LARGE-SIGNAL P.C.M. BEHAVIOUR OF INJECTION LASERS WITH COHERENT IRRADIATION INTO ONE OF THEIR OSCILLATING MODES

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The effect of coherent irradiation on the modulation characteristics is investigated theoretically. A p.c.m. simulation has been performed using a multimode rate-equation model. A significant improvement in the modulation behaviour is predicted if the laser is subject to an external irradiation.

Considerable effort is at present spent on applying injection lasers to fibre-optic communication systems with modulation rates in the Gbit/s range. Suitable lasers have to meet special requirements not only with regard to a fast modulation capability, but also to a high spectral purity.[1] The purity condition is of great importance for such applications, since pulse distortion due to fibre dispersion can only be kept small enough if the single-mode character of the laser is not affected by fast modulation.[2]

There are three basic phenomena which are mainly encountered in the modulation behaviour as the modulation speed exceeds the 100 Mbit/s range. These are the delayed photon response,[3] the occurrence of relaxation oscillations[4] and the tendency to favour the excitation of additional lasing modes,[5] which implies a deterioration of the spectral purity. Since the delay of the photon response is easily eliminated by biasing the laser diode near or above threshold, problems merely arise from the latter effects. To overcome these difficulties, coherent irradiation into the oscillating mode of the laser diode has been proposed.[6, 7] Coherent irradiation acts as a damping mechanism and reduces the relaxation oscillations. It is also expected to increase the stimulated emission into the irradiated mode at the expense of other lasing modes.[6, 8] Although the damping effect has been furnished by both theory and experiment, only little attention has been paid to the improvement of the spectral purity so far.

This letter is concerned with a theoretical study of the irradiation effects. It is based on an extended form of the well known rate-equation model.[9] To treat the lasing modes individually, the photon ensemble is separated into subsystems, each representing a single mode. Assuming that N different lasing modes are taken into consideration, the model is defined by a system of $N+1$ rate equations:

$$\frac{dn}{dt} = \frac{I}{eV} - \frac{n}{\tau_{sp}} - \sum_{i=1}^{N} g_i n s_i \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

$$\frac{ds_i}{dt} = V\alpha_i \frac{n}{\tau_{sp}} - \frac{s_i}{\tau_{ph}} + V g_i n s_i + R_i \qquad i = 1, \ldots N \quad (2)$$

where n and s_i denote the electron density and the photon number belonging to the ith mode, respectively. Most terms appearing on the right-hand side are identical or analogous to those of the conventional single-mode model. Some terms need to be discussed in more detail. Stimulated emission is represented by a bilinear approximation containing products ns_i. The optical gain $g_i n$ is assumed to be different for different modes, accounting for the fact that the stimulated emission rate depends on the photon energy. Spontaneous emission is introduced in the usual form by the first term of eqn. 2. The factor α_i is defined as the ratio of those spontaneous recombination processes emitting into the ith lasing mode to all occurring recombination processes. In a 1st-order approximation the value of α_i is assumed to be the same for all modes. The spontaneous emission has been included for two reasons. It may have a significant influence on the relaxation oscillations[10, 11] and it is necessary to make the multimode model self consistent. This will be discussed later. The term R_i represents external irradiation into the ith mode.

The laser characteristics are specified by the set of device parameters τ_{sp}, τ_{ph}, g_i and α_i. These parameters have been estimated by measurements. In particular, spectral measurements have been used to determine the g_i values. In this way, the photon subsystems can be related to their corresponding frequencies. In a forthcoming paper,[12] this procedure will be demonstrated in more detail. It will be shown that a reasonable agreement with experiments has been obtained in the nonirradiated case.

Computer simulations have been performed on a d.h. laser produced by the AEG-Telefunken Research Institute. The laser is of multimode type with six major lasing modes. There is one predominant mode at 8922 Å and five other modes whose intensities differ from the predominant one by one order of magnitude on steady-state conditions. The effect of irradiation will be demonstrated by simulating a 2 Gbit/s pulse-code modulation for both the irradiated and the nonirradiated laser. The results are described with reference to Fig. 1, showing the driving current (normalised to the threshold current) and the photon responses for both cases. Without irradiation, the modulation behaviour is very poor. There are significant pattern effects and a considerable contribution of the nondominant modes (s_2, ..., s_6) to the total photon number $\sum s_i$. In comparison to the steady-state conditions, the amount of the nondominant modes is significantly increased, particularly at the maximum of the output pulses. Quite a different situation is observed when irradiation into the dominant mode s_1 is involved. Pattern effects have disappeared and the excitation of nonirradiated modes has been almost completely suppressed. The irradiation rate which effects this excellent behaviour is rather small. It is less than 1 %, in comparison with the light output produced by the laser when it is operated at twice the threshold and without irradiation.

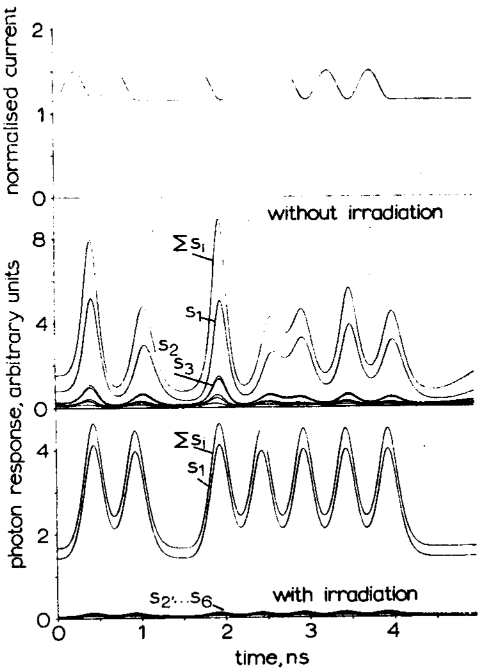

Fig. 1 *Simulated photon response to 2 Gbit/s pulse-code modulation*

Some insight into the mechanisms causing the irradiation phenomena is obtained by making use of the fundamental properties of the rate-equation model. Some of these properties become apparent by considering the steady-state case. Using eqn. 2, s_i can be expressed in the form

$$\frac{s_i}{\tau_{ph}} = \frac{V\alpha_i n/\tau_{sp} + R_i}{1 - n/n_{ci}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

By this equation, the annihilation of photons due to the internal losses and to the laser output is related to the creation of photons by spontaneous emission and irradiation. The quantity n_{ci} is a critical electron density belonging to the ith mode, which is defined as

$$n_{ci} = \frac{1}{g_i \tau_{pn} V} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

The factor $(1-n/n_{ci})^{-1}$ can be interpreted as amplification caused by stimulated emission. Obviously, the intensity of a mode is governed by this amplification factor. Since n must be lower than any of the n_{ci}, the amplification factor takes its maximum value for the mode with the lowest critical electron density. When irradiation is absent, this mode will be predominant. It is also the only one which will be excited in the limiting case where the α_i tend to zero. Thus a multimode laser could not be described if spontaneous emission had been omitted.

Irradiation into any mode of a multimode laser effects a reduction in the electron density when the current operating conditions remain unchanged. In the steady-state, this can be easily verified by eqns. 1 and 3. As shown by various simulations, this also applies to dynamic operation conditions. Thus, the amplification factors which are very sensitive to variations of the electron density are significantly reduced. In the steady-state case, the consequences are obvious. The excitation of nonirradiated modes is considerably reduced or even suppressed. On the other hand, this reduction forces the irradiated mode to be increased to balance eqn. 1. For dynamic operation, similar arguments can be applied by writing eqn. 2 in the form

$$\frac{ds_i}{dt}+(1-n/n_{ci})\frac{s_i}{\tau_{ph}}=V\alpha_i\frac{n}{\tau_{sp}}+R_i \quad . \quad . \quad . \quad . \quad (5)$$

Since s_i/τ_{ph} exceeds $V\alpha_i n/\tau_{sp}$ and R_i by several orders of magnitude, the effect connected with variations of the electron density is mainly concerned with the second term on the left-hand side. When, during the dynamical overshoots, the electron density exceeds the critical value of a mode, this term becomes negative and the photon number increases without any damping. On the other hand, when the electron density is below the critical value, the term acts as a damping mechanism. This behaviour is responsible for relaxation oscillations. For irradiation, the electron density if permanently below the critical values. Relaxation oscillations cannot occur. The photon system is strongly damped and follows immediately any changes of n. Therefore eqn. 3 does also apply in a good approximation to dynamic operation. The improvement of the spectral purity as derived from eqn. 3 in the steady-state is also predicted for dynamic operation.

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