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Distributed feedback laser amplifiers combining the functions of amplifiers and channel filters

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A dynamic model for distributed feedback amplifiers, including the mode coupled equations and the carrier rate equation, is established. The presented mode coupled equations have taken into account the interaction between fast changing optical signal and the waveguide with corrugations. By showing the possibility of amplifying 100 ps pulses without pulse broadening, we anticipate that a distributed feedback amplifier can be used as a combined amplifier and channel filter in high bit rate transmission systems.

Distributed feedback (DFB) amplifiers are very attractive for optical filtering because they can serve both as channel and noise filters and at the same time provide optical amplification. They may be used as filters in switching networks or as receiver amplifiers in multichannel direct detection systems.[1] Amplifiers incorporating DFB structures have also been suggested for wavelength converters.[2] For such applications, it is important to understand the dynamic behavior of DFB amplifiers when they are used at high bits rate. It is especially interesting to observe the influence of the very narrow gain spectrum on short optical pulses.

Here we report a dynamic model for DFB amplifiers. It accounts for both the temporal and longitudinal variation of the electric field distribution and the carrier distribution. Using this model, the amplification of narrow optical pulses has been studied. Due to the gain spectrum with a bandwidth in the GHz range, the behavior of DFB amplifiers in pulse amplification is fundamentally different from that of traveling wave amplifiers, which have been studied extensively.[3,4] In this letter, we are going to report amplification of 100 ps pulses to ensure that DFB amplifiers can be used as combined channel filters and amplifiers in high bite rate transmission systems.

If ultrafast phenomena, including amplification of very short optical pulses or fast optical switching are considered, then the terms which account for the variation of the electric field with time have to be included in contrary to the static mode coupled equations that are normally derived for DFB structures.[5,6] Starting from Maxwell's equations and following the same procedure as in Ref. 5, the dynamic coupled equations are[7]

$$\frac{\partial A}{\partial z}+\frac{1}{v_g}\frac{\partial A}{\partial t}-\frac{1}{2}(1-j\alpha)(\Gamma g-\alpha_i)A = \kappa\exp(2j\delta z)\left(B+\frac{j}{\pi\nu}\frac{\partial B}{\partial t}\right), \tag{1}$$

$$-\frac{\partial B}{\partial z}+\frac{1}{v_g}\frac{\partial B}{\partial t}-\frac{1}{2}(1-j\alpha)(\Gamma g-\alpha_i)B = \kappa\exp(-2j\delta z)\left(A+\frac{j}{\pi\nu}\frac{\partial A}{\partial t}\right), \tag{2}$$

where $A(z,t)$ and $B(z,t)$ are the electric field distributions along the cavity for the wave propagating in the positive and negative z directions, respectively. δ is the detuning of the propagation constant from the Bragg condition, and v_g is the group velocity of light inside the cavity. κ is the mode coupling coefficient, α the linewidth enhancement factor, α_i the internal loss and ν the optical frequency. g is the material gain per unit length and varies linearly with the carrier density, N which is governed by[3]

$$\frac{\partial N(z,t)}{\partial t}=\frac{I}{qV}-\frac{a[N(z,t)-N_0]}{h\nu}[|A(z,t)|^2+|B(z,t)|^2]-\frac{N(z,t)}{\tau_c}, \tag{3}$$

where I is the bias current, q the electron charge, and V the volume of the active region. The carrier lifetime is denoted by τ_c and a is the differential gain. h is Planck's constant, and N_0 is the carrier density at transparency.

From the right side of Eqs. (1) and (2), we can see that the time variation of the forward and backward traveling electric fields A and B will affect the coupling between the two fields. The modification of the coupling coefficient will result in changes in peak gain level and the detuning of the optical frequency for the gain peak. This will change the transmission characteristics of DFB amplifiers.

Equations (1)–(3) constitute the theoretical framework for the description of the dynamics of DFB laser amplifiers. In the following, the facets are assumed have zero reflectivity and the influence of spontaneous emission is ignored since it is not important for studies of fast phenomena.[4] The numerical simulations have been performed by adopting the method of characteristics.[8] The method of characteristics is difficult to explain in a simple manner, but the basic idea is to transform the differential equations to another coordinates system

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TABLE I. The value of the parameters.

Parameter	Value
Wavelength, λ (μm)	1.55
Group refractive index, n_g	3.5
Carrier lifetime, τ_c (ns)	2.0
Differential gain coefficient, a (m^2)	2.7×10^{-20}
Confinement factor, Γ	0.3
Thickness of the active layer, d_a (μm)	0.15
Width of the active layers, w (μm)	3.0
Cavity length, L (μm)	500
Electronic charge, $q(C)$	1.6×10^{-19}
Planck's constant, h (J-s)	6.62×10^{-34}
Transparency's constant, N_0 (cm^{-3})	1×10^{18}
Group light velocity, $v_g=c/n_g$ (ms^{-1})	0.86×10^8
Volume of the active layer, $V=d_awL$ (μm^3)	225

where the partial differential equations are transferred to normal differential equations. Thereby the necessary computer time is significantly reduced. The values of the parameters used in the calculation are listed in Table I.

The steady-state gain characteristics of DFB laser amplifiers can be investigated by using Eqs. (1) and (2) with $\partial/\partial t=0$. An example of the static gain spectrum for a DFB amplifier with $\kappa L=3.0$ is shown in Fig. 1 for a bias of 99% of the threshold. Since we consider an ordinary DFB structure without a $\lambda/4$ shift, the maximum gain of 36 dB is found for a detuning of 121 GHz from the Bragg frequency (only half of the spectrum is shown here). The high bias level results in a very sharp gain spectrum with a 3 dB bandwidth lower than 1 GHz. The above calculation shows that the filtering characteristics of DFB amplifiers is only valid for a weak unmodulated optical signal (optical power is so low that gain saturation does not occur inside the cavity) since the filter is built up by multiresonance of the optical signal. Here we have studied the transmission of a short optical pulse by DFB laser amplifiers, where the interaction between the fast optical signal and the medium with the grating will play an important role.

Different from the case of traveling wave amplifier, there are output from both front and rear facets of a DFB amplifier when signal is injected from front facet. As an example, Fig. 2 shows the transmitted and reflected pulses from the amplifier when a weak pulse is injected. The input pulse is Gaussian shaped with a width of 100 ps (full width at half-maximum) and the bias current is 99% of threshold. For the weak input case, which has a peak power of 1 μW (energy of 0.15 fJ), the output pulses are broadened to 235 ps due to the filtering characteristics of the amplifier. The gain of the pulse is 23.4 dB, which is 12 dB lower than that of Fig. 1.

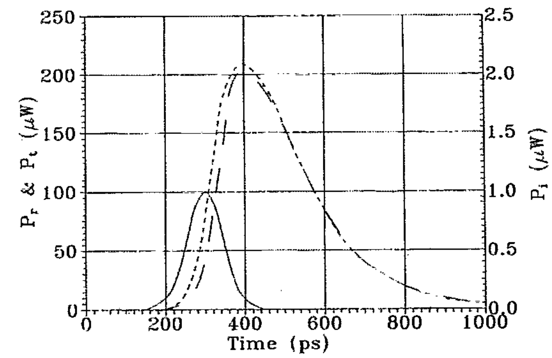

FIG. 2. Power of reflected (short-dashed), transmitted (long-dashed) and input pulses(solid). The input pulse have a FWHM of 100 ps and a peak power of 1 μW. $\kappa L=3.0$, I/I_{th}=99%. P_i, P_r, and P_t represent the power of input, reflected, and transmitted pulses, respectively.

The pulse broadening is very much dependent on the bias current and the coupling coefficient of the DFB amplifiers. In Fig. 3, we have calculated the pulse amplification characteristics of a DFB laser amplifier with $\kappa L=0.5$ and 3.0. Similar to Fig. 3, the input pulse is 100 ps wide with a peak power of 1 μW. For $I/I_{th}\leqslant0.9$ the pulse broadening is insignificant in accordance with static gain spectra with 3 dB bandwidths of 19 and 6 GHz for $\kappa L=0.5$ and 3.0, respectively. As I/I_{th} increase from 0.90 to 0.99, the pulsewidth is broadened considerably, in agreement with a decrease in the filter bandwidth. The corresponding gain for the case of Fig. 3 is shown in Fig. 4, the gain is increasing with the bias level of the DFB amplifiers relative to its threshold current. The simulation results indicated that DFB amplifiers can be used as a combined filter and preamplifier even at high bitrates if the bias is 10% below threshold.

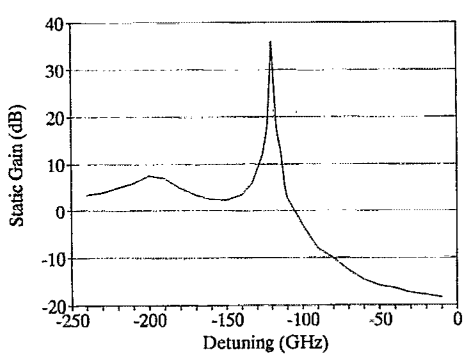

FIG. 1. Steady-state gain spectrum of a DFB amplifier with $\kappa L=3.0$ and I/I_{th}=99%.

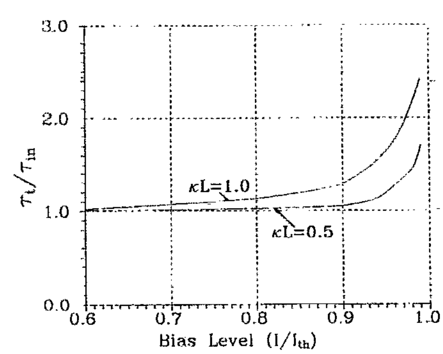

FIG. 3. Pulse broadening as a function of bias level for a 100 ps input pulse, where τ_t and τ_{in} are the full width at half-maximum of the transmitted and input pulses.

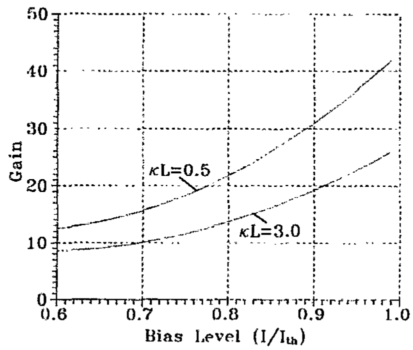

FIG. 4. Gain vs bias level for a 100 ps input pulse.

A dynamic model for DFB amplifiers has been established. The model accounts for the time and position dependence of both the electric field and the carrier density in the DFB amplifier cavity. Simulation results have shown that low power input pulses may be amplified without pulse broadening if the bias is 10% below threshold. We anticipate that DFB amplifiers can be used as combined preamplifiers and filters in high bit rate transmission system.

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