On the quantum-limited intensity noise and linewidth of nanolasers

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In recent years there has been tremendous progress in the experimental realization of ultra-small semiconductor lasers containing only a few modes [1],[2]. In such nanolasers, the spontaneous-emission $\beta$-factor approaches unity, see Fig. 1, implying that spontaneous emission only occurs into the laser mode and there is no clear transition from the LED regime to lasing when considering the intensity of the output light. The question we address in this paper, is whether it is an advantage to have a high value of $\beta$, when considering the noise characteristics of the laser, or should one rather reduce the value of $\beta$, in order to reduce random spontaneous emission into the laser mode? While this is a quite fundamental question, the literature does not provide a unified view, e.g. regarding the conditions under which to achieve the minimum linewidth [3],[4].

In this paper we present numerical and analytical results for the intensity and phase noise in semiconductor lasers, with emphasis on the role of the $\beta$-factor and how to modify it in order to reduce the quantum noise. While conventional rate equations can be used for analyzing the case of good-cavity lasers [5], where the material polarization can be adiabatically eliminated, the case of bad-cavity lasers requires the inclusion of collective effects [1]. We show that in this regime the laser displays drastically different characteristics below the laser threshold [6].

![Fig. 1. The $\beta$-factor is the rate of spontaneous emission into the lasing mode relative to the total spontaneous emission rate. It is of the order of $1/M$, where $M$ is the total number of modes. For conventional lasers (left) one has $M>>1$ and consequently $\beta<<1$, while current nanolasers (right) approach the case of $M~\sim \beta~\sim 1$, where all spontaneous emission occurs into the laser mode.](image)