughly absorb the pulse energy of the center part so

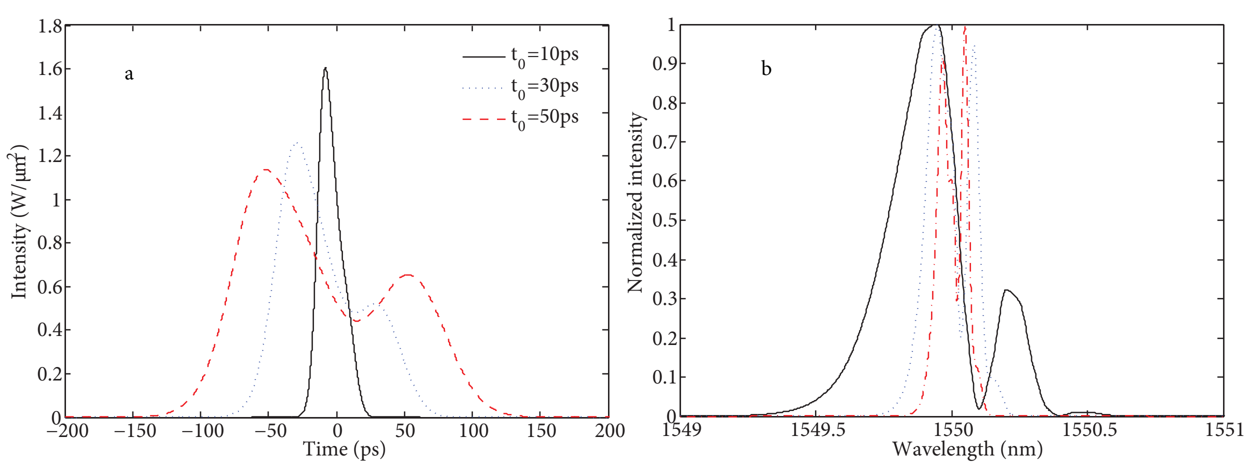

Figure 3. Output pulses for different input pulse width cases with input peak intensity of 20 W/μm^2, (a) temporal shapes, (b) normalized frequency spectra. Here, same line styles in temporal and spectral shapes with identical pulse duration.

that the double pulse can successfully be produced. In practice, the first (front) and second (back) pulses are formed in the regions of the pulse front and back. However, it is worth noting that the peak intensity of the back pulse is lower compared with the front pulse in the case of $t_0 = 100$ ps because of its steep edges. In contrast, equal peak intensity for the double pulse can be observed for $t_0 = 300$ ps and 500 ps as a result of the longer rising (falling) time. In addition, the time duration of each pulse is gradually extended with the increase in initial pulse width, which is still shorter than that of the input pulse. Another issue that should be pointed out is that the double pulse cannot be observed if a pulse with steep edges (e.g., rectangle shape) is considered as an input signal, namely, only a single ultrashort pulse is outputted [25]. In reality, to effectively generate a double pulse, both the input intensity and initial time duration are very critical parameters that will remarkably affect the properties of the output pulse, i.e. both the input intensity and time duration should be judiciously selected to generate the required double pulse. In addition, the output spectrum with oscillation structures is gradually compressed due to the extended initial pulse duration, which is illustrated in Figure 4b. Here, another notable issue is that the intensity of the outcome double pulse from the GaAs waveguide is enhanced by an optical amplifier, and the double pulse with large pulse width may also be developed into 4 pulses after it is again introduced into another cascaded highly nonlinear GaAs waveguide. However, the mentioned case is not presented in this study; it will be thoroughly discussed in a future investigation.

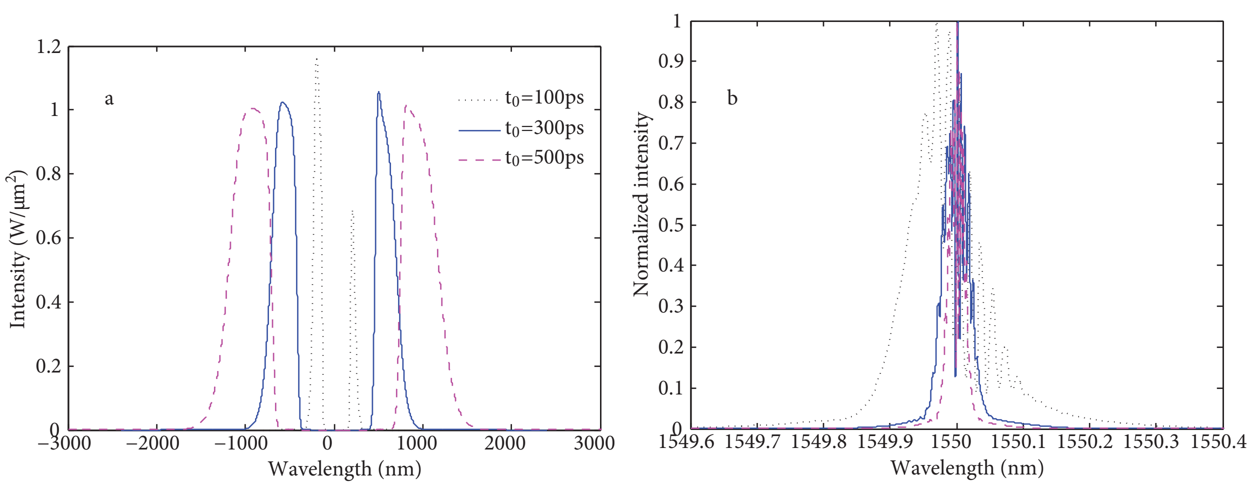

Figure 4. Generated double pulse at the end of 1-mm-long GaAs waveguide in the case of 200 W/μm^2 input intensity, (a) temporal shapes, (b) normalized frequency spectra. Here, same line styles in temporal and spectral shapes with identical pulse duration.

Figure 5 clearly shows the different cases of output pulses versus input optical intensity with initial time duration of $t_0 = 500$ ps. As can be seen from the figure, while the input peak intensity is below $\sim$30 W/μm^2, only a single pulse is outputted because the free carrier caused by the low intensity pulse cannot effectively absorb the energy of the middle part of the propagating pulse in the waveguide. Nevertheless, as the input intensity is up to $\sim$30 W/μm^2, the corresponding nonlinear processes will be significantly enhanced so that the double pulse is gradually formed as a result of the enhanced free carrier absorption. Additionally, once the double pulse is formed in the high intensity regime, its properties including the duration of both pulses and separation between them are nearly independent of the input intensity owing to the absorption saturation effect.

The output pulse against the different initial pulse width at the high input peak intensity of 200 W/μm^2

is also depicted in Figure 6, where one can see that the behavior of the output pulse is strongly dependent on the input pulse duration. While the initial pulse duration is shorter than the carrier recovery time, the input pulse cannot be evolved into a double pulse. In contrast, a double pulse with various separation times can be achieved by means of extending the initial pulse width that should be up to carrier recovery time. Another notable issue is that although a double pulse can be observed with the initial time duration of ∼50 ps, the energy of the front pulse is remarkably higher than that of the back pulse due to the remaining carrier absorption. It is surprising that with increasing input pulse width, the intensity of the back pulse is gradually enhanced until it is comparable with that of the front pulse, i.e. the 2 pulses have nearly identical properties when the t_0 is up to ∼200 ps. In addition, it is easily understood that the separation between 2 pulses and the pulse width is gradually extended as the initial pulse duration increases. Even so, each output pulse width is still short compared to the corresponding input pulse.

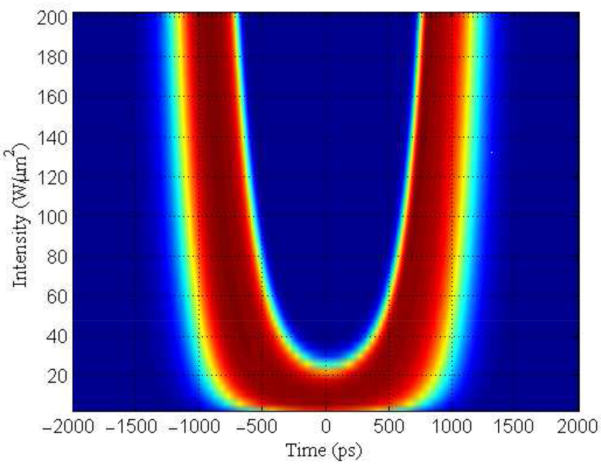

Figure 5. Output pulse at the end of 1-mm-long waveguide for $t_0 = 500$ ps with respect to the input peak intensity.

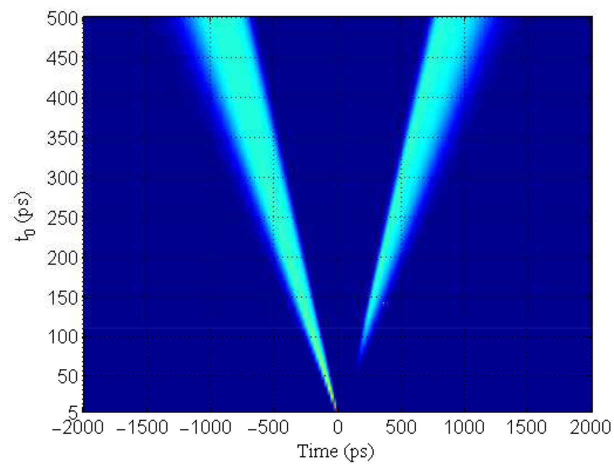

Figure 6. The output pulse at the end of 1-mm-long waveguide with input intensity of 200 W/μm^2 against the initial time duration.

4. Conclusion

In summary, we have numerically investigated the influences of the nonlinear processes including the Kerr effect, 2-photon absorption, and free carrier related effects on the picosecond optical pulse in the GaAs waveguide. The 2-photon absorption will broaden the time duration of the output pulse. In contrast, the corresponding free carrier absorption will shorten the time duration. Therefore, the output pulse is obviously compressed in the time domain at the high intensity level, whose frequency spectrum is significantly spread because of the Kerr and carrier related effects. When the initial pulse duration is longer than the carrier recovery time, the input pulse will evolve into a double pulse owing to the strong free carrier absorption process. Therefore, our research has further expanded the potential application for highly nonlinear GaAs waveguides.

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