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Picosecond Pulse Generation in a GaAs/GaAlsAs Single-Quantum-Well Laser at the First and Second Subband Transition

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***Abstract*—Picosecond optical pulses are generated in a single-quantum-well laser at the $n = 2$ or $n = 1$ quantized transition, respectively, by tuning the optical gain spectra via the intracavity losses. The results for the generated pulses are discussed with respect to the influence of differential gain (dg/dN) and nonlinear gain saturation (ϵ) effects.**

Introduction

PICOSECOND laser pulse generation with semiconductor lasers by, e.g., mode-locking or gain switching are important tasks for, e.g., high-speed optical communication applications [1]. In this respect, quantum-well lasers are of particular advantage, because of the possibility of tailoring the emission wavelength and because of their improved dynamic response [2]. This improved dynamic response can be basically attributed to the higher differential gain of quantum-well lasers as compared to conventional bulk semiconductor lasers. In addition, gain saturation might be also different in quantum well and bulk lasers. Along these lines, the question arises whether in quantum-well lasers higher subband transitions are of advantage for picosecond pulse generation and ultrafast modulation purposes due to the differential gain and saturation characteristics as compared to the lowest ($n = 1$) transition.

In this letter, we report on the generation of picosecond optical pulses in a GaAs/GaAlAs single-quantum-well (SQW) laser at the transition corresponding to the first ($n = 1$) or second ($n = 2$) subbands, depending on the value of the intracavity losses. We discuss the obtained results for the pulse width and shape in terms of the influence of the nonlinear gain and differential gain. We conclude that the generation and dynamics of mode-locked pulses from a higher subband ($n = 2$) can be accounted for by assuming a higher differential gain dg/dN and a lower gain saturation parameter ϵ, respectively, as compared to the $n = 1$ transition.

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Experimental

The GaAlAs/GaAs single-quantum-well laser (Daimler Benz Research Center, Ulm) investigated was a MBE-grown GRINSCH-structure with a thickness L_z of the active layer of 80 Å. The laser was antireflection (AR) coated on one facet with a residual reflectivity $R < 0.1\%$ and was operated in an external cavity consisting of a microscope objective and a high reflecting dielectric end mirror. The losses of the external cavity could be varied by a high-quality neutral density filter with continously adjustable attenuation. The emitted light was analyzed in the temporal and spectral domain by a synchroscan streak camera (time resolution ≤ 8 ps) and a grating spectrometer, respectively.

Results

Fig. 1 shows the light-intensity versus dc-current (P–I) characteristics and the emission spectra under various operation conditions. Without additional losses, the dc laser threshold current amounted to 33 mA (Fig. 1(a), trace A) and the laser emitted at a wavelength of $\lambda = 846$ nm (Fig. 1(b), trace A) corresponding to the lowest lying energetic transition from the $n_e = 1$ electron to the $n_h = 1$ hole state. One of the key features of quantum-well lasers is the threshold like transition from lasing at the $n = 1$ to the $n = 2$ subbands with an increase of the cavity losses and respective increase of laser threshold current and carrier density. This behavior results from the step-like joint density of states function. An increase of the losses can be accomplished either by decreasing the length of the cavity [4], increasing the material losses, [5], or decreasing the facet reflectivity [6]. In the present study, we have varied the intracavity losses by introducing a variable intracavity neutral density filter into the external cavity in order to obtain lasing at the different quantized levels. The P–I characteristics for additional cavity losses resulting in a dc threshold current of 48 mA is shown in Fig. 1(a), trace B. Under this condition lasing at the $n = 1$ subband transition is already suppressed and lasing occurs at considerably shorter wavelength ($\lambda = 807$ nm) corresponding to the $n = 2$ subbands transition, as depicted in Fig. 1(b), trace B. The energetic position of the respective transitions is in accordance with the energies calculated for a $L_z = 80$ Å Grinsch structure.

The switching from lasing at the $n = 1$ to $n = 2$ subband transition should also influence the dynamic properties as, e.g., the differential gain dG/dN [7] and the gain saturation behavior are expected to be different for the respective subband transitions. In order to study this, we compare the performance of the picosecond pulse generated when lasing occurs at the $n = 1$ or $n = 2$ subband transition, respectively. The time behavior of the generated laser pulses reflects the dynamical properties of the respective transition involved. Differences in the dynamical properties of the $n = 1$ and $n = 2$ subband transition in quantum well lasers have been infered already from the difference in modulation bandwidth [7].

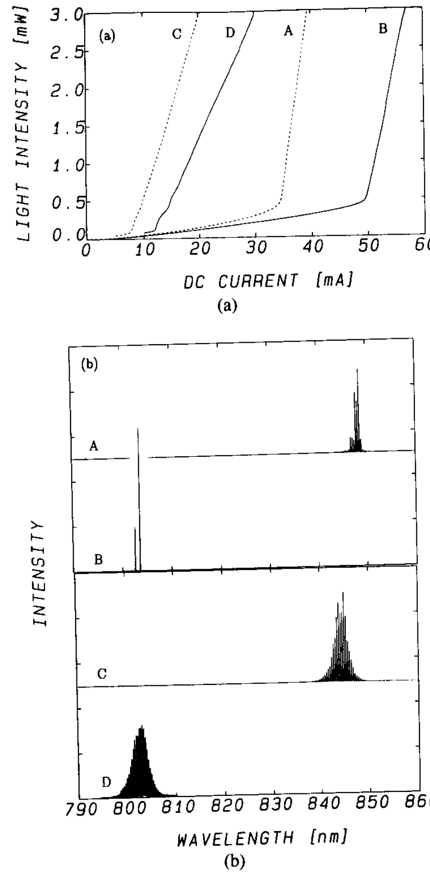

Fig. 1. P–I characteristics [top, (a)] and emission spectra [bottom, (b)] of the external cavity SQW laser for the following conditions: dc-operated without (A, - - - -) and with (B, ——) additional intracavity losses and rf-modulated without (C, - - - -) and with additional losses (D, ——).

We have applied sinusoidal current modulation to generate picosecond pulses. The RF current is superimposed onto the dc bias with a frequency synchronous to the external-cavity roundtrip frequency (150 MHz in our configuration); however, the conditions are not yet optimized to achieve proper mode-locking. The P–I characteristics under these conditions are also shown in Fig. 1(a). Trace C corresponds to no additional internal losses, while trace D depicts the case of additional internal losses, where lasing at the $n = 2$ subbands is obtained. The corresponding lasing spectra are depicted in Fig. 1(b), trace C and D, respectively.

The difference of the transition between the $n = 1$ subbands and the $n = 2$ subbands with respect to the dynamical behavior will be discussed now. The emitted pulses corresponding to the $n = 2$ and $n = 1$ subband transition are depicted in Fig. 2 for two different pumping conditions. In both cases, the dc and the ac components of the injection current were adjusted to equivalent values with respect to the threshold current for the $n = 1$ and $n = 2$ transition, respectively, to ensure equivalent operat-

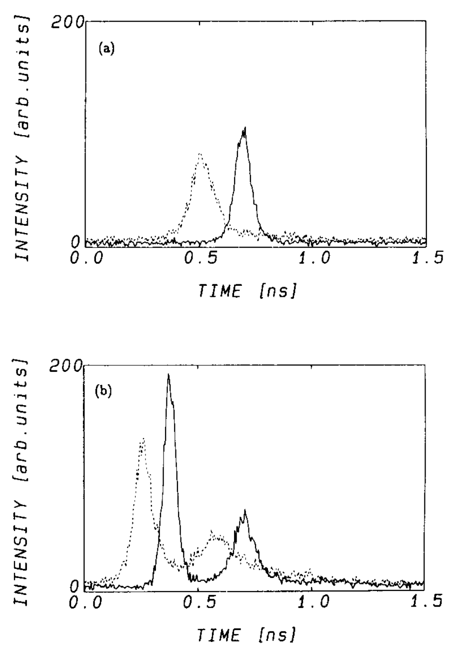

Fig. 2. Mode-locked pulses for the $n = 1$ (- - - -) and then $n = 2$ (——) transition for a injection current $I_{dc} + I_{ac} = 0.28 \cdot I_{th} + 1.2 \cdot I_{th}$ (a) and $I_{dc} + I_{ac} = 0.34 \cdot I_{th} + 1.2 \cdot I_{th}$ (b), respectively.

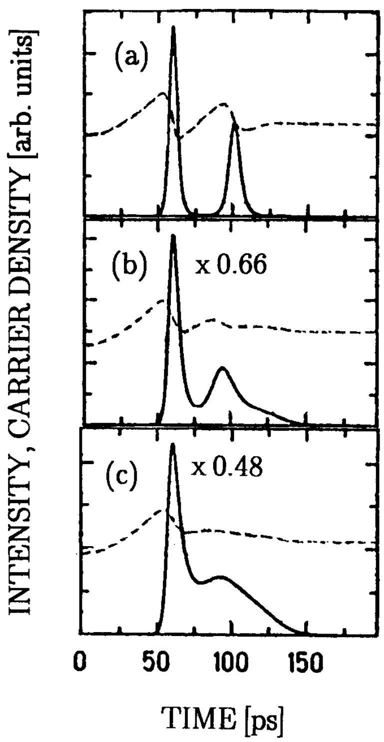

Fig. 3. Numerically calculated influence of the nonlinear gain saturation parameter ϵ on the pulse shape (——) and the carrier density (- - - -) under RF modulation [(a) $\epsilon = 0 \cdot 10^{-18}$ cm^3; (b) $\epsilon = 2 \cdot 10^{-18}$ cm^3; (c) $\epsilon = 4 \cdot 10^{-18}$ cm^3. The light intensity has to be scaled by the factor given in the figure, respectively].

ing conditions. The pulse shapes for the $n = 2$ subband (Fig. 2, solid traces) and $n = 1$ subband transition (Fig. 2, broken traces) are different with respect to their width and recovery behavior. We find for an injection current of $I_{dc} + I_{ac} = 0.28 \cdot I_{th} + 1.2 \cdot I_{th}$ pulse widths (FWHM) of 118 and 84 ps [Fig. 2(a)] for the $n = 1$ and $n = 2$ transition, respectively. At an injection current of $I_{dc} + I_{ac} = 0.34 \cdot I_{th} + 1.2 \cdot I_{th}$ a satellite appears and the difference in pulse width of the main peak is even more pronounced [Fig. 2(b)]. We obtain 104 and 64 ps pulse width for the $n = 1$ and $n = 2$ transition, respectively. Simultaneously, the pulse narrowing is accompanied by a reduction of the intensity in the trailing edge of the pulses and intensity of the satellite emission (the occurence of satellite emission is a general feature observed for sinusoidal current modulation). The satellite emission can be suppressed if synchronous excitation is provided by short current pulses.

Discussion

The optical gain function of SQW lasers shows a step-like behavior in the transition regime between the $n = 1$ and the $n = 2$ emission [8]. Therefore the differential gain dg/dN depends strongly on the operation conditions. The value of dg/dN can be higher by a factor of 2 for the $n = 2$ in comparison to the $n = 1$ subband transition as recently reported for a laser structure with comparable parameters [7]. This higher differential gain will result in shorter optical pulses for the emission corresponding to the $n = 1$ subband transition under mode locking conditions [9].

The saturation behavior of the optical gain function for high light intensities S is phenomenologically described by the ansatz $g = g_0 \cdot (1 - \epsilon \cdot S)$ where g_0 is the unsaturated gain and ϵ the nonlinear gain saturation parameter. The ϵ parameter is now well known to be different for quantum well and bulk lasers [10]; however it is still an open question how ϵ behaves for different subband transitions. The influence of ϵ on the numerically calculated pulse shapes is illustrated in Fig. 3 for different values of ϵ ranging from $\epsilon = 0$ cm^3 to $\epsilon = 4 \cdot 10^{-18}$ cm^3. We find that the nonlinear gain parameter ϵ affects sensitively the pulse shape, in particular the occurence of satellite emission, whereas the pulse width is only minor influenced. In contrast, the pulse width of the main peak is mainly determined by the value of the differential gain dg/dN [9]. On the base of these simulations we are able to discuss our results at least qualitatively. We conclude that the $n = 2$ laser transition is characterized by a higher value of the differential gain dg/dN and a smaller value of the nonlinear gain parameter ϵ as compared to the $n = 1$ transition. The smaller nonlinear gain saturation parameter ϵ of the $n = 2$ transition may be attributed to the higher joint density of states as compared to the $n = 1$ transition; however, it has to be noted that the microscopic origin of the nonlinear gain is still not completely understood. Nevertheless, on the base of our findings it seems beneficial to consider higher subband transitions in quantum-well lasers for ultrahigh speed applications. Yet, a tradeoff in terms of laser threshold has to be made.

SUMMARY

We have compared the performance of picosecond pulse generation of $n = 1$ and $n = 2$ subband lasing transitions in a single-quantum-well GRINSCH laser structure with $L_z = 80$ Å by changing the intracavity optical losses. The threshold like switching from lasing at the $n = 1$ to the $n = 2$ transition with increasing optical losses is accompanied by a decrease in pulse width and an improvement of the pulse shape. This behavior is attributed to a higher differential gain and a lower gain saturation parameter of the $n = 2$ transition as compared to the $n = 1$ laser transition.

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Measurement of 50 fs Nonlinear Gain Time Constant in Semiconductor Lasers

C. B. Kim, En T. Peng, C. B. Su, W. Rideout, and G. H. Cha

Abstract—**The symmetric and asymmetric nonlinear gain in 1.3 μm semiconductor laser are measured in the frequency domain by a novel pump-probe technique using an external cavity traveling-wave semiconductor ring laser. A very short time constant of about 50 fs is measured as the dominant process. The data also indicated the presence of a smaller contribution approximately 15% of the magnitude of the dominant process and with a long time constant consistent with hot carriers effect.**

SPECTRAL-HOLE burning [1] and hot carriers [2] are the physical processes generally thought to be responsible for gain nonlinearity in semiconductor laser. The time constant associated with hot carriers has been identified to be about 600 fs in long-wavelength semiconductor laser [2]. On the other hand, the nonlinear gain time constanst associated with spectral hole burning is usually assumed to be less than 300 fs. From a modulation experiment on Fabry–Perot and DFB lasers, it was determined that the time constant associated with the dominant nonlinear gain process must be less than 150 fs [3]. Nondegenerate four-wave mixing experiments by Kikuchi *et al.* claims that spectral-hole burning with a time constant smaller than 300 fs [4] is the main contribution to the nonlinear gain, while similar four-wave mixing experiment by Tiemeijer [5] found that hot carriers with a time constant of 650 fs is an important contribution to the nonlinear gain. However, the present of a much faster process cannot be ruled out unless higher frequency separation greater than 500 GHz between the signal waves is used [5]. Measurement of the gain cross-saturation spectrum by Frankenberger and Schimpe indicated that spectral hole burning with a time constant of 70 fs is present [6]. Conversely, using the time domain ultrafast pump-probe experiment with 180 fs pulse widths, Hall *et al.* [2]

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