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Mutually Quenched Injection Lasers as Bistable Devices

Introduction

The optical interaction of lasers attracts widespread interest for a number of reasons, a prominent one being the possibility that logic or memory systems using optically coupled elements may some day be realized. The quenching of one laser by the coherent light of another has been observed for GaAs injection lasers[1] and for neodymium glass lasers.[2] When the coherent output of one laser is passed through the active region of a second, the second laser is stimulated to emit in the same direction as the incident light. The power added to the amplified incident light is subtracted from the power in the normal lasing mode or modes of the second laser. We refer to this process as quenching and define a *quenching ratio* to be the power extracted from the quenched laser divided by the incident power, noting that for identical lasers the incident power will be equal to the power available for stimulated emission in the quenched laser. We will derive some simple expressions for the quenching ratio in certain ideal situations. Then we will compare these expressions with the results of some quenching experiments reported by one of the authors.[1]

In the next section we argue that two identical lasers which quench each other with quenching ratios somewhat greater than unity have two stable states of operation. Finally, possible configurations for bistable devices are discussed. These devices would have many properties in common with bistable lasers which depend upon nonlinear absorption of light,[3] but their construction and principles of operation are quite distinct.

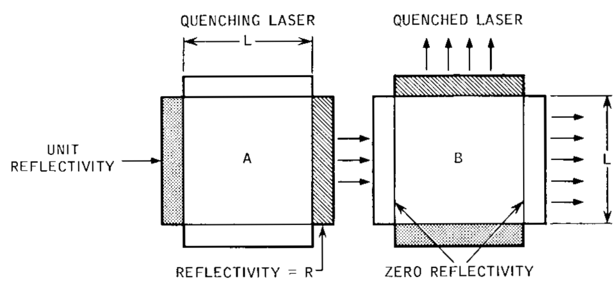
Prediction of quenching ratios

It will become apparent that quenching ratios greater than unity may be achieved only in very special circumstances. We will derive expressions for quenching in three idealized cases. The *first case* is sketched in Fig. 1 and consists of two identical injection lasers, A and B, with square cross-section. The lasing mode of each is determined by having a perfectly reflecting coating on one side and a coating of controlled partial reflectivity, R, on the opposite side. The two remaining sides bear zero-reflectivity coatings. The coherent light produced in A passes through B and, by virtue of the zero-reflectivity coating on the side of B from which the beam emerges, no feedback effect on A results. The threshold condition for either laser is

$$e^{2gL}R = 1, \tag{1}$$

where g is the gain per unit length in the active region for diode currents equal to or greater than the threshold current. Let P be the power delivered by laser A in the directional coherent beam and η be a collection efficiency, that is, the fraction of the power emitted by A which passes through the active region of B. As the light beam passes

Figure 1 **Two injection lasers, A and B, in an ideal quenching configuration.**



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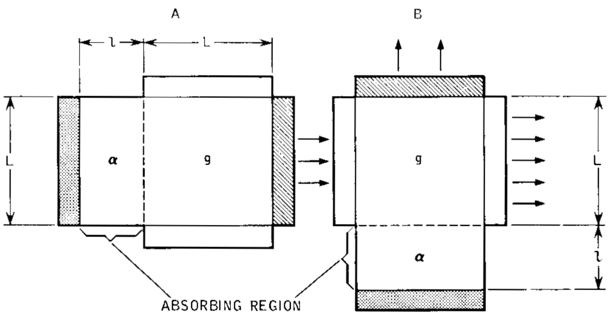


Figure 2 **The use of absorbing regions in quenching.**

through B it will also experience a gain per unit length of g and emerge with power $\eta P e^{gL}$. The quenching ratio is then

$$q = \eta(e^{gL} - 1) = \eta[(1/\sqrt{R}) - 1]. \tag{2}$$

For perfect light collection, $\eta = 1$, the reflectivity must be less than 1/4 to obtain a unit quenching ratio. (The reflectivity of an untreated GaAs-air surface is about 0.35.) The quenching ratio increases as reflectivity decreases because low reflectivity implies a large gain at and above threshold. Actually, with a quenching ratio greater than unity, the carrier densities and gain of the quenched laser will be reduced because it will be effectively operating below threshold, and the quenching ratio will be somewhat less than that predicted by Eq. (2). In all of this reasoning we assume that the gain and spontaneous emission do not vary with current above threshold current.

It is also assumed that no internal reflecting modes exist with quality factors greater than that of the desired directional mode. The quality factors of the undesired modes may be lowered by roughening the side of the quenched laser through which the quenching beam emerges, or by slanting this surface to make an acute angle with the plane of the *p-n* junction of the laser.

The coherent modes of injection lasers are observed to have the shape of narrow filaments.[4] We believe the above description of quenching to be valid in the presence of this behavior. It is presumably caused by some very small variations of one or more of the optical or electrical properties of the crystal in the junction region giving certain modes a threshold that is slightly lower than that for modes which cover other regions of the junction. The power is extracted from the quenched laser by a narrow beam from the active filament of the quenching laser, but the current in the quenched laser will distribute itself to provide full gain in the part of the emitting region traversed by the beam. Such an inhomogeneous current distribution is present in an ordinary laser when the filaments persist well above threshold, as can be deduced from the fact that the power of the stimulated emission must be delivered by the current to these narrow filaments.

In the *second case* we introduce absorbing regions in the lasers to increase the quenching ratio. As shown in Fig. 2, there is still a square active region with gain per unit length, g, but there is an added region, of thickness l and absorption per unit length α, between the active region and the perfect reflector. Now the threshold condition is

$$Re^{2(gL - \alpha l)} = 1. \tag{3}$$

The power produced by stimulated emission is equal to the emitted power P plus the power internally absorbed:

$$P + P\frac{R}{1-R}e^{gL}(1 - e^{-2\alpha l}), \tag{4}$$

where $PRe^{gL}/(1 - R)$ is the power entering the absorbing region. The quenching ratio may be written as:

$$q = \eta\frac{(R^{-1/2}e^{\alpha l} - 1)}{1 + \dfrac{2R^{1/2}}{1-R}\sinh \alpha l}. \tag{5}$$

In the limit of large αl the quenching ratio approaches $\eta(1 - R)/R$. Both this case and the preceding one show that quenching ratios may be increased by raising the threshold current. Obviously one can go only so far in this direction, particularly for continuously operated lasers. However, since present lasers can be operated continuously at ten times threshold current, it is quite possible that quenching ratios greater than one may be achieved by this technique.

In the *third case*, another way to improve quenching is to use rectangular lasers emitting out of the broad side and to focus the emission to pass through the long dimension of the quenched laser. Fig. 3 shows the configuration, and the quenching ratio is

$$q = \eta\frac{1}{R^{L/2l}} - 1. \tag{6}$$

Here the quenching ratio is increased by increasing the path length and hence the amplification in the quenched laser.

The most severe basic limitation on the collecting efficiency, η, arises from the diffraction spreading of the beam between the lasers in a direction perpendicular to the junctions. Thus one will obtain a sizeable η only if the distance between lasers does not exceed the square of the thickness of the active region divided by the wavelength of the radiation in the medium. Optical fibers or lenses may of course be used to increase η. The effect of spreading within the lasers is reduced by the existence of dielectric guided modes within the lasers.[5]

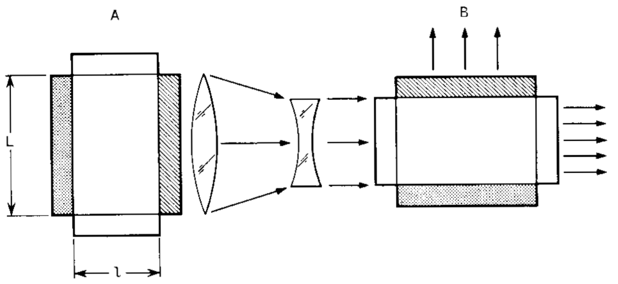


Figure 3 **The use of focussing in quenching.**

Quenching experiments

Preliminary results of quenching experiments have been reported.[1] Two Fabry-Perot type lasers, with the ends cleaved and the sides sawn, were mounted on tabs and aligned by eye. The lasers were about 300μ long and 75μ wide, and were separated by about 75μ. As is shown in Fig. 4, the quenching (or staff) laser pointed at the center of the quenched (or cross) laser of the tee. Thus the emission from the staff probably passed through the most active region of the cross.

The greatest departure from the model was that the surfaces of the cross on which the quenching radiation fell were sawn and therefore rough. As a result the emission was scattered and η was greatly reduced; for example, if the sawn surfaces scattered the light uniformly in all directions, only about 1% of the light would pass through 75 microns or more of the active region. The samples were made with contacts at the centers so that probably there were inactive absorbing regions at both ends of the staff. Also, no reflecting coating was put on the end of the staff away from the cross, thus eliminating the factor of 2 in the threshold relation, Eq. (1).

The current level of the square pulses passing through the two lasers was varied and the fractional decrease in the light output of the cross laser due to the pulse in the staff laser was observed. To make this decrease measurable it was necessary to pass from five to ten times the threshold current through the staff laser while the cross laser was usually operated at currents less than one-tenth above threshold values. The quenching ratio in the experimental configuration is computed by dividing the observed decrease in directional output of both sides of the cross laser by the directional output of the free end of the staff laser. The observed quenching ratios were generally of the order of 0.01, the largest ratio being 0.07.

In this experimental situation the quenching ratio is given by

$$q = P_x/P_i = \eta(e^{gl} - 1), \tag{7}$$

where P_x is the power extracted from the cross beam; P_i is the incident power; and, as before, η is the collection efficiency and g is the gain per unit length as the radiation passes through the width l of the cross laser. The gain per unit length, g, is given by the threshold condition, $g = (1/L) \ln (1/R)$, where L is the length of the cross laser and R is the reflectivity of the cleaved ends. The efficiency η is equal to $dT/\theta t$, where d is the width of the active region of the laser, T is the effective transmission of the sawn surfaces, θ is the vertical beam spread, and t is the separation of the lasers. Thus we have

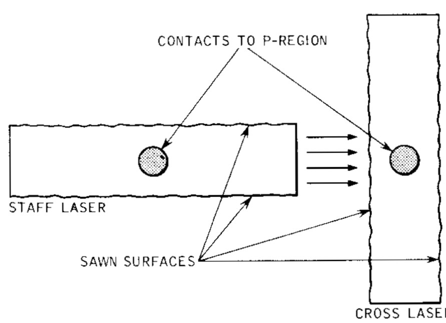
$$q = \frac{dT}{\theta t}\left(\frac{1}{R^{l/L}} - 1\right), \tag{8}$$

which yields, for $d \approx 1.0\mu$, $T \approx 1$, $\theta = 1/6$ radian, $t = 75\mu$, $l = 75\mu$, $L = 300\mu$, and $R = .35$, a calculated quenching ratio of about 0.02. Hence, the experimental results are reasonably consistent with the model.

Bistability and quenching ratio

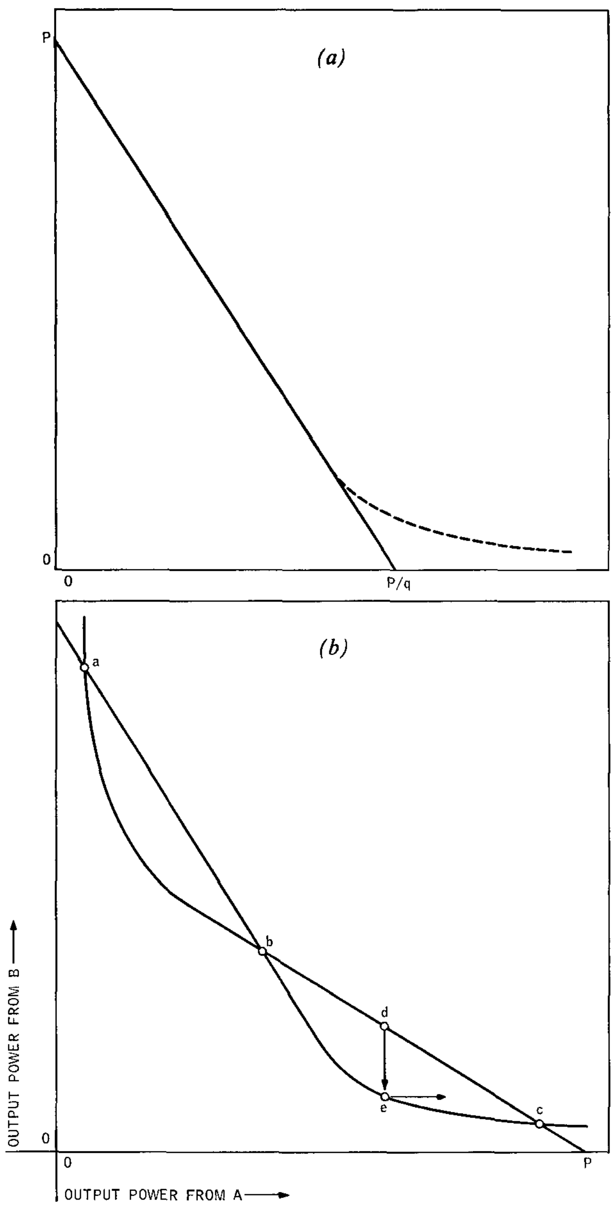
In order to discuss in a semiquantitative manner the relation between bistability and quenching ratio, we assume two identical lasers which pass the same superthreshold current and which are arranged symmetrically so that each can quench the other with a quenching ratio greater than unity. Consider the effect of varying the output power of A on the output power of B (assuming that A can quench B but not vice-versa). The solid line of Fig. 5a is a quenching curve in the ideal case. The output power of B decreases linearly from its undisturbed value, P, to 0 as the output of A increases from 0 to P/q. The broken line indicates how, for a real laser, this function might tail off because of spontaneous emission. When each laser can quench the other one, their power outputs must satisfy two relations. One relation is that plotted in Fig. 5a and the other is that obtained from Fig. 5a by exchanging the labels of the two axes. The two relations are plotted together in Fig. 5b. The possible steady states of the system are the intersections of the two curves, a, b, and c and one easily sees that a and c are stable points of operation and

Figure 4 **Configuration of two Fabry-Perot type lasers in the quenching experiment.**



that b is an unstable point. For example, if the instantaneous output is at point d, the power output of B is too large and the operating point will move down. If e is the instantaneous operating point, the output A is too small and the operating point will move to the right. This then completes our argument that a mutual quenching ratio somewhat greater than unity implies the existence of two stable states.

Figure 5 **(a) Quenching curves for the ideal and the actual cases, shown respectively as solid and broken lines; (b) Stability diagrams combining two relations from (a) that are necessary for bistability. See text.**



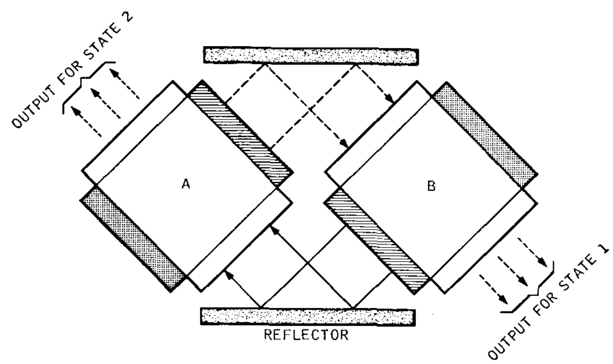
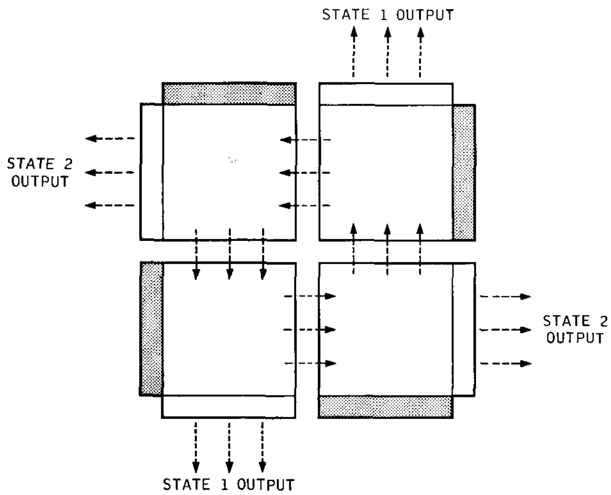


Figure 6 **The two-laser bistable configuration.**

Figure 7 **The four-laser bistable configuration.**



Bistable configurations

The simplest symmetric geometry in which two lasers can quench each other is shown in Fig. 6. The use of absorbing regions or focussing can also be resorted to in this configuration, but it would suffer from the fact that the optical distance between units is at least equal to the length of the side of the lasers. The two lasers would thus have to be smaller than present units to limit the diffraction spread between units. This difficulty is overcome by the configuration suggested by J. B. Gunn,[6] shown in Fig. 7, which uses four lasers and dispenses with extra reflectors.

In the quenching situation the quenching beam emerges with about twice the stimulated power of a single laser. By beam splitting, the two-laser device of Fig. 6 could switch two other such devices (i.e., these devices have a fan-out of two), while that of Fig. 7 could switch four others. Hence such devices might someday be used to realize logic and memory systems wherein light pulses provide the sole information-carrying medium and the chief function of electrical currents is to provide laser excitation.

Acknowledgments

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References and footnotes

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