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Laser Stabilitron

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Abstract. We consider a new method for producing intensity stabilization of cw lasers. This method incorporates negative feedback from a nonlinear saturable absorber to provide wideband noise-reduction and may produce an output beam for which shot noise is below the quantum limit. This new method can be used with a large variety of cw lasers and is particularly applicable to frequency-stabilized lasers which are locked to absorption lines.

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New methods for the reduction of laser noise are of general experimental and theoretical interest and have an obvious value in fields of laser application ranging from metrology and spectroscopy to delicate forms of laser surgery. Recent theoretical attention has been given to the production of squeezed photon states [1] and a decrease in noise level below the quantum limit has been reported [2]. We consider here a new method which should not only provide a substantial reduction in common sources of amplitude noise, but also may reduce shot noise below the level expected from the quantum effect. This type of device, which we will refer to as a *laser stabilitron*, involves a three-mirror system in which two coupled cavities are produced. One cavity contains an amplifier, and the other contains a saturable absorber. Due to nonlinear effects, there are two different regions of operation in the system: One of these is characterized by hysteresis and instability. The other is stable and should permit strong suppression of fluctuations in the laser intensity. Although we are primarily concerned here with laser stabilitrons working in the optical domain, the same type of stabilization method involving coupling between two cavities could also be used with maser oscillators and saturable absorbers operating at microwave frequencies.

It is well-known that saturated absorption inside a single laser cavity produces a bistable regime and hysteresis phenomena [3]. Positive feedback between the optical field and absorption is evident. Increasing the field leads to a reduction in saturable absorption. Conversely, decreasing the effective losses in the cavity increases the intensity inside the laser resonator. Hence, hysteresis phenomena appear when the change in saturated absorption exceeds the change in saturated gain. Theoretical analysis has shown that a large increase in quantum fluctuations can occur in a laser with intra-cavity saturable absorption [4]. It has also been noted that propagation of a strong beam through a nonlinear absorbing medium can exhibit regions of instability in which fluctuations are amplified [5]. Further, when the laser beam is transmitted through a Fabry-Perot interferometer filled with absorber, bistability and differential amplification of noise fluctuations can occur [6]. However, when the incident and output beam from such an absorber-filled cavity are combined interferometrically and the system is operated near the turning points in the bistable region, photon noise can be reduced below the shot noise at nonzero frequency [7]. This photon noise reduction is associatd with a temporal redistribution of the photons inside the cavity. Unfortunately, the optimum squeezing condition in the passive case occurs right at the turning points where the system is on the edge of instability. As we will show, one can decrease these amplitude fluctuations by using negative feedback between the field and the absorber inside the cavity. Indeed, the optimum stabilization point in this new system appears to be equivalent to the optimum squeezing condition for photon noise reduction in the passive, absorber-filled Fabry-Perot discussed in [7].

A schematic diagram of the method is shown in Fig. 1. The amplifying and absorbing media are separated by a high-reflecting mirror (M_2 in Fig. 1a) which divides the system into two coupled resonators. The first cavity contains the amplifying medium and the second one contains the saturable absorber. If the resonant frequencies of the two cavities are

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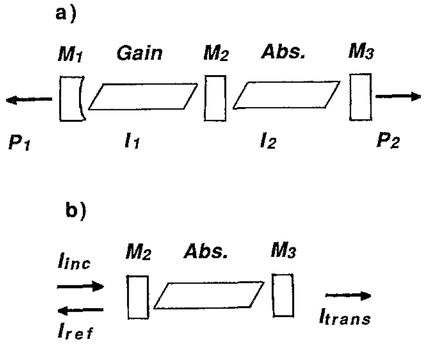

Fig. 1. a The coupled cavity method used to produce noise reduction. **b** Effective laser mirror composed of cavity *2*. $T_{ef} = I_{trans}/I_{inc}$ and $R_{ef} = I_{ref}/I_{inc}$ are used to determine the laser oscillation conditions

different, the coupling between the cavities is negligible. In that limit, oscillation in this system may be considerd as that in a conventional laser with a cavity formed by mirrors M_1 and M_2. However, when the frequencies of the two resonators coincide, interaction between the two cavities occurs. Then, saturation of the absorber by a strong field leads to an increase in output intensity through mirror M_3. The strong negative feedback mechanism between the field intensity in cavity *1* and the absorption in cavity *2* works as follows. Increasing the gain and intensity in cavity *1* leads to increased field intensity in cavity *2* and, correspondingly, to a decrease in absorption. That, in turn, leads to increased transmission from cavity *1* to *2* – hence, an increase in the loss of the laser and a decrease of the laser intensity in cavity *1*. In this system, the intensity I_1 in cavity *1* (hence, the power output P_1 to the left in the Fig. 1a) is stabilized, whereas the intensity I_2 in cavity *2* (hence, the power output P_2 to the right in Fig. 1a) is strongly variable.

For simplicity, consider the case where all the mirrors have the same transmission coefficient T. Here, the total loss involves the transmission of mirror *1* and of mirror *3*, the internal dissipative losses, and the absorption in cavity *2*. Due to the difference between the field intensities in cavities *1* and *2*, the laser power P_1 emitted to the left from cavity *1* and P_2 emitted to the right cavity *2* in Fig. 1a are given by

$$P_1 = I_1 T \quad \text{and} \quad P_2 = I_2 T \,, \tag{1}$$

where I_1 and I_2 are the field intensities in the first and second cavity.

Two different operating regimes for such a laser are possible. In the first regime, coupling between the two resonators is considerable. It occurs when the resonator losses are comparable to the middle mirror transmittance. In this case, the second resonator may be considered as a reactive load. The fields in the two resonators are comparable and transmission from one resonator to the other is the determining factor for three-mirror resonator laser operation. Some aspects of this regime have been considered elsewhere in the literature [8, 9].

The second regime is the most important one for the present purposes. In this case the transmittance of the intermediate mirror is less than the loss in the second cavity. If the length of the second resonator is less than that of the first, the field in the second resonator will follow the field in the first. These conditions result in a stable oscillation regime in which the influence of the second resonator may be considered as a small additional load on the first cavity.

To determine the laser oscillation conditions, it is convenient to consider the second cavity as a mirror (see Fig. 1b) with an effective transmission coefficient T_{ef} and an effective reflection coefficient R_{ef} together with an effective phase shift which determines the oscillation frequency. This approach has been used previously by several authors to analyze three-mirror cavities for the purpose of mode selection [10]. To obtain the desired noise-reduction effect from the saturated absorber in cavity *2*, it is essential that the frequency of the second cavity be tuned to provide a maximum intensity in the second cavity. This corresponds to a minimum intensity in the first cavity and, of course, does not produce the maximum laser intensity. Due to coupling between the two cavities, the frequency is shifted from the resonant frequency of the isolated second cavity. However, in the limit of small coupling considered here, this shift is negligible. At the resonance condition for the second cavity, it may be seen by summing the infinite series for the transmitted and reflected field amplitudes by the second (Fabry-Perot) cavity at resonance that

$$T_{ef} = T^2/(T + f + A_s)^2$$

and

$$R_{ef} = (f + A_s)^2/(T + f + A_s)^2 \,, \tag{2}$$

where the total fractional energy loss per pass in cavity *2* during oscillation is given by $(T+f+A_s)$, A_s is the saturated absorption, f is the dissipative loss from sources such as scattering and it has been assumed that f, $A_s \ll 1$. Note that $T_{ef} + R_{ef} \neq 1$ because of the loss in cavity *2*.

Clearly, from (1) and (2), the power out of the absorption end of the laser is $P_2 = I_2 T = I_1 T_{ef}$ (see Fig. 1b). Hence,

$$I_2 = I_1 T_{ef}/T \,, \tag{3}$$

and from (2)

$$I_1 = [A/(T/T_{ef}^{1/2} - T - f) - 1]T/g_2 T_{ef} \,. \tag{4}$$

In practice, the system requires *hard excitation* in the sense that the gain must be turned up high enough to exceed the threshold,

$$\begin{aligned} 2G &> 1 - R_{ef} + T + 2f \\ &= 1 - (f + A)^2/(T + f + A)^2 + T + 2f, \end{aligned} \tag{5}$$

involving the *unsaturated* gain and loss for oscillation to occur. However, after oscillation starts, G and A are reduced to their saturated values and the condition for cw laser oscillation becomes

$$2G_s = L_{ef} = 1 - (f + A_s)^2/(T + f + A_s)^2 + T + 2f, \tag{6}$$

where L_{ef} is the effective loss in the laser (cavity *1*) *after* oscillation has reached steady-state, G_s is the saturated gain per pass, and the fractional dissipative loss per pass f is assumed to be the same in each cavity. Formula (5) is valid for small gain and states that the round trip saturated gain $2G_s$ equals the effective loss L_{ef} at steady state. The latter, of course, includes the saturated absorption A_s in cavity 2. We shall assume homogeneous saturation in both media, hence

$$G_s = G/(1+g_1 I_1) \quad \text{and} \quad A_s = A/(1+g_2 I_2) \tag{7}$$

are used in (6), where I_1 and I_2 are related by (3) and I_1 is given in terms of T_{ef} by (4).

Equation (6) and relations (1), (3), (4), and (7) permit determining the output laser intensities P_1 and P_2. However, the equations are very nonlinear and the analytic solution of (6) is complicated [11]. Eliminating I_1 in (6) permits expressing G directly in terms of the intensity I_2:

$$\begin{aligned} G = {} & (1/2)\,[1 + g_1 I_2 (A/(1+g_2 I_2) + T + f)^2/T] \\ & \times [1 - (f + A/(1+g_2 I_2))^2/(A/(1+g_2 I_2) \\ & + T + f)^2 + T + 2f]\,. \end{aligned} \tag{8}$$

Graphic solutions to (6) will help to explain the behavior and the main properties of the proposed three mirror systm. As noted, steady-state laser oscillation corresponds to the requirement that $2G_s(I_1) = L_{ef}(I_1)$. Although the saturated gain has a simple, monotonic dependence on I_1, the effective loss L_{ef} has a much more complex behavior. As shown in Fig. 2, there are two distinctly different regions: For small values of A, the effective loss is also monotonic in its dependence on intensity I_1. Solutions to (6) in that region at the points a, b, and c in Fig. 2 would be stable, but the system would have noise properties similar to a conventional laser. For large values of the absorption parameter, L_{ef} has a triple-valued dependence on the intensity. As indicated by the dashed vertical lines at the right in Fig. 2, strong hysteresis effects would occur if the intensity I_1 were tuned back and forth through the triple-valued region; however, the vertical jump upwards to the right of point e would not occur without a substantial increase in the unsaturated gain. The points e and f are near the edges of a region of instability (the turning points in Fig. 2). Because $\partial L_{ef}/\partial I_1 < 0$, oscillation in between the points e and f would be completely unstable.

These two different regions are separated by a critical value for the absorption, $A_{crit} = 8(T+f)$, for which there is a point of inflection labelled d in Fig. 2, where the two solutions for $\partial I_1/\partial L_{ef} = 0$ coincide. Hence, by adjusting the parameters so that the saturated gain curve ($2G_s$)) intersects the effective loss at point d on A_{crit}, very stable low-noise oscillation should be obtained. The actual intensities in the two cavities for this condition can be determined from (8) and are shown as a function of G in Fig. 3 for the same conditions assumed in Fig. 2. Note that the intensity in the left cavity (I_1) goes through a plateau at point d on the curve for A_{crit} (= 0.18 for the parameters assumed) where $\partial I_2/\partial G = 0$, whereas that in the right cavity (I_2) increases strongly with G. The desired condition for oscillation corresponds to the saturated gain curve (dashed curve for $G = 0.11$ in Fig. 2) intersecting the effective loss at point d on the critical absorption curve and leads to oscillation at point d in the middle of the plateau on the curve of I_1 vs G for $A = 0.18$ in Fig. 3. Although the intensity (I_2) in the absorption cavity will depend strongly on variations in the gain (G), the intensity (I_2) in the gain cavity will be nearly independent of fluctuations in the gain at operating point d. Thus, the output (P_1) to the left in the apparatus

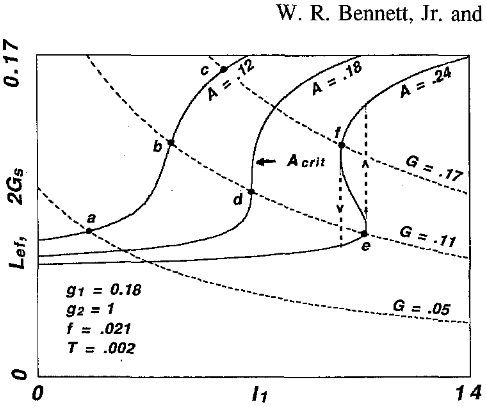

Fig. 2. Effective loss L_{ef} (solid curves) and $2G_s$ (dashed curves) as a function of intensity I_1 in the laser cavity for different values of A. Graphical solutions for oscillation condition by intersections of the solid and dashed curves. The optimum low-noise condition is obtained by adjusting the gain so that $2G_s$ (dashed curve) intersects L_{ef} at the point d on A_{crit}. As indicated by the dashed vertical lines on the curve at the right, strong hysteresis effects would occur for $A > A_{crit}$ as I_1 is tuned through the triple-valued region. In regions such as points between e and f, oscillation would be unstable

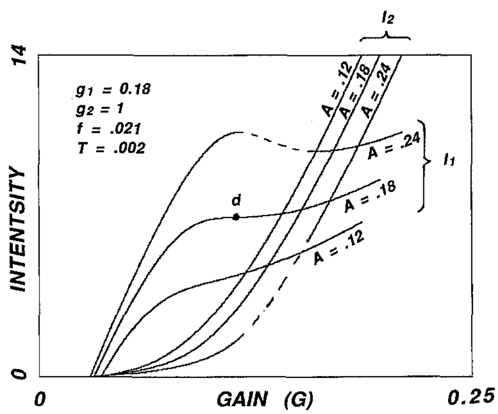

Fig. 3. Intensities I_1, I_2 as a function of unsaturated gain for different values of A. The optimum low noise condition (point d) corresponds to point d in Fig. 2. The dashed region on the curves for $A = 0.24$ correspond to the region of instability between points e and f in Fig. 2

shown in Fig. 1a should be unusually noise free. The dashed portion of the curves for $A = 0.24$ in Fig. 3 correspond to the unstable region of oscillation in between points e and f in Fig. 2. The particular conditions assumed in Figs. 2 and 3 are intended primarily for illustration, but are representative of realistic values of the loss and saturatioon parameters. Based on theoretical studies of the passive absorber-filled Fabry-Perot [7], quantum noise reduction may increase with increasing values of the loss in the system. (Increasing f increases the ratio of I_1 to I_2 in Fig. 3.)

In principle, this method could be used to stabilize the power of most known lasers. The method, of course, requires that the laser frequency should closely correspond to the resonant frequency of cavity 2 and that requirement provides the main experimental difficulty. At one extreme, the laser could simply be phase-locked to the absorber cavity. There are, of course, many examples of amplifier-absorber pairs where the frequencies are closely matched: e.g., He–Ne/CH_4 at 3.39 μm, He–N_2–CO_2/SF_6 at 10.6 μm, He–Ne/I_2 at 0.633 μm, and Ar^+/I_2 at 0.5145 μm. In these cases, frequency stabilization can also be achieved by locking the laser cavity to the center of the saturable absorber line using well-known methods [12]. It should also be possible to use solid state or diode lasers matched to crystals with color centers as saturable absorbers.

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