Bit-error rate and frequency response in superregenerative semiconductor laser receivers

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A superregenerative receiver scheme developed for radio communications is translated to the scope of optical communications. Starting from application of the quasi-deterministic theory to the single-mode Langevin rate equations, closed expressions for basic parameters and features, such as bit-error rate and frequency response, are obtained. A comparison of superregenerative receivers with well-established optical receivers shows that improvements in direct-detection receiver sensitivities of more than 10 dB can be obtained; this places superregenerative receiver sensitivities closer to the shot limit. Moreover, the intrinsic frequency selectivity of the superregenerative scheme makes it especially suitable for wavelength-division multiplexed systems. Finally, appropriate devices for implementation of this receiver are suggested. © 1999 Optical Society of America
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Direct-detection (DD) optical receivers, owing to their simplicity, are the most extensively used type of receiver. However, within the spectral range in which optical fibers possess their best transmission characteristics, the sensitivity of these receivers becomes limited. On the other hand, coherent optical communications systems, which appeared later, aroused great expectations, because of their higher sensitivities and frequency selectivity. Nevertheless, coherent systems have supplementary technological requirements for their components, making these solutions much more complex and expensive.

The superregenerative receiver was developed during the first stages of radiocommunication history. Because of its excellent sensitivity and acceptable selectivity, in addition to extraordinarily simple implementation, this receiver is still suitable in some applications today.

Along with other ideas and techniques from radio and microwave engineering that have been successfully applied to optical communication systems, the fundamentals of the superregenerative receiver could also be adapted to this field of telecommunications. New optical receivers designed in this way could fit certain applications, presumably improving other options, since it is expected that they would inherit the good properties from their radiocommunication counterparts.

Although detection of a weak external signal through the switch-on time statistics for a semiconductor laser was analyzed previously, this was done exclusively from a physical phenomenon point of view. However, this Letter presents the main results of a detailed and conclusive study concerning the feasibility of translating the principles of the superregenerative receiver to the scope of optical communications, in which the received signals are modulated at high frequencies and therefore the receiver sensitivity is related to the bit-error rate (BER) obtained for a given input bit rate.

In a superregenerative receiver for radio communications, the weak signal is injected into an oscillator that is periodically switched on and then quenched. If the frequency of this signal is close to the oscillator eigenfrequency, it helps speed up its switch-on process, which otherwise, would be started only by the oscillator’s internal noise. At that rate, pulses generated with an external signal are produced in advance and present less jitter. The response of the receiver can be linear or logarithmic, depending on whether the oscillator is quenched before reaching its steady state or is not, respectively.

Provided that the nucleus of this reception scheme is a pulsed oscillator, it can be replaced with a laser, into which the optical signal is injected. For suitable laser selection several conditions must be taken into consideration. On the one hand, the ability of the receiver to detect very weak signals depends on the level of spontaneous emission in the active medium. Accordingly, lasers with long spontaneous-emission life times would suit this application. However, the long transients that they usually present (approximately several microseconds) unfortunately force one to reject their use in optical communications, in which modulation frequencies above hundreds of megahertz or gigahertz are used. Moreover, the degree of coherence needed for the input signal is directly related to the transient duration. On the other hand, even though the high level of intrinsic noise in the laser diode makes its use as a superregenerative detector questionable, this device can be directly modulated by low-power electrical excitation at typical communication rates. Thus, was chosen as a starting device, and the focus of our analysis was on single-mode lasers.

Single-mode semiconductor laser dynamics under injection are described by two coupled rate equations, one for the complex field and one for the electronic density inside the laser cavity. Consequently, unlike for other kinds of lasers, such as class A lasers, the laser diode transient dynamics associated with the detection process are quite different from and more complex than those of oscillators from radio communication, thus requiring specific analysis.
In a gain-switched laser diode, if the applied current pulses are kept short enough, the oscillation threshold is overcome only momentarily. Therefore, the output is a train of single light pulses whose repetition rate equals the frequency of the modulation current. To achieve a high operation rate, one must ensure that each current pulse begins before the carrier density reaches the value associated with the bias current, following a periodic modulation scheme. Finally, the optical pulses emitted from the receiver laser are converted into an electric signal by means of a classical DD receiver, which also acts as a low-pass filter. An example of the complete receiving process for a linear-mode receiver, obtained by use of computer simulations, is illustrated in Fig. 1. Here, as the input signal, a binary sequence of on-off keying Gaussian pulses was used, and four pulses were generated by the receiver laser during a bit period.

Computer simulations, for which appropriate tools were developed, were used to calculate sensitivities in linear and nonlinear mode. In the linear mode, for which the best results were obtained, closed analytical expressions were also deduced. Taking into account the spontaneous-emission randomness responsible for a certain error probability in the decision process, we followed a whole statistical treatment based on quasi-deterministic theory.

Quasi-deterministic theory is devoted to the study of transitions through instabilities of certain physical systems and has been successfully applied to the semiconductor laser. This theory relies on the observation that as soon as the system leaves the instability point because of random fluctuations it moves along a trajectory that is very close to deterministic. So the true process can be properly written as an associated deterministic one with an effective initial condition. With this assumption, the statistical moments of the system variables at a given instant above threshold can be easily calculated from the probability distribution function of the photon density through threshold. This distribution function, which is a negative exponential with exponential tails, can be calculated from the probability distribution function of the photon density through threshold.

In expressions (3) and (4) \( P_{\text{inj}} \) is the external injected optical power, \( k_{\text{inj}} \) is the coupling coefficient, and \( f_d \) is the inverse of the round-trip time. The customary semiconductor laser rate-equation terminology is shown in Table 1.

\( H(\omega) \) represents the frequency response of the receiver, which has a Gaussian profile, whose expression is

\[
H(\omega) = \exp[-2\Delta \omega^2 \tau_e/(\Gamma G_{\text{inj}}/(I_{\text{inj}}/I_u - 1)(1 + \alpha^2))],
\]

where \( \Delta \omega \) is the detuning between the input signal frequency and the receiver laser frequency. If not only one pulse but several pulses are generated during a bit period, an additional relationship between pulsation frequency and bit rate appears, as is analyzed below.

For comparison with other receivers the \( Q \) factor must be related to the maximum achievable bit rate. In the periodic modulation regime, if the current pulses are kept short enough, the pulsation period can be estimated from

\[
T_{\text{per}} \approx \tau_e \ln \left[ n_{\text{min}} + \frac{(I_{\text{ON}} - I_{\text{bias}})\tau_e \exp(t_{\text{ON}}/\tau_e)}{eV} \right] / \left( n_{\text{min}} - I_{\text{bias}}\tau_e/eV \right),
\]

Fig. 1. Detection process for a linear-mode superregenerative semiconductor laser receiver: dotted curve, input binary sequence; solid curve, optical pulses emitted from the detector laser; dashed curve, output from the DD receiver (all normalized to unity).
Table 1. Symbols for the Parameters Used in This Study

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>τ_e</td>
<td>Carrier lifetime</td>
<td>1.5 ns</td>
</tr>
<tr>
<td>τ_p</td>
<td>Photon lifetime</td>
<td></td>
</tr>
<tr>
<td>a_{int}</td>
<td>Internal power-absorption coefficient</td>
<td></td>
</tr>
<tr>
<td>R_1, R_2</td>
<td>Mirror reflectivities</td>
<td>0.5</td>
</tr>
<tr>
<td>L_t</td>
<td>Total cavity length</td>
<td>250 μm</td>
</tr>
<tr>
<td>V_r</td>
<td>Volume of active region</td>
<td>157.5 μm^3</td>
</tr>
<tr>
<td>Γ</td>
<td>Mode confinement factor</td>
<td>0.35</td>
</tr>
<tr>
<td>G_0</td>
<td>Stimulated-emission factor</td>
<td></td>
</tr>
<tr>
<td>n_0</td>
<td>Carrier density at transparency</td>
<td>4 × 10^{-6} cm^3 s^{-1}</td>
</tr>
<tr>
<td>n_u</td>
<td>Carrier density at threshold</td>
<td>1.2 × 10^{18} cm^{-3}</td>
</tr>
<tr>
<td>B</td>
<td>Radiative spontaneous recombination factor</td>
<td>2 × 10^{-10} cm^3 s^{-1}</td>
</tr>
<tr>
<td>β</td>
<td>Fraction of spontaneous emission coupled into the lasing mode</td>
<td>10^{-5}</td>
</tr>
</tbody>
</table>

Fig. 2. Receiver sensitivity versus driving current for a BER of 10^{-9}: dashed curve, common laser diode; solid curve, Q-enhanced laser diode.

The term t_{ON} represents the time interval in which the current is above threshold, and n_{min} denotes the minimum value reached by the carrier density.

Because all these expressions strongly depend on the physical structure of the diode and on the driving-current parameters, particular situations with the usual device parameters (listed in Table 1) were studied, and sensitivities approximately 3–5 dB better than those for DD schemes were obtained.

Owing to this tight dependence on the device parameters, the choice of the appropriate diode structure is of vital importance. For example, the receiver sensitivity is roughly inversely proportional to the linewidth-enhancement factor, α. So devices with α close to 0, such as quantum-well lasers, should be chosen. In the same way, since fluctuations originating in spontaneous emission are the main limiting factor for sensitivity, other laser diode structures with reduced output fluctuations, such as Q-enhanced lasers, have been tested. For these lasers, in which a passive region is included in the cavity, sensitivities ~10 dB better than those for usual lasers and very close to the shot limit were obtained. This sensitivity increase is shown in Fig. 2, in which receiver sensitivities are plotted versus driving currents for a BER of 10^{-9}. The length of the active region was taken to be equal to 10 μs, the total cavity length was maintained, and the reflectivity of one mirror was increased to 0.9.

This receiver also presents an intrinsic frequency selectivity, given by expression (4). Substituting the parameters in expression (4) for common values yields a FWHM bandwidth of approximately several gigahertz.

In conclusion, the superregenerative laser receiver clearly appears to be a promising alternative to DD receivers, notably improving on sensitivities, with a value closer to the shot limit. This improvement adds an intrinsic frequency selectivity. Both outstanding qualities make superregenerative receivers especially suitable for wavelength-division multiplexed systems.

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References