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# Modulation Behaviour of Injection Lasers with Coherent Irradiation into their Oscillating Mode *

By coherent irradiation into an injection laser the spectral and modulation behaviour can be improved. The irradiation causes an aperiodic damping of the transient oscillations.

### Modulationsverhalten von Injektionslasern bei kohärenter Einstrahlung in den schwingenden Modus

Durch kohärente Einstrahlung in einen Injektionslaser können das spektrale und das Modulationsverhalten verbessert werden. Die Einstrahlung bewirkt eine aperiodische Dämpfung der Einschwingvorgänge.

Because of their direct modulation capability up to very high bit rates semiconductor injection lasers are of special interest for optical fibre communication systems [1]. For direct modulation at very high bit rates injection lasers have to be biased above threshold to avoid the delay between an applied current pulse and the optical output pulse [2]. If the laser is biased above threshold the bit rate is limited by the transient oscillations of the laser [3]–[5]. A strong damping of the transient oscillations occurs if the spontaneous emission into the oscillating modes is high. Unfortunately, the damping by the stimulated emission is strong enough only for multimode operation [6]. But multimode lasers are not suited for application in communication systems with extremely high transmission bandwidth, since their broad emission spectrum causes a too large dispersion even in single mode fibres.

In this letter we show that the damping of the transient oscillations can be improved in a similar way by coherent irradiation into the oscillating mode. Furthermore, it is known, that frequency locking of the laser radiation is possible by coherent irradiation into the laser [7]. Thus, the coupling of a monofrequent coherent radiation to the oscillating mode of the laser also leads to an improvement of its spectral purity.

For the calculation of the dynamic behaviour of the laser we use the monomode rate equations

$$\frac{\mathrm{d}N}{\mathrm{d}t} = \frac{I}{eV} - \frac{N}{\tau_{\mathrm{sp}}} - gNS\,, \tag{1}$$

$$\frac{\mathrm{d}S}{\mathrm{d}t} = R - \frac{S}{\tau_{\mathrm{ph}}} + VgNS\,, \tag{2}$$

where $N$ denotes the electron density, $S$ the photon number, $I$ the injection current, $R$ the number of photons injected into the oscillating mode per unit of time, $V$ the volume of the active layer, $e$ the electron charge, $\tau_{\mathrm{sp}}$ the spontaneous electron lifetime, $g$ the coefficient for the stimulated recombination in the bilinear approximation and $\tau_{\mathrm{ph}}$ the photon lifetime. With the threshold current $I_{\mathrm{th}} = e/g\,\tau_{\mathrm{sp}}\,\tau_{\mathrm{ph}}$ we introduce the following normalized parameters:

$$x = eS/I_{\mathrm{th}}\,\tau_{\mathrm{ph}}\,, \qquad z = Vg\,\tau_{\mathrm{ph}}\,N\,, \qquad (3),\ (4)$$

$$\eta = I/I_{\mathrm{th}}\,, \qquad \zeta = eR/I_{\mathrm{th}}\,. \qquad (5),\ (6)$$

The photon injection rate is normalized in such a way that for $\zeta = 1$ and no injection current the photon density in the mode is the same as for twice the threshold current without photon injection.

In the stationary case the photon number and electron density in dependence of the current and photon injection are given by

$$x = \frac{\zeta + \eta - 1}{2} + \sqrt{\left(\frac{\zeta + \eta - 1}{2}\right)^2 + \zeta}\,, \tag{7}$$

$$z = 1 - (\zeta/x)\,. \tag{8}$$

Fig. 1 shows the normalized photon number versus the normalized injection current for $\zeta = 0$, 0.01 and 0.1. As in the case of strong spontaneous emission we have an increasing photon density below threshold. Fig. 2 shows the influence of the coherent irradiation upon the electron density. For coherent irradiation the electron density is below the electron density for no irradiation. According to eq. (8) the gain factor by which the external radiation $\zeta$ is amplified to $x$ is $(1-z)^{-1}$. Without external irradiation above threshold this gain factor becomes

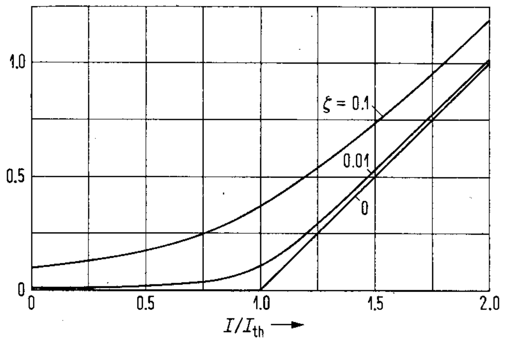

Fig. 1. Normalized photon number $x$.

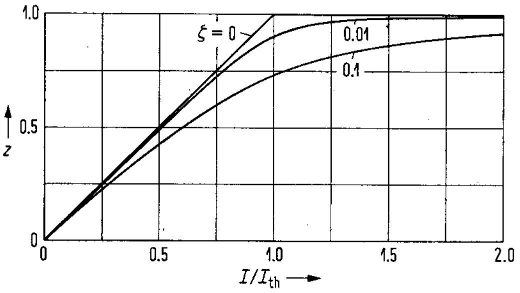

Fig. 2. Normalized electron density $z$.

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infinity. In the case of external irradiation only finite gain is necessary for amplifying the external radiation to the saturation value, limited by the current injection. If we take into consideration the spontaneous emission the gain factor is finite even with no external irradiation. Since the external irradiation into the oscillating mode can be made much higher than the spontaneous emission into this mode the gain factor is considerable lower and does not allow for a high amplification of the spontaneous emission in modes where no external irradiation exists. From this a suppression of all non-irradiated modes results. Further we expect an enhancement of the modulation bandwidth as a consequence of the gain factor reduction.

For the investigation of the small signal modulation behaviour we take

$$x = x_0 + x_1\,\mathrm{e}^{\mathrm{j}\omega t} + x_1^*\,\mathrm{e}^{-\mathrm{j}\omega t} \tag{9}$$

and the same ansatz for $z$, $\eta$ and $\zeta$. Substituting into eqs. (1) to (6) we get by first order small signal approximation (10)

$$\begin{pmatrix}\eta_1\\ \zeta_1\end{pmatrix} = \begin{pmatrix}1 + x_0 + \mathrm{j}\,\omega\,\tau_{\mathrm{sp}} & z_0\\ -x_0 & 1 - z_0 + \mathrm{j}\,\omega\,\tau_{\mathrm{ph}}\end{pmatrix}\begin{pmatrix}z_1\\ x_1\end{pmatrix}.$$

If the external radiation is not modulated ($\zeta_1 = 0$) the complex amplitude of the normalized photon density $x_1$ depends on the complex amplitude $\eta_1$ of the ac current superimposed to the dc bias by

$$x_1 = \frac{x_0\,\eta_1}{\omega_0^2 + \mathrm{j}\,\omega\,\beta - \omega^2} \tag{11}$$

with

$$\beta\,\tau_{\mathrm{sp}} = 1 + x_0 + \frac{\tau_{\mathrm{sp}}}{\tau_{\mathrm{ph}}}\,(1 - z_0) \tag{12}$$

and

$$\omega_0^2\,\tau_{\mathrm{ph}}\,\tau_{\mathrm{sp}} = 1 + x_0 - z_0\,. \tag{13}$$

The damping constant $\beta$ and the angular resonance frequency $\omega_0$ are strongly influenced by the external irradiation. The normalized damping constant $\beta\,\tau_{\mathrm{sp}}$ and the normalized angular frequency $\omega_0\sqrt{\tau_{\mathrm{sp}}\,\tau_{\mathrm{ph}}}$ are shown in Figs. 3 and 4 for the ratio $\tau_{\mathrm{sp}}/\tau_{\mathrm{ph}} = 1000$, corresponding to the realistic values $\tau_{\mathrm{sp}} = 2$ ns, $\tau_{\mathrm{ph}} = 2$ ps. For no external irradiation $\omega_0$ is much higher than $\beta/2$. Aperiodic damping with $\beta > 2\,\omega_0$ can be achieved for $\zeta_0 \neq 0$. For example, taking $\tau_{\mathrm{sp}} = 2$ ns, $\tau_{\mathrm{ph}} = 2$ ps and $\eta_0 = 1.2$ for $\zeta_0 = 0$ we get $\beta = 0.6 \cdot 10^9\,\mathrm{s}^{-1}$, $\omega_0 = 7.07 \cdot 10^9\,\mathrm{s}^{-1}$ and $2\,\omega_0/\beta = 23.56$; for $\zeta_0 = 0.01$ we get $\beta = 20.6 \cdot 10^9\,\mathrm{s}^{-1}$, $\omega_0 = 8.52 \cdot 10^9\,\mathrm{s}^{-1}$ and $2\,\omega_0/\beta = 0.827$.

Thus the modulation behaviour is considerably improved by the coherent irradiation. For practical applications we propose an arrangement of two optically coupled injection lasers. A laser 1 oscillates in a single mode and does not need a good modulation behaviour. A laser 2 is modulated and does not need a good spectral purity since it is frequency locked by the laser 1. To get a weak influence of laser 2 on laser 1, the laser 1 should be biased well above threshold and laser 2 below or near threshold. A further reduction of the reaction from laser 2 on laser 1 could be achieved by an antireflection coating on the mirrors of laser 2.

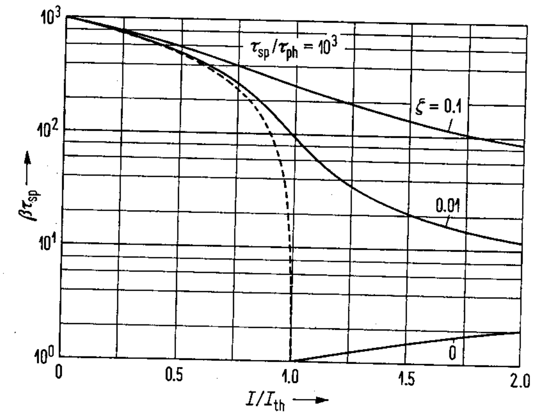

Fig. 3. Normalized damping constant $\beta\,\tau_{\mathrm{sp}}$.

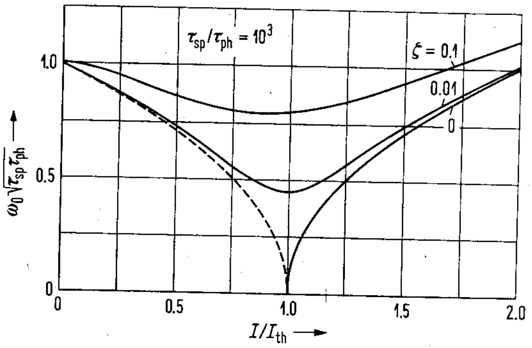

Fig. 4. Normalized angular resonance frequency $\omega_0\sqrt{\tau_{\mathrm{sp}}\,\tau_{\mathrm{ph}}}$.

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## References

[1] Börner, M., Ein optisches Nachrichtenübertragungssystem mit Glasfaser-Wellenleitern. Wiss. Ber. AEG-Telefunken **44** [1971], 41—45.

[2] Konnerth, K. and Lauza, C., Delay between current pulse and light emission of a Gallium Arsenide injection laser. Appl. Phys. Letters **4** [1964], 120—121.

[3] Paoli, T. L. and Ripper, J. E., Direct modulation of semiconductor lasers. Proc. Inst. Elect. Electron. Engrs. **58** [1970], 1457—1465.

[4] Ikegami, T., Kobayashi, K., and Suematsu, Y., Transient behavior of semiconductor injection lasers. Electronics and Communications in Japan **53-B** [1970], 82—89.

[5] Russer, P. and Schulz, S., Direkte Modulation eines Doppelheterostrukturlasers mit einer Bitrate von 2,3 Gbit/s. AEÜ **27** [1973], 193—195.

[6] Röss, D., Einfluß der spontanen Emission auf das Einschwingverhalten von Lasern. Z. Naturforsch. **19a** [1964], 1169—1177.

[7] Salathe, R., Voumard, C., and Weber, H., Optical coupling of two diode lasers with variable coupling coefficient. Phys. stat. sol. (a) **23** [1974], 675—682.