# DYNAMICAL EFFECTS IN SEMICONDUCTOR LASERS DUE TO OPTICAL FEEDBACK

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الخلاصة :

يُبدي ليزر أشباه الموصلات سلوكا غير مستقر عند خضوعه لتغذية ضوئية خلفية ولو بطريق الخطأ . ولقد تَمَّ في هذا البحث إيجاد الشروط العملية - لليزر أشباه الموصلات الموضوع في تجويف خارجي - اللازمة لإحداث عدة أنواع من الاستقرارية ومن ثم رسم ذلك باعتبار التيار ونسبة التغذية الخلفية كإحداثيات . وقد وُجد أنه من اللازم لمعظم التطبيقات أن يتم تشغيل الليزر عند ظروف يمكن فيها تلافي السلوك غير المستقر ، كما يُمكن تحديد هذه الظروف باستخدام المنحنيات الناتجة التي تبين كذلك ظروف الاستقرار في عمل الليزر .

## ABSTRACT

Semiconductor lasers subjected to accidental or intentional feedback are prone to instabilities. Operating conditions for long external cavity laser diodes which resulted in various instabilities were determined and plotted on a current *versus* feedback ratio graph. For most applications, it is essential that the lasers be operated under conditions which avoid accidental instability behavior, and the graphs produced identify the stable operating conditions for laser diodes.

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## 1. INTRODUCTION

Semiconductor lasers subjected to external optical feedback exhibit quite complex dynamical behaviors. They have been found to exhibit static bistable behavior [1] and various kinds of dynamical instabilities [2–7]. The range of phenomena seen includes:

### 1.1. Low Frequency Pulsation (LFP)

This is attributed to a regular longitudinal mode hopping [5]. The modal instability is introduced by effects of the different phases of the internal and external feedback on the threshold gain. The frequency range of LFP is normally a few tens of MHz.

### 1.2. High Frequency Pulsation (HFP)

The sinusoidal HFP results from the interference of the external cavity modes superimposed on the single longitudinal mode of the laser and occurs at the resonance mode of the outer cavity [9] with a frequency $f \approx c/2L_{ex}$, where $L_{ex}$ is the external cavity length. The HFP frequencies are harmonics of the LFP ones.

### 1.3. Low Frequency Fluctuation (LFF)

Such fluctuations are believed to be a result of competition between the external resonator mode of maximum gain reduction and another mode of smaller linewidth [6]. The latter mode can only live on a time scale of less than one round trip in the external cavity. In [9], LFF is explained as a relaxation oscillation in the presence of external optical feedback. It appears as a regular build up and decay of mode, which becomes regular (LFP) and eventually chaotic (LFCP) with increased levels of excitation. Coherence collapse in the laser is expected to occur through the route of LFF [7].

### 1.4. Chaos

For higher levels of excitation at a constant feedback ratio, the HFP exhibits a period-doubling due to competition between the fundamental and subharmonics of the outer cavity. Further excitation may lead to increased competition which leads eventually to a chaotic instability.

Satisfactory explanations of the nature of chaos and the occurrence of the so-called coherence collapse under conditions of moderate external feedback has been the subject of quite fundamental debate [7–11]. The present paper aims to make a contribution to the debate on the nature of the dynamics of lasers with external cavities.

## 2. EXPERIMENTAL

Modified channelled substrate planar (MCSP) AlGaAs/GaAs lasers were used. These lasers showed single longitudinal / lateral mode with a typical wavelength of 780 nm. The laser facet facing the external cavity could be AR coated in order to increase the feedback level if desired.

Long external cavities ($L_{ex}$ >> effective diode length, $l_D$) were provided by a microscope objective / front surface plane Al-mirror combination of length between 0.1–1 m. In all cases the lasers were excited from a current controlled source and was maintained at constant temperature of 25°C. A beam splitter was arranged so that a proportion of the output was directed to a silicon avalanche photodiode (APD). A broadband, 0.5 to 1000 MHz, amplifier (Dale Man-2) was connected in series with the APD and the output recorded using a 1 GHz programmable transient Digitizer (Tektronics 7912 AD), whose output was transferred to a VAX Mainframe computer for storage and analysis.

A variable neutral density filter was used to vary the feedback ratio from 0 to about 0.3, where the feedback ratio can be estimated from the reduction in the threshold current. The external mirror reflectivity was about 0.9 to give the maximum feedback ratio. Figure 1 shows the experimental setup used, which was completely isolated from environmental disturbances using an antivibration optical table (NRC).

Analysis of the stored digitized waveform was carried out by Fourier analysis to determine the frequency spectrum and by phase trajectory to illustrate the path from a regular to chaotic trajectory. Furthermore, in this work, the dimensionality of the recorded waveforms have been checked in order to decide whether a chaotic behavior is reached.

## 3. RESULTS AND DISCUSSION

Operating conditions, of the laser, which result in the various instabilities are shown in the two-dimensional diagram in Figure 2. It shows the various regions of distinct feedback characteristics with feedback ratio (β) and biasing current as axes. The cavity length was fixed at 30 cm. In this figure, the *L–I* characteristics are also shown for reference.

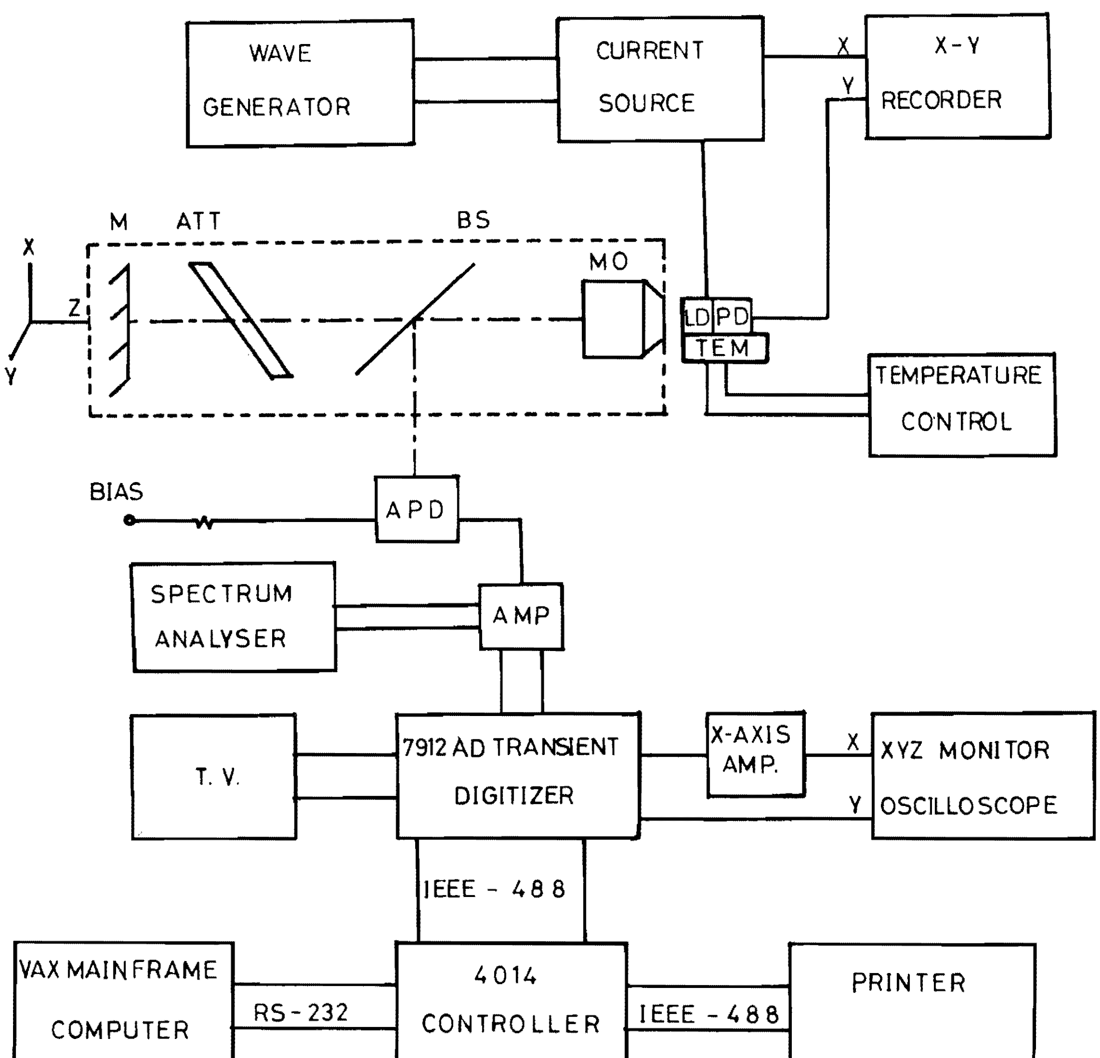


*Figure 1. Schematic Diagram of the Experimental Setup.*

The threshold current decreases with increasing feedback, as well known, so the inflection point shifts up to higher current values and the LFF region expands to cover a larger area of the diagram. Chaotic operation was located near the inflection point (on the *L–I* curve) within the LFF region. The LFCP appears well above the inflection point.

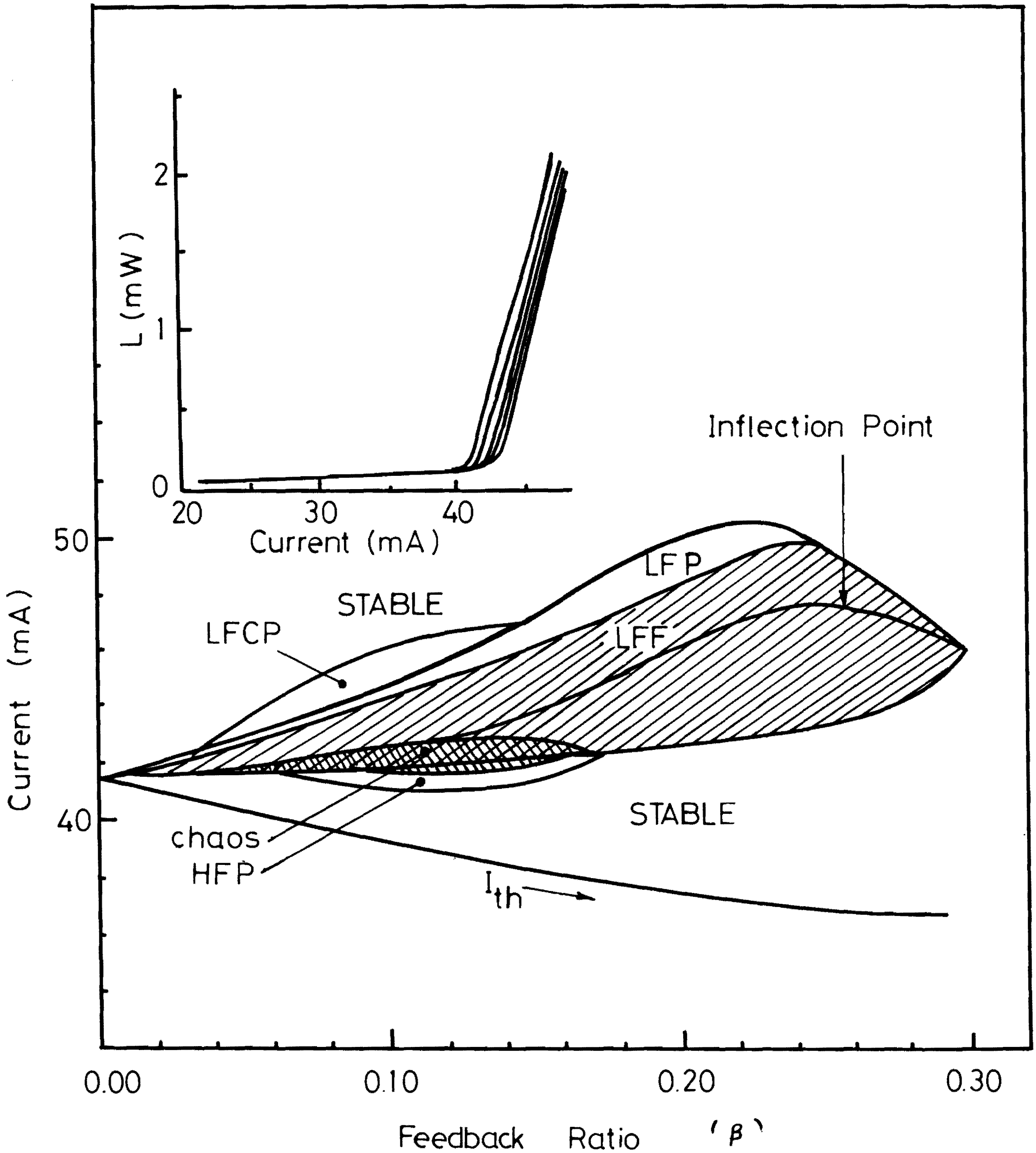


*Figure 2. Two-Dimensional Diagram with Feedback and Current being Variables, the L/I Characteristics with Different Values of Feedback at Which the Diagram is Recorded* ($L_{ex}$ *= 30 cm).*

If the biasing current was varied at a fixed feedback, for example 0.10, the light output goes through spontaneous, stable lasing, HFP, chaos, LFF, LFP, and LFCP regions, before reaching a second stable lasing stage. The temporal evolution of these steps are shown in Figure 3. A transition from the LFF to a sinusoidal pulsation (LFP) occurs at a current values above the threshold current of the solitary laser and well above the inflection point. The pulsation frequencies are higher than those of the LFF but still within the low frequency range (<100 MHz). As shown, the LFP frequency increases with current then breaks into irregular (may be chaotic,

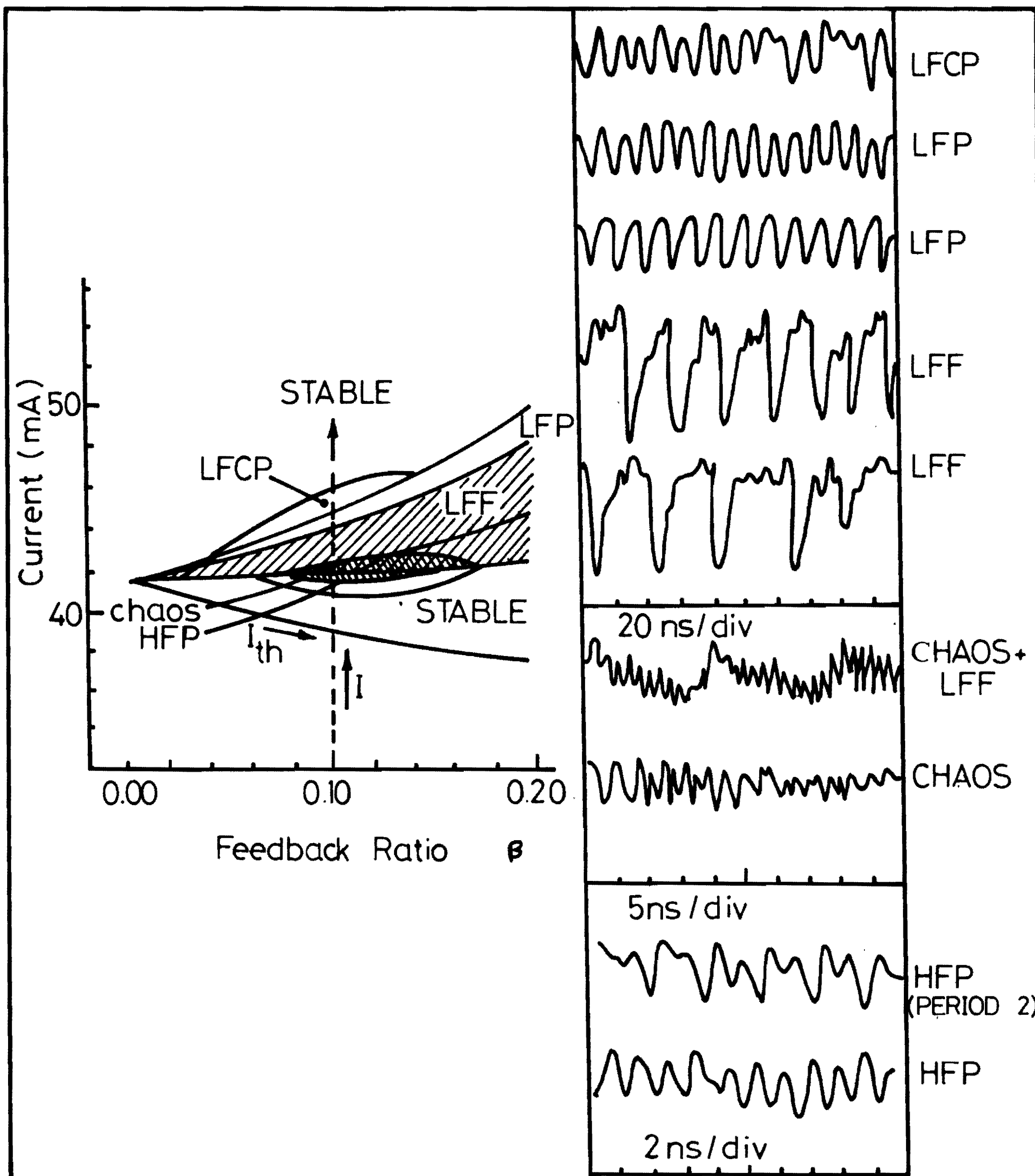


*Figure 3. Two-Dimensional Diagram with Current Which Increases at Fixed Feedback Ratio. Also shown: the temporal evolution of light output waveform through various regions in the diagram.*

LFCP) pulsations over a certain feedback range, 0.03–0.14, within which chaos could be observed at lower current values. To our knowledge, such phenomena were not recorded previously.

On the other hand, if the current was kept at a constant value (say at 45 mA > $I_{th}$) and the feedback is gradually increased, a different behavior could be observed. At low feedback, the laser was stable and with increasing feedback the LFCP appears; then these pulsations become regular, then the LFF start before and after the inflection point until at higher feedback these fluctuations switch off and the laser becomes stable.

Superposition between the HFP and the LFF may occur, as shown in Figure 4, where the HFP is enhanced to maximum intensity. The HFP could be removed by slight tilting of the external mirror. In Figure 4, the light output shows a random sudden drop to a low value followed by a stepwise buildup to the original level where step time is equal to the round trip time ($\tau_{ex}$) of the light in the external cavity, which was ~1.4 ns.

An undulation in the *L–I* curve was observed to occur with the LFF, although such a phenomenon was not shown in the *L–I* curves in Figure 2. The *L–I* characteristics at maximum feedback shown in Figure 2 were reproduced but with shorter length of the external cavity. Figure 5 was obtained at $L_{ex}$ = 12 cm instead of $L_{ex}$ = 30 cm for Figure 2. It is noticed experimentally that the separation between each two undulation valleys increased as we shortened $L_{ex}$. Comparing such undulations with the LFF behavior, one can conclude the existence of bistability behavior. As shown in Figure 5, the lower portion of the undulated curve will give an inflection point, similar to those curves of Figure 2, and less linearity above the inflection point. If we connect between the peaks,

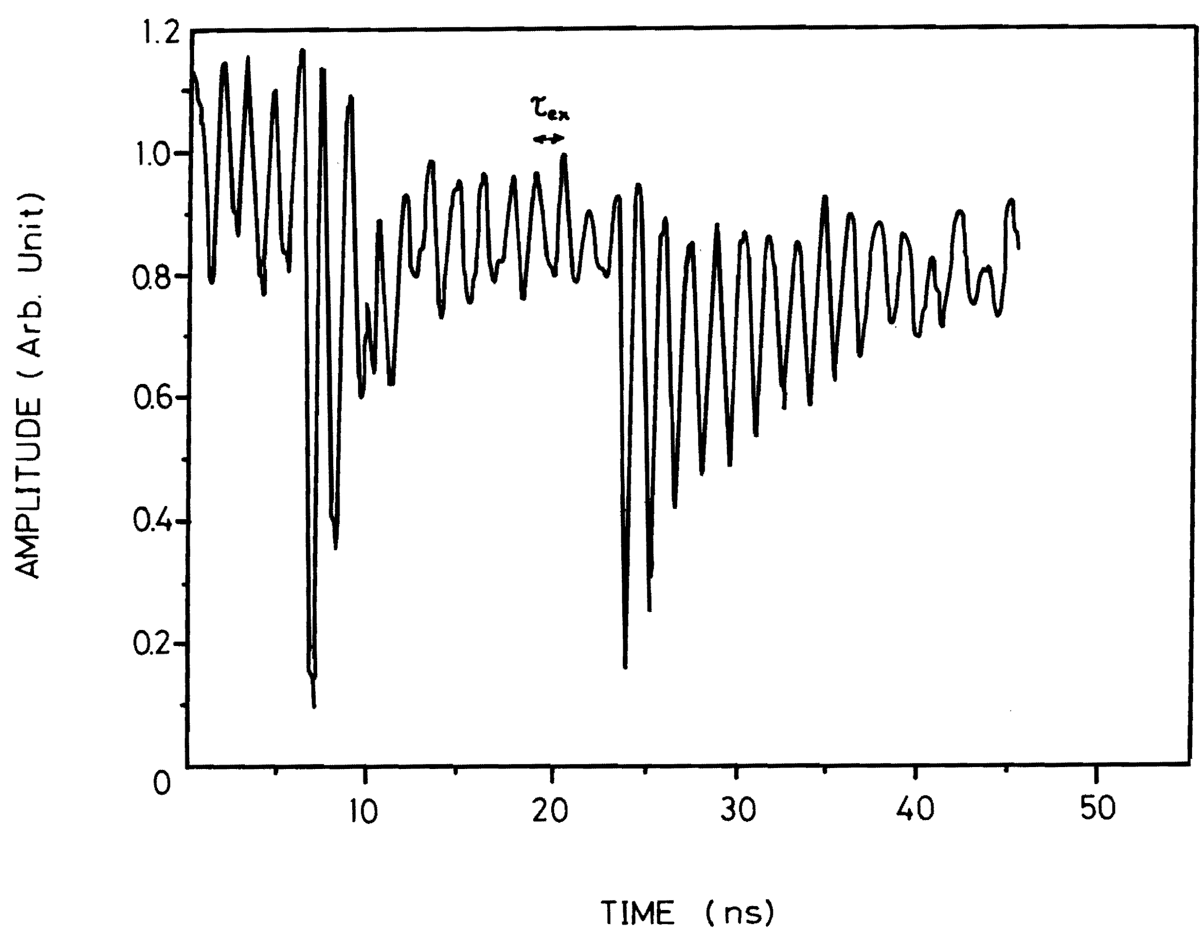


*Figure 4. HFP Superimposed on LFF.*

we will get a linear $L-I$ curve without kink and with higher efficiency. However, the laser was unstable at this state.

The feedback coefficient is given by [11].

$$C = \kappa \tau_\alpha \sqrt{1+\alpha^2} \tag{1}$$

where $\alpha$ is the linewidth enhancement factor, $\tau_{ex}$ is the round trip time in the external cavity, and $\kappa$ measures the amount of feedback (in $s^{-1}$) and is given by

$$\kappa = \frac{c}{n\ell_D}(1-r_2)\sqrt{r_{eff}/r_2}\,, \tag{2}$$

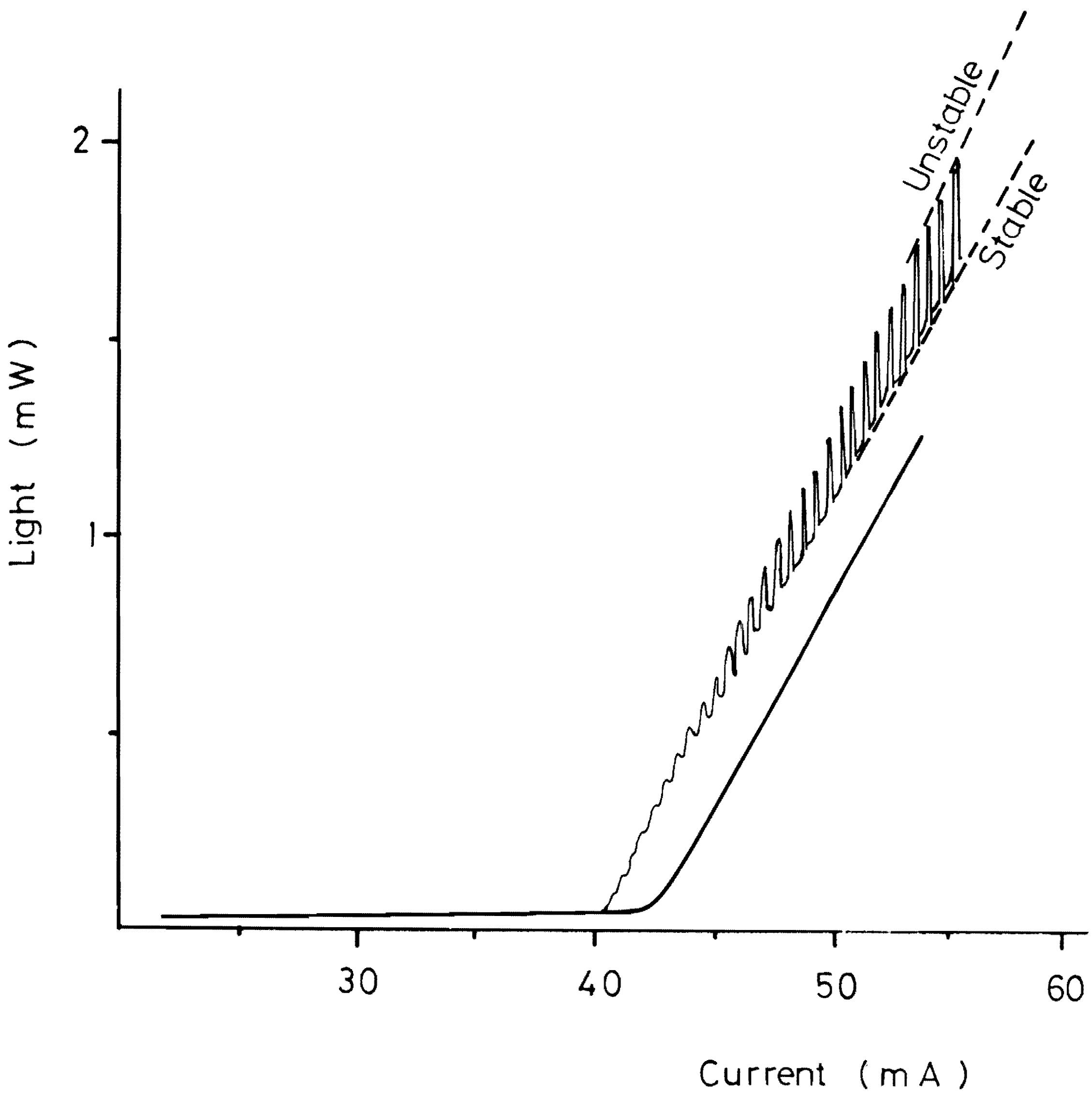


*Figure 5.* L/I *Characteristics with Bistability at Maximum Feedback* ($L_{ex}$ *= 12 cm). The facet is not AR coated.*

where $C$ is the speed of light in vacuum, $n$ is the active layer refractive index, $r_2$ is the reflectivity of laser facet facing the external mirror, and $r_{eff}$ is the effective power reflectivity of the external cavity / diode facet combination and can be expressed as [12]:

$$r_{eff} = r_2 + (1 - r_2)\beta \tag{3}$$

where $\beta$ is the feedback ratio or the fraction of light reflected back into the laser diode, and can be estimated from the reduction in the threshold current (for our setup) by [12]:

$$\beta = \frac{2.2 \cdot \Delta I_{th}}{I_{th}} \tag{4}$$

where $I_{th}$ is the threshold current without feedback.

Figure 2 covered the regions of moderate and strong feedback starting from $\beta = 8 \times 10^{-3}$ up to 0.3. Back reflections of the order of $\beta = 0.01$ were enough to drive the laser into the instability region, as shown, starting with LFF behavior which was an indication of the coherence collapse state. In [14], the coherence collapse (trajectory of chaotic behaviors) could be obtained at $\beta$ values down to ~0.02 ($\kappa = -31$ dB). Up to values of 0.04 LFF start above the inflection point, as reported in [7], and not below.

Period doubling route to chaos was shown to occur between two values of $\beta = 0.04$ and 0.16 regions just below the kink, which is in agreement with the results recorded in [9]. The appearance of the LFCP may be attributed to a chaotic behavior which starts at higher current values. Chaos by intermittent switching or competition between LFF and HFP was recorded [14] well above threshold although a DFB laser was used.

For strong feedback ($\beta > 0.3$), instabilities cease to exist, where the external reflectivity exceeds the facet reflectivity. In this regime, the external cavity has a relatively high quality factor which may stabilize the system and force it to operate in an external cavity mode [15]. The multiple external reflections are not neglected any more [1]. The *L–I* characteristics in such regime showed an improvement in the laser efficiency without kink, within the current range used in this work.

Referring to Figure 5, the upper line indicated an unstable state whereas the lower line indicated a more stable state, remembering that the LFF might be attributed to a competition between the mode with lowest line width and the mode with lowest gain [see for example 14], the undulation in Figure 5 could be explained as a result of such bistability with longer life time for the mode of minimum gain (*i.e.* the lower portion of the curve). The frequency of the LFF was reduced such that, the X–Y recorder was able to sense such instability of the laser output.

## 4. CONCLUSION

The most detrimental operation for laser diodes with an external cavity, occur between two values of $\beta = 0.005$ and 0.3, and between two values of current $I/I_{th} = 1$–1.3. Chaotic behavior, through a period doubling, could be obtained near the inflection point for a certain range of feedback level. Intermittent route to chaos might occur well above the inflection point. All types of instabilities could be suppressed with feedback above 0.3. Optical bistability was recorded statically (*L–I* curve) and temporally (LFF) simultaneously.

For coherent systems, these unstable regions must be strictly avoided. It is apparent that the unstable behavior may be avoided in the CW operation by insuring that any external feedback is maintained at a very low feedback ratio and the laser at a current well above threshold (> 1.3 $I_{th}$).

Preliminary results of multi-quantum well lasers under feedback indicated marked difference from the bulky laser diodes. We are planning to use multi-quantum well lasers at various operating conditions of feedback. The temperature dependence of dynamical behavior of laser diodes with external feedback has not been investigated before which will be of interest later since the laser diode may be operated at various environmental temperatures in the field.

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