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Theory of Ultrashort Pulse Generation and Amplification by Gain-Switched Semiconductor Lasers

By

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A theory of the nonlinear ultrashort dynamic response of unbiased gain-switched semiconductor laser amplifiers is presented. For suitable time delays between the incident laser pulse and the injection current pulse driving the laser amplifier, optical pulse compression due to self-induced gain depletion is found. The finestructure of the emitted pulse resulting from multiple reflections is shown to depend crucially upon the detuning off cavity resonances and upon the ratio of input signal width to cavity round-trip time.

Eine Theorie des nichtlinearen ultraschnellen dynamischen Verhaltens von elektrisch modulierten Halbleiterlaser-Verstärkern wird vorgestellt. Für geeignete Zeitverzögerungen zwischen dem einfallenden Laserpuls und dem Injektionsstrompuls, der den Laserverstärker treibt, ergibt sich eine optische Pulsverkürzung aufgrund der selbstinduzierten Gain-Erschöpfung. Es wird gezeigt, daß die Feinstruktur des emittierten Pulses durch Vielfachreflexion entscheidend von der Verstimmung aus der Hohlraumresonanz und dem Verhältnis der Eingangssignalbreite zur Laufzeit im Resonator abhängt.

1. Introduction

The generation and amplification of short optical pulses by semiconductor injection lasers is of great current interest because of their potential application in optical communication systems [1 to 5]. When a semiconductor laser is driven by an electrical injection current pulse of a few hundred ps width and a maximum of several times its cw threshold current, single stable laser pulses of less than 15 ps full width at half maximum (FWHM) in the 0.8 to 1.3 μm wavelength range can be generated [6]. If such an unbiased gain-switched semiconductor laser is operated as a dynamical optical amplifier it acts as a high-speed optical gate for an external laser pulse [7]. A theoretical understanding of these phenomena requires modelling of the internal nonlinear dynamics of the laser amplifier as well as the time-dependent coherent amplification of the incident optical signal. In a recently developed approach [8] the incident signal is not described by a rate equation for the photon density, but by an extension of the static, active Fabry-Perot theory of semiconductor laser amplifiers [9, 10] to time-dependent injection currents and incident signals. This theory has been used to explain the physical mechanism of the observed optical gate effect [11]. Here we study the dynamic response of the laser amplifier, i.e., the emitted laser pulse in dependence on the wavelength and the FWHM of the incident signal.

2. Coherent Dynamical Amplification

The signal wave is described by space- and time-dependent electric field amplitudes $E^+(z, t)$ and $E^-(z, t)$ travelling in the positive (forward) and negative (backward) z-

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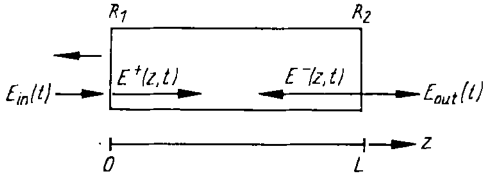


Fig. 1. Schematic representation of the signal fieldamplitudes in a laser amplifier

direction of the laser resonator, respectively (Fig. 1). All remaining laser modes excluding the signal mode are treated incoherently and described by an axially averaged photon density $N(t)$ of the amplified spontaneous emission, which is a reasonable approximation for facet reflectivities larger than 20% [10, 12]. The dynamic equations for E^+ and E^- are given by

$$\frac{\partial E^\pm}{\partial t} \pm v_g \frac{\partial E^\pm}{\partial z} = \frac{1}{2} (\Gamma g(n) - \alpha) E^\pm - ikv_g E^\pm , \tag{2.1}$$

supplemented by the boundary conditions for the crystal facets at $z = 0$ and $z = L$ (reflectivities R_1 and R_2, respectively),

$$\begin{aligned} E^+(0, t) &= (1 - R_1)^{1/2} E_{in}(t) + R_1^{1/2} E^-(0, t) , \\ E^-(L, t) &= R_2^{1/2} E^+(L, t) , \\ E_{out}(t) &= (1 - R_2)^{1/2} E^+(L,t) , \end{aligned} \tag{2.2}$$

where $v_g = c/n_g$ is the group velocity, c the vacuum velocity of light, n_g the optical group index, Γ the optical confinement factor, $g(n)$ the modal gain function depending on the carrier density n, α the optical loss constant for absorption and scattering, k the wave vector of the signal in the cavity, and $E_{in}(t)$, $E_{out}(t)$ are the incident and the emitted signal field amplitudes at the facets. (Note that all electric fields are normalized to the dimension of (length)$^{-3/2}$.)

Under the assumption that the electron density $n(t)$ can be approximated by a constant during each single-pass transit time $\tau = L/v_g$ of the signal, we obtain from (2.1), (2.2) the recursion relation

$$\begin{aligned} E_{out}(t + 2\tau) = [G_s(t + 2\tau)]^{1/2} [(R_1R_2)^{1/2} e^{-2ikL} G_s(t + \tau)^{1/2} E_{out}(t) + \\ + (1 - R_1)^{1/2} (1 - R_2)^{1/2} e^{-ikL} E_{in}(t + \tau)] \end{aligned} \tag{2.3}$$

with the single-pass gain

$$G_s(t) = \exp \{[\Gamma g(n(t)) - \alpha] \tau\} \tag{2.4}$$

and the axially averaged photon density of the travelling signal wave

$$\bar{S}(t) = |E_{out}(t)|^2 \frac{(G_s(t) - 1) (1 + R_2 G_s(t))}{(1 - R_2) G_s(t) \ln G_s(t)} . \tag{2.5}$$

The recursion relation (2.3) may be iterated to express $E_{out}(t)$ as an infinite series of time-delayed E_{in} and G_s terms [8].

The coupled nonlinear dynamics of the electrons and photons is described by (2.5) together with the usual rate equations for n and N [8, 12, 13],

$$\frac{dn}{dt} = \frac{\eta J(t)}{ed} - R_{sp}(n) - g(n) (N + \bar{S}) , \tag{2.6}$$

$$\frac{dN}{dt} = [\Gamma g(n) - \varkappa] N + \beta R_{sp}(n) , \tag{2.7}$$

where η is the electron injection efficiency, $J(t)$ the given injection current density, d the thickness of the active layer, $R_{sp}(n)$ the spontaneous recombination rate, $\varkappa$ the total optical loss coefficient, and β the spontaneous emission factor. Equations (2.5) to (2.7) represent a system of nonlinear delay differential equations. Such nonlinear dynamic systems contain a great wealth of complex time-dependent behaviour [14].

3. Optical Pulse Compression

For suitable time delays τ_d between the incident laser pulse $E_{in}(t)$ and the injection current pulse $J(t)$ there is a strongly nonlinear self-induced dynamic gain depletion [8]. If the laser pulse is injected at about the time when the electron density $n(t)$, and thus the single-pass gain $G_s(t)$, is maximum, the leading shoulder of the laser pulse encounters a large amplification factor. The amplified signal immediately induces a sharp decrease of n by strongly enhanced stimulated emission and thereby depletes the gain G_s. This results in reduced amplification and subsequent suppression of the trailing shoulder of the laser pulse. This nonlinear feedback leads to a strong optical pulse compression. Simulations with a FWHM of the optical input pulse of 60 ps, and a FWHM of the electrical current pulse of 180 ps yield optical output pulses of less than 10 ps. A detailed investigation of the dependence upon τ_d, upon the peak of $E_{in}(t)$, and upon the injection current driving conditions is reported elsewhere [8, 11].

4. Dependence upon Signal Wavelength and Width

In order to elaborate the effects of multiple beam interference of the coherent signal field in the cavity, we vary the wavelength off the cavity resonances. We have performed numerical simulations of (2.5) to (2.7) using Gaussians

$$J(t) = J_0 \exp\left\{-\left(\frac{t}{t_J}\right)^2\right\}, \tag{3.1}$$

$$E_{in}(t) = E_0 \exp\left\{-\left[\frac{(t+\tau_d)}{t_s}\right]^2\right\} \tag{3.2}$$

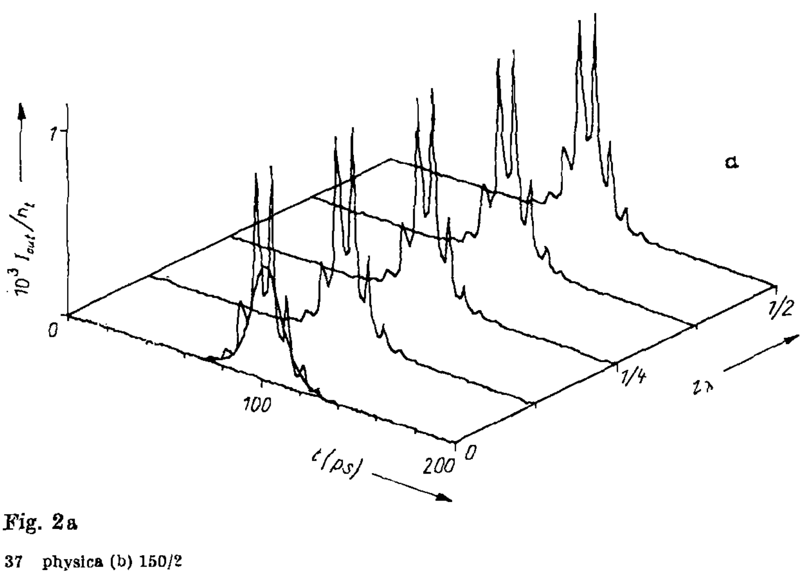
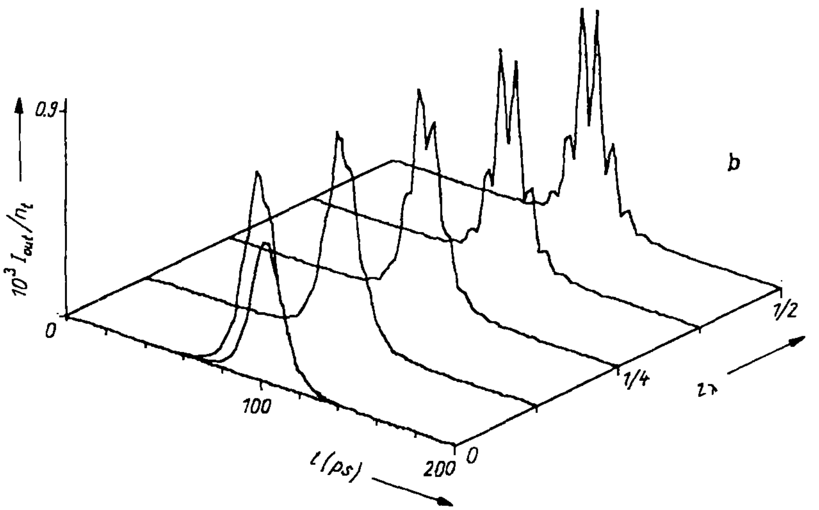


Fig. 2a



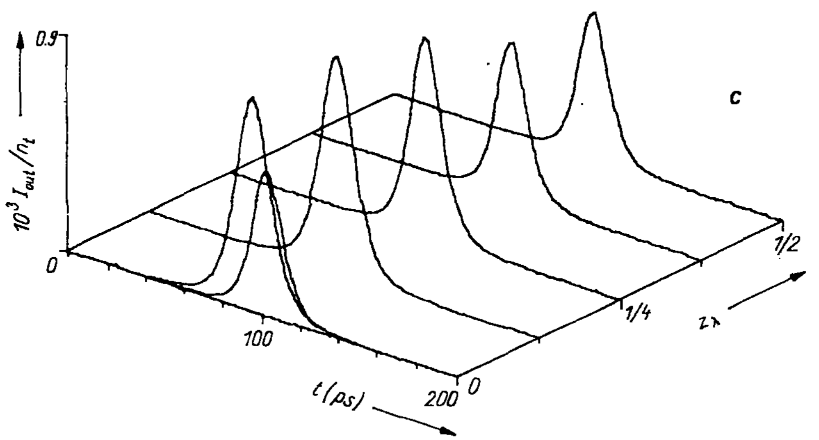


Fig. 2. a) Total emitted photon density $I_{out} = |E_{out}|^2 + N$ in units of n_t as a function of time in ps for five different signal wave vectors $k = k_r + z_\lambda \pi/L (0 \leq z_\lambda \leq 1/2)$ where $k_r = 3000\pi/L$ is the cavity resonance corresponding to a vacuum wavelength $\lambda_0 = 0.8$ μm. The electrical and optical input pulses are modelled with $J_0 = 7J_t$, where J_t is the cw threshold current density, $t_J = 145$ ps, $E_0^2 = 10^{-6} n_t$, $t_s = 2$ ps, $\tau_d = -45$ ps, corresponding to a FWHM of $J(t)$ and $E_{in}(t)$ of 240 ps and 3.3 ps, respectively. $\bar{S}(t)$ has been varied in discrete time steps of 0.5 ps. b) Same as a) but with $t_s = 5$ ps corresponding to 8.3 ps FWHM of E_{in}; c) same as a) but with $t_s = 10$ ps, corresponding to 16.6 ps FWHM

as electrical and optical input functions, and

$$R_{sp}(n) = Bn^2\,, \qquad g(n) = g_0(n - n_0) \tag{3.3}$$

as spontaneous recombination rate and modal gain, respectively. The material parameters are $B = 1.6 \times 10^{-10}$ cm^3 s^{-1}, $g_0 = 4 \times 10^{-6}$ cm^3 s^{-1}, $n_0 = 1.25 \times 10^{18}$ cm^{-3}, $\Gamma = 0.2$, $\beta = 10^{-4}$, $\varkappa = 1$/ps, $\alpha = 0.722$/ps, $R_1 = R_2 = 0.33$, $L = 300$ μm, $n_g = 4$, resulting in a cw threshold carrier density $n_t = 2.5 \times 10^{18}$ cm^{-3}, and a single-pass transit time $\tau = 4$ ps. Here $\varkappa = \alpha - [\ln(R_1 R_2)]/(2\tau)$ has been chosen in order to secure equal cw laser thresholds for the signal mode and the other cavity modes. Fig. 2a shows the total emitted intensity $I_{out}(t) = |E_{out}(t)|^2 + N(t)$ for five different wavelengths of the signal, and for an injection current pulse corresponding to excitation conditions slightly above the dynamic effective threshold such that for $E_{in} = 0$ a small single relaxation oscillation $N(t)$ of about 20 ps FWHM (smooth curve at $z_\lambda = 0$) is emitted. The output pulse exhibits a distinct fine structure of subpeaks separated by the cavity round-trip time 2τ. They are due to multiple reflections of the input pulse and do not depend upon the cavity detuning z_λ. There is no interference because the FWHM of the signal is smaller than the round-trip time 2τ. In Fig. 2 b and c analogous plots are shown for longer incident pulses. In Fig. 2b the signal FWHM is of the order of 2τ. There is a strong dependence on wavelength. For maximum detuning ($z_\lambda = 0.5$) the signal is effectively narrowed by destructive interference at the edges, and the multiple reflections are still clearly shown. In Fig. 2c the signal FWHM is much larger than 2τ. The multiple pulse reflections are smeared out for all wavelengths. The maximum of the emitted pulse decreases with the detuning just as the total amplifier intensity gain does under static conditions (cf. [8], (15)).

These results illustrate that our theory covers a wide range of relevant operating conditions. If smooth pulses and maximum amplification is required, the input signal should be tuned to a cavity resonance.

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