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Direct modulation of semiconductor injection lasers at high bit rates

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Methods for direction modulation of injection lasers at bit rates from 100 Mbit s^{-1} up to the Gbit s^{-1} region are discussed. By pre-equalization of the modulation signal and prebiasing of the laser the modulation distortions can be reduced. The spectral distribution of the laser radiation is influenced by the modulation. The transient and spectral behaviour can be improved by coherent irradiation.

Verfahren zur direkten Modulation von Injektionslasern bei Bitraten von 100 Mbit s^{-1} bis in den Gbit s^{-1} Bereich werden diskutiert. Durch Vorentzerrung des Modulationssignales und Vorspannung des Lasers lassen sich die Modulationsverzerrungen reduzieren. Die spektrale Vertailung der Laserstrahlung wird von der Modulation beeinflußt. Durch kohärente Einstrahlung lassen sich das Einschwingverhalten und das Spektrum des Lasers verbessern.

Introduction

For their simple construction, small dimensions, uncomplicated pumping by d.c.-current, high efficiency and direct modulation capability up to very high frequencies semiconductor injection lasers are well suited as optical sources for broadband optical communication [1]. By the invention of the double heterostructure and stripe geometry and technological improvements threshold currents under 100 mA, monomode operation and lifetimes of 10 000 hours and more can now be achieved [2].

This contribution deals with the direct modulation of injection lasers at bit rates ranging from 100 Mbit s^{-1} up to some Gbit s^{-1}. In fibre-optical communication systems broadest bandwidths are obtained with monomode fibres [3, 4]. The monomode fibre requires coherent optical sources which oscillate in one single mode. As the dispersion of usual monomode fibres is 1 ns km^{-1} for 1 % relative bandwidth [5, 6] the spectral width of the source at a wavelength of 9000 Å has to be smaller than 4.5 Å if a bit rate of 2 Gbit s^{-1} and a fibre length of 10 km are assumed. The linewidths of injection lasers are smaller than 1 Å and the line distance is several Å. Therefore, multimode lasers are not suitable for gigabit rates, whereas the linewidth of monomode lasers can be neglected.

The emission spectrum of injection lasers can be considerably broadened by direct modulation [7, 8, 9]. The qualification of injection lasers for communication at high bit rates depends on its fast direct modulation capability, its monomode operation, the maintenance of the monomode operation in the case of direct modulation and the absence of spontaneous fluctuations [7, 8, 9]. From different methods of direct modulation [10] for broadband communication only pulse code modulation is of interest and this only will be treated here.

The modulation behaviour of injection lasers is governed by the spontaneous electron lifetime τ_{sp}, the photon lifetime τ_{ph} [11, 12], the number of oscillating modes and the ratio of spontaneous processes radiating into the oscillating modes to the total number of spontaneous recombinations [13, 14, 15]. In DHS lasers, τ_{sp} is in the order of 5 ns at room temperature [16] and τ_{ph} is some ps [11]. In the following sections modulation without and with prebiasing the laser will be discussed.

1. Direct modulation of injection lasers which are either unbiased or biased below threshold

If a step current of amplitude I is applied to an injection laser the delay time t_d between the rising edge and the onset of coherent emission is given by [12, 17, 18]:

$$t_d = \tau_{sp} \ln [I/(I - I_{th})] \qquad (1)$$

where I_{th} is the threshold current. After the initial delay, the light intensity first increases rapidly and is then subject to damped relaxation oscillations. These oscillations are generated in the following way. As a result of the injection current the electron density in the active layer is increased. When the electron density reaches its threshold value the photon number has not yet attained its equilibrium value, where the stimulated processes would effect a high electron recombination rate. Therefore a further increase of the electrons above their threshold value is possible. The increase in the number of photons in the laser modes starts from the initial value, corresponding to spontaneous processes. The increase is at first very slow since the rate of photon creation is proportional to the actual photon number. However, the final stages of photon production occur rapidly. If the photon number exceeds the equilibrium value expected from the injection current the electron recombination rate exceeds the injection rate and the electron number decreases rapidly as the photon density is high. Although the electron density is rapidly decreasing, the photon number may continue to increase as long as the electron density is above its threshold value. When the electron density falls below the threshold value,

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the photon density rapidly decreases again. The fast electron density decrease continues. As soon as the photon number falls below its stationary value the electron density rises again, but since the electron density is now again far below its threshold value the photon number may decrease to a very small value and conditions are similar to those at the start of the cycle. The electron density increases slowly with the time constant τ_{sp}. When the electron density again gets close to its threshold value the photon number again is strongly amplified and oscillation may continue. For pulse code modulation, a small delay time t_d and strong damping of the relaxation oscillations is desirable. If the extent of spontaneous emission into the oscillating modes is high, the initial value of the photon density is larger when the electron density approaches threshold, and the number of photons in the oscillating modes exceeds the equilibrium value at a stage. when the electron density is not far above threshold, and the amplitude of the relaxation oscillations is reduced. Unfortunately the required contribution from spontaneous processes can only be achieved with multimode lasers which are not suitable for long distance communication at high bit rates.

According to equation (1) a delay time $t_d = 1.1\ \tau_{sp}$ is obtained for a pulse amplitude equal to $1.5\ I_{th}$. Since a higher injection current may degrade the laser too much, τ_{sp} is practically the lower limit for the delay time of the unbiased laser. A further reduction of delay time is possible if the laser is prebiased with a d.c. current I_0 [19, 20]. If a step pulse of amplitude I_p is superimposed, the delay time is now given by:

$$t_{d1} = \tau_{sp} \ln [I_p/(I_p - I_{th} + I_0)] \qquad (2)$$

Using this method Ozeki and Ito achieved a bit rate of 200 mbit s^{-1}.

2. Pre-equalization of the modulation signal when the laser is unbiased or biased below threshold

After the modulation pulse the electron density decays exponentially with a time constant τ_{sp} to a value corresponding to the bias current. In the case of two consecutive modulation pulses, the second pulse has a lower delay time, provided that the pulse spacing is not significantly greater than τ_{sp}. These pattern effects, caused by a delay dependant on the preceding pulse, can be eliminated by a compensating modulation. Ozeki and Ito have described an equalizing circuit which generated a compensation pulse before every modulation pulse which followed a logical '0' [21]. The compensation pulse preceded the modulation pulse by a quarter period and raised the electron density to the same value as a preceding logic 1 would have done. The method is applicable up to bit rates of $1/\tau_{sp}$. Ozeki and Ito achieved 200 Mbit s^{-1} without prebiasing the laser. Lee and Derosier have shown two similar methods for pre-equalization [22]. In the first case the pulse amplitude was varied according to the preceding bit. In the second the modulation signal consisted of double pulses. The first forward swing of the double pulse caused the light emission, and the following reverse swing removed the stored charge in order to establish initial conditions similar to the case of a preceding logical '0'. A pulse spacing of 2 ns has been achieved with a laser which had a τ_{sp} of 3.9 ns.

3. Direct modulation of injection lasers biased above threshold

For modulation in the Gbit s^{-1} region, biasing at or above threshold is necessary to avoid the light-emission delay [19, 23–27]. When the laser is biased above threshold by the modulation pulses relaxation oscillations can also be excited. The frequency and damping constant of the relaxation oscillations depend on the laser parameters and the bias current [10, 19, 28]. Chown et al. have performed modulation experiments at 1 Gbit s^{-1} with optimum results when the laser was biased at threshold. When the bias current was 7 to 20% above threshold dampled relaxation oscillations of frequency between 1 and 1.3 GHz were observed. Just above threshold, where many modes have been excited, no relaxation oscillations could be observed. Figure 1 shows the direct modulation of an injection laser at 2.3 Gbit s^{-1} [25]. Schicketanz has taken advantage of the resonance in the modulation characteristics [26]. A laser, biased above threshold was sinusoidally modulated at its resonance frequency. This gave rise to generation of spikes. By a transitory reduction of the bias current, one or more light pulses can be removed. This method requires only a low modulation power, but is critically dependent, both on the time constants fo the particular laser and, on its bias current.

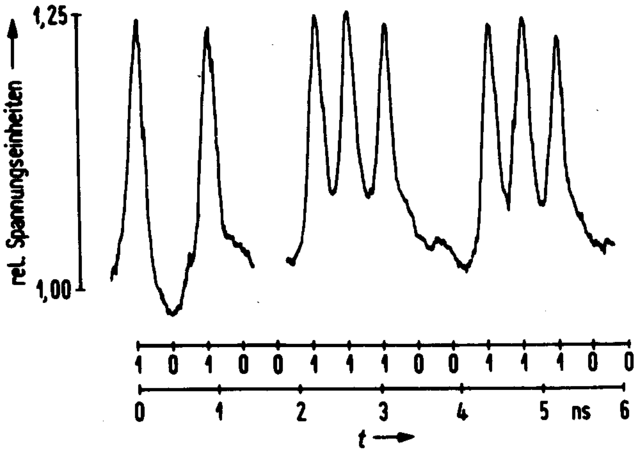

Figure 1 Modulation with the words 10100 and 11100 at 2.3 Gbit s^{-1}

Harth and Siemsen have shown that the damping becomes aperiodic when the fraction of the total spontaneous transitions which give rise to photons in oscillating modes exceeds 5×10^{-3} [14]. It is only possible to realize this degree of excitation by spontaneous processes in the case of a high number of oscillating modes. With a lower number of modes a region above threshold exists where the damping is aperiodic. Furthermore, just above threshold the mode number is higher, thus increasing the probability of strong damping. During 1 Gbit s^{-1} modulation experiments, Yanai et al. observed risetimes a factor of 10 lower than the values calculated without taking into account damping by the spontaneous processes [27].

Damping can also be achieved by injection of coherent light into one of the oscillating modes of the laser [29, 31, 32]. The mode into which the coherent radiation is coupled is now mainly excited by the external radiation. This excitation by coherent irradiation can be higher by several orders of magnitude than the natural spontaneous excitation of the laser itself. Since the photon number is limited by the pumping rate, the amplification by stimulated emission adjusts itself to a lower value. As in the case of higher excitation by spontaneous emission, lowering of the amplification factor is accompanied by damping of the relaxation oscillations and a corresponding increase in modulation bandwidth. Figures 2, 3 respectively show the variation of the resonance frequency ω_0 the damping constant β of the relaxation oscillations with the injection current for a value $\tau_{sp}/\tau_{ph} = 10^3$. The parameter ζ is the intensity of the coherent irradiation when normalized to the steady-state photon number in the resonator at double threshold current with no external irradiation.

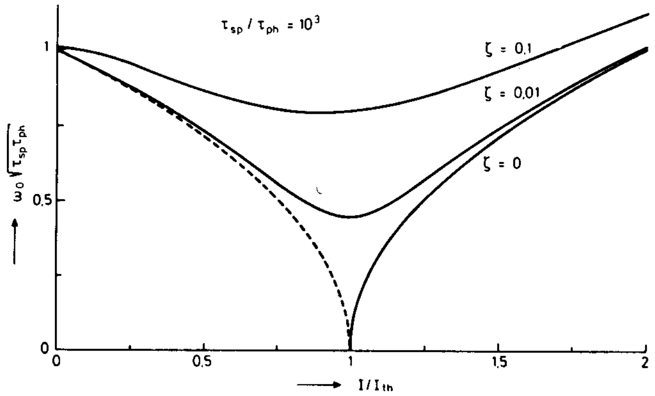

Figure 2 Resonance frequency with coherent irradiation

4. The influence of modulation on the emission spectrum

When the laser intensity pulsates, injection lasers show a broadening of both the spectral lines and the intensity distribution over the spectral lines [7, 8, 9]. This occurs regardless of whether the oscillations occur spontaneously or as a result of the modulation signal. During laser output pulsations the electron density also varies. As a result there are periods when modes with a higher threshold electron density may have net gain and the number of oscillating modes is increased. This effect is more significant in lasers with a broad spectral gain curve.

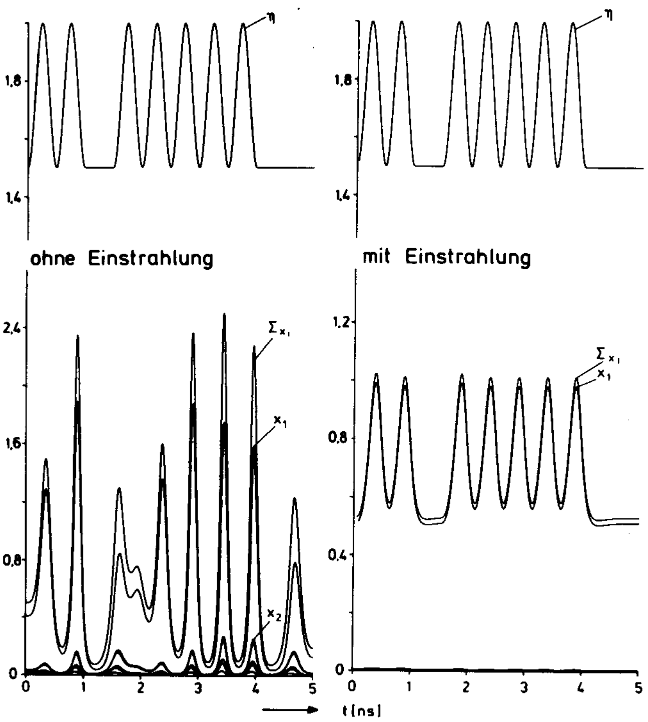

Figure 4 Modulation behaviour at 2 Gbit s^{-1}

A numerical analysis of the multimode rate equations has shown that when a step pulse is applied to an unbiased laser, the mode number at the onset of lasing is considerably higher than under steady-state conditions [15].

By injecting coherent light into one oscillating mode of the laser, synchronization of the laser to the incident wavelength may occur [30, 32]. Figure 4 shows a numerical simulation of pulse code modulation at 2 Gbit s^{-1} both with and without injection of coherent light [31]. Calculations have been performed for a laser with 1 ps photon lifetime, 2 ns electron lifetime bias to $1.5 I_{th}$, and a ratio for the spontaneous emission rate into one oscillating mode to

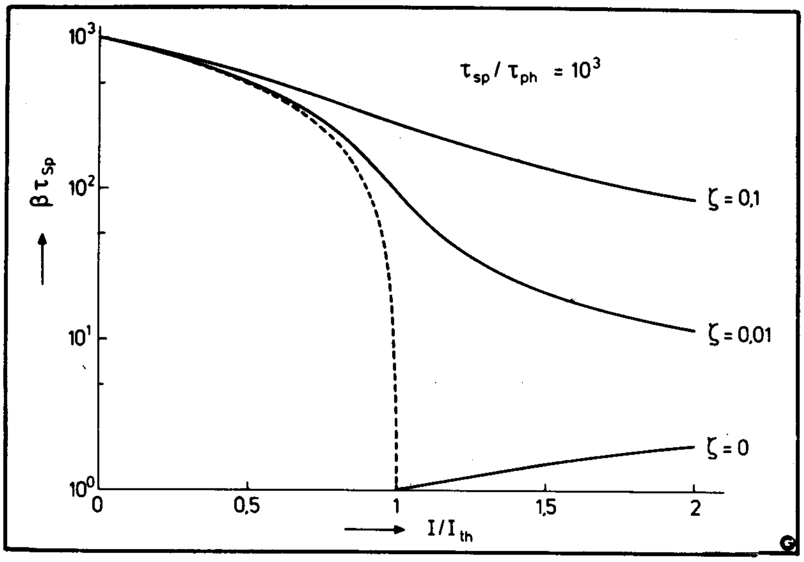

Figure 3 Damping constant with coherent irradiation

the total spontaneous recombination rate of 2×10^{-4}. For the description of the stimulated processes, the approximation which is bilinear in electron density and photon number has been used. The stimulated emission coefficients of the modes have been adjusted to the steady-state distribution of the six strongest modes of an injection laser. Figure 4 shows, from top to bottom, the injection current η normalized to I_{th}, the sum of the photon numbers in the six modes Σx_i normalized to the total photon number at twice threshold current, and the normalized photon number x_i in each mode. The lefthand side shows the calculation without light injections, the righthand with coherent light injection.

In our example the incident radiation is only one per cent of the level that the laser would produce at double threshold current. In the case of coherent light injection, only one mode dominates and the pattern effects disappear.

In a preceding contribution, Hayashi has shown that by an optically-coupled arrangement of two injection lasers a narrow spectrum and good modulation capability may indeed be achieved in practice [32].

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