COMMENT

QUANTUM MECHANICAL EXPLANATION OF SPONTANEOUS EMISSION *K*-FACTOR

In a recent letter by Marcuse, gain-guided lasers are described in the following manner:[A] 'Gain-guided modes are actually not guided at all. Their apparent confinement stems from the fact that energy is constantly generated in an active region. . . . a substantial amount leaks sideways into the medium outside the active laser region. The transverse distribution of energy in a gain-guided mode is determined by the interplay between the creation of energy in the gain medium and outflow of energy due to diffraction. As a consequence of their inherently lossy nature, gain-guided modes have curved wavefronts'.

Let us first recall that the above statement refers to the optical field distribution in the plane of the junction (say y) of a laser. Only the two-dimensional (y, z) problem is considered. The current is injected in a narrow strip (perhaps 4 μm wide) where there is gain. The real part of the refractive index is less in the strip region than outside the strip because of the presence of free carriers. The situation is thus, in that respect, opposite to that of ordinary dielectric waveguides. Outside the strip, the medium may have losses. However, to simplify the argument without loss of generality, we shall assume in the following that there is neither gain nor loss outside the strip.

It is true that in an inverted waveguide (index smaller inside than outside) there is a leak of power in the transverse (y) direction, while the wave gets attenuated in the axial (z) direction. It is true, also, that the wavefront is not perpendicular to the z-axis. It is curved (more accurately, tilted, in our model) in a diverging manner. However, as we increase the gain g in the strip region (stimulated emission) there is a threshold g_0 above which the propagating wave experiences a net gain γ. This obviously happens in all useful lasers. The main point of this comment is that when this happens, i.e. $\gamma > 0$, the propagating wave ceases to be leaky. There is then no lateral leak of power at infinity and no loss: the field intensity decreases exponentially away from the strip region (yet the wavefront remains curved and diverging; this peculiarity is unrelated to lateral loss).

To prove the above statements, it is unnecessary to go into the details of the propagation theory. It suffices to consider the inhomogeneous plane wave in the (lossless, gainless) medium. Let the field be denoted by

$$\psi(y, z) = \exp\,[i(k_y y + k_z z)] \tag{A}$$

where an $\exp(-i\omega t)$ factor has been suppressed.

We have, as usual,

$$k_y^2 + k_z^2 = k^2 \tag{B}$$

where k is real. Furthermore, let us set:

$$k_y = k_{yr} + ik_{yi} \tag{C}$$

$$k_z = \beta_0 - i\gamma \tag{D}$$

where $\gamma > 0$ represents the net gain. Thus the real part of k_y^2, obtained by squaring eqn. D and using eqn. B, is given by

$$\mathrm{Re}\,(k_y^2) = k^2 - \beta_0^2 + \gamma^2 \tag{E}$$

may be either positive or negative, but the imaginary part is given by

$$\mathrm{Im}\,(k_y^2) = 2\gamma\beta_0 \tag{F}$$

is certainly positive ($\gamma > 0$, $\beta_0 > 0$). By taking the square root of k_y^2 in the complex plane, it becomes clear that either the real and imaginary part of k_y are both positive or they are both negative. However, the lateral outflow of power is easily calculated from Reference B (p. 345 with the dagger replaced by complex conjugation, or see any textbook on quantum mechanics). For $y > 0$,

$$\begin{aligned} P_{lateral} &= \mathrm{Im}\,(k^{-1}\psi^*\, d\psi/dy) \\ &= k^{-1}k_{yr}\exp\,(-2k_{yi}y) \end{aligned} \tag{G}$$

Therefore, we have a net outflow of power if $k_{yr} > 0$. But then, by the previous argument, $k_{yi} > 0$ and, therefore, from eqn. G, this lateral power flow decays exponentially away from the strip region. In other words, the lateral outflow does exist at $y = 0$, but it does not propagate at infinity ($y \to \infty$). It serves only to supply power to the growing wave ($\gamma > 0$) outside the strip region.

What had perhaps not been made clear earlier is that the same conclusions apply just as well to index-guided lasers, i.e. a guided wave can grow in the propagation direction only if there is some lateral power flow away from the central region, where the medium has gain, into the (gainless, lossless) outer region. This power flow in turn implies that the wavefront is curved and diverging. The only difference between the two cases is that, in gain-guided lasers with inverted profiles, the field extends much further away from the central region, and thus more power is carried outside that region. The central region (stripe) therefore must supply more power to the outer region to sustain the growing wave. Consequently, the wavefront curvature is larger. In terms of Petermann's K-factor,[A] this means that $K \gg 1$, but it must be recognised that K also exceeds unity (perhaps only slightly) in index-guided lasers.

The important point of that letter is that it is possible in principle to match perfectly an incident beam to the guided mode of laser amplifiers, whether gain- or index-guided, and similarly it is possible to match perfectly the amplified mode at the output end of the laser to outer optical components. Of course, because any mode extends in principle to infinity, some truncation is needed that involves a loss, but this truncation loss can be made as small as we wish, and is, in any case, unrelated to the gain-guiding mechanism. In the mode-matched configuration just described, all the power generated by the active medium is always the difference between the output power and the input power. This is why we feel that it is misleading to call the gain-guided configuration with net gain 'inherently lossy'.

Our conclusion is that, whenever there is a net gain, gain-guided modes and index-guided modes do not differ in nature but only in degree. Both are inherently lossless.

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