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NOISE ENHANCEMENT IN LASER AMPLIFIERS CAUSED BY GAIN NONUNIFORMITY

Indexing terms: Lasers and laser applications, Laser amplifiers

We have calculated the noise-enhancement factor of a semiconductor laser amplifier with a very thin active region. This (somewhat academic) model exhibits large Petermann's K-factors. However, the calculated noise-enhancement factor K' is only about half the K-value. The reason for the discrepancy is that in evaluating K' the radiation modes of the guiding structure have been taken into account. Similar conclusions have been reached for realistic laser models. These theoretical considerations show that gain-guided laser amplifiers are not as noisy as was originally thought.

In coherent-optics communication systems, it may be advisable to amplify weak signals before detection.[1] If the laser gain is large enough, the noise/signal ratio at the detector output may be reduced down to

$$N/S = 4hf/P_0 \tag{1}$$

In eqn. 1, S is the square of the signal detected current, N is the average square of the detector current fluctuations per unit bandwidth, hf represents the photon energy and P_0 the received optical signal before optical amplification. The result in eqn. 1 applies only if the lower level of the laser medium is unpopulated and if only the beat between the signal optical field and the field spontaneously emitted by the amplifier medium needs to be taken into account. We assume that this is the case.

More importantly for our discussion, eqn. 1 also requires that the amplifying medium be homogeneous in the region where the signal field intensity is significant. This latter condition has perhaps not been sufficiently appreciated up to now. A few years ago, Petermann[2] did notice, however, that in gain-guided semiconductor lasers, spontaneous emission in the amplified mode is very much enhanced compared to what happens in index-guided lasers by a factor K that may be as large as 50 in typical situations. Concerning this important observation we would like to make two comments:

(i) First, for laser amplifiers (and perhaps also for laser oscillators), the significant noise-enhancement factor is not K but a smaller factor K'. This is because the concept of spontaneous emission 'in the mode' is ambiguous for multimode or open guiding structures.[3] We show in this letter that in typical situations the noise is enhanced by a factor K' which is only about half the K-factor because of the existence of radiation modes.

(ii) Secondly, we would like to point out that noise enhancement (factors K or K') is not so much related to gain guidance as to gain nonuniformity. As a matter of fact, we find large K-factors in normally guiding thin slab geometries, if the slab thickness is only about 0·01 μm. Large noise enhancements can be found also in nonuniform surface-emitting laser amplifiers (with the optical beam perpendicular to the amplifying slab, rather than guided by it).[4]

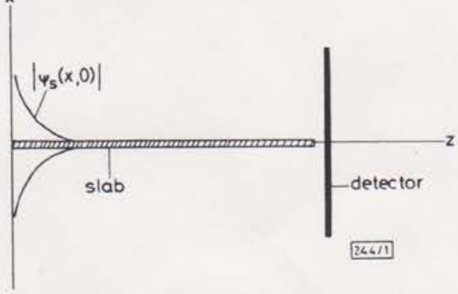

Fig. 1 *Thin slab model*

Input plane $z = 0$, detector plane $z = L$. The slab is normally guiding and has gain (susceptance $s = a - ib$, $b > 0$). $\psi_s(x, 0)$ represents the input optical field, supposed to be in the fundamental mode

Let us consider a thin slab of amplifying medium according to Fig. 1. The slab is supposed to be thin enough to be replaced by a reactive surface. That slab has a real index of refraction larger than that of the surrounding medium and is therefore normally guiding. However, because it is very thin (about 0·01 μm) the optical wave is only weakly guided and extends over a rather large distance on both sides of the active region. Let $s = a - ib$ denote the slab susceptance.[5] The field amplitude of the guided mode decays as $\exp(-a|x|)$, so that we can define the mode thickness as the width which contains half the modal power $2e = \log(2)/a$. Petermann's K-factor is simply

$$K = 1 + (b/a)^2 \tag{2}$$

We have calculated the noise-enhancement factor K' due to the beat between the signal field and the spontaneously emitted field, taking into account the excitation of both the guided mode and of the radiation modes by spontaneous emission. The former wave is amplified while the latter are neither amplified nor attenuated. We have arrived at an essentially closed-form expression for K':

$$K' = K \int_0^L 2\gamma \exp(-2\gamma z_0) f(z_0)\, dz_0 \tag{3}$$

The $f(z_0)$ function describes spontaneous emission from a point of the slab located at a distance z_0 from the input plane, the total laser length being L. The expression for $f(z_0)$ can be written in closed form, but it is somewhat too lengthy to be given here. In eqn. 3, $\gamma = ab/k_0$ denotes the guided-mode gain factor. The laser power gain is $G = \exp(2\gamma L)$. k_0 is the propagation constant in the outer medium, a real quantity.

In the numerical application, we have considered a laser length $L = 200\ \mu m$ and a gain $G = 10$ (10 dB). This constant gain can be achieved either with a large confinement factor and a small medium gain, or a small optical confinement and a large medium gain, or intermediate situations. We have plotted in Fig. 2 Petermann's K-factor, given in eqn. 2 with a logarithmic scale, and the ratio K'/K of the effective noise-enhancement factor K' to K, as given in eqn. 3, as a function of e. As one can see, for typical gains and typical laser lengths, K'/K is about one half.

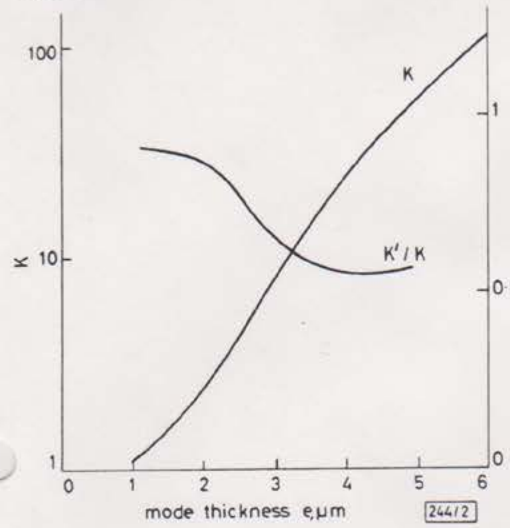

Fig. 2 *Ratio K'/K of the effective noise enhancement factor K' to Petermann's K-factor for a very thin slab semiconductor laser amplifier*

Length $L = 200\ \mu m$, gain = 10 (10 dB) and different mode thicknesses $2e = \log(2)/a$. Also shown is Petermann's K-factor, from eqn. 2, in logarithmic scale

Let us recall that we are presently dealing not with gain guidance in the junction plane as in Reference 2 but with normal guidance in the plane perpendicular to the junction. In present-day devices, the K factor in that xz-plane is very close to unity, either because the slab is thick (about $0{\cdot}1\ \mu m$) or, in the case of quantum-well lasers, because separate optical confinement is provided. Therefore the weak guidance situation considered in this letter is not directly applicable to present-day lasers. Our purpose was to show on a mathematically tractable model that the effective noise-enhancement factor may be significantly smaller than K, as was first suggested in Reference 3. In fact, similar results for K'/K have been obtained by Sansonetti (private communication) for realistic three-dimensional lasers, using the beam propagation method. Spontaneous emission is modelled in Sansonetti's numerical technique by a narrow Gaussian beam instead of a $\delta(x)$ function as in our mathematical work. The full details of eqn. 3 and the range of validity of the thin slab approximation will be given elsewhere.

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SURFACE-ACOUSTIC-WAVE PROPAGATION ON A PIEZOELECTRIC SUBSTRATE WITH A PERIODIC METAL GRATING

Indexing terms: Surface acoustic waves, Periodic metal grating, Piezoelectric substrates

An analysis is presented for modes propagating via a periodic metal grating on the surface of a piezoelectric substrate. Assuming no loss in the structure, the numerical solution is exact in the limit, combining the effective permittivity function formulation with the least-squares residual applied at the surface.

Introduction: For any guided-wave system, the periodic grating is a classic structure for effecting control over phase and group velocities, field distribution and possibly coupling between specific modes or transducers. As part of a study of surface skimming bulk waves, experiment has shown[1,2] that a periodic planar grating of metal is indeed a useful way of controlling the guiding of particular surface acoustic waves. One experiment[2] used a $LiNbO_3$ substrate with a 20 μm period metal grating between the input and output interdigital transducers. Unfortunately, the only existing theory[1] is very approximate in assuming that the piezoelectric substrate is isotropic (sic) and considers only 'the lowest order harmonics'. The purpose of this letter is to describe a new theory that is numerically 'exact-in-the-limit'. It consists of a combination of two theories, that of the 'effective permittivity function'[3] and the 'least-squares residual'.[4]

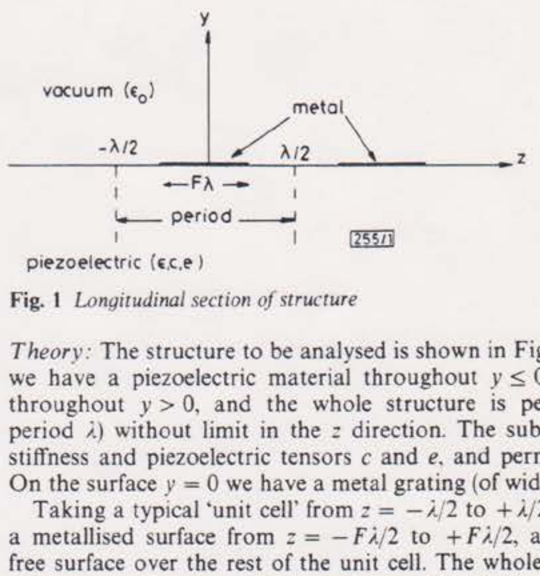

Fig. 1 *Longitudinal section of structure*

Theory: The structure to be analysed is shown in Fig. 1, where we have a piezoelectric material throughout $y \le 0$, vacuum throughout $y > 0$, and the whole structure is periodic (of period λ) without limit in the z direction. The substrate has stiffness and piezoelectric tensors c and e, and permittivity ε. On the surface $y = 0$ we have a metal grating (of width $F\lambda$).

Taking a typical 'unit cell' from $z = -\lambda/2$ to $+\lambda/2$, we have a metallised surface from $z = -F\lambda/2$ to $+F\lambda/2$, and metal-free surface over the rest of the unit cell. The whole system is taken to be loss-free. We look for modal solutions, namely fields such that, for a given structure and given frequency ω, we want a phase shift per unit cell of $k_0\lambda$ such that for any z_0

$$\{\text{all fields at } z = z_0 + \lambda\} = \exp(jk_0\lambda)\cdot\{\text{all fields at } z = z_0\} \quad (1)$$

For any such solution we note that:

(*a*) via Floquet's theorem field dependence must be of the form

$$\sum_{n=\infty}^{\infty} F_n(x, y)\exp(jk_n z) \quad (2)$$

where

$$k_n = k_0 + (n2\pi/\lambda) \quad (3)$$