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# Optical Bistability in Semiconductor Laser Amplifiers:- Assessment of Switching Speed

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Non-linearity and Optical Bistability are observed in the transfer characteristics of Fabry-Perot semiconductor laser amplifiers at optical input powers as low as 2 μW. Measured and theoretical hysteresis characteristics are presented for a bistable Fabry-Perot laser amplifier operating at high switching rates. Results indicate switching times in the order of the carrier recombination time which will restrict operation to data rates below around 400 Mbit/s.

## INTRODUCTION

Current interest in optical computing and optical logic gives rise to the need for an optical switching element whose optical output state can be switched by changes in optical input. Non-linearity and Optical Bistability (OB) are observed in the transfer characteristics of Fabry-Perot semiconductor laser amplifiers [1] at optical input powers as low as 2 μW in InGaAsP devices [2,3]. The low switching energies, significant contrast between high and low output states (> 5 dB) and fast optical transitions between states makes this device attractive for optical logic and pulse-shaping applications. However, it has been suggested [4] that even though the output intensity is seen to change rapidly, the time taken to switch from one stable state to another is in the order of the carrier recombination time giving rise to nanosecond switching speeds.

The rate at which a logic element can pass information is obviously a critical parameter to consider when assessing the suitability of a device to high speed processing applications. To determine the maximum clock-rate at which a non-linear or bistable laser amplifier will operate we have examined the variation in performance of a Fabry-Perot semiconductor laser amplifier when the period of the intensity modulated input signal approached the carrier recombination time.

## THEORY

Optical bistability in semiconductors arises from the relatively strong dependence of refractive index on carrier concentration. In a semiconductor laser operated just below threshold, the effect of an input optical signal undergoing amplification is to reduce the material gain per unit length and hence the free-carrier concentrations in the active region of the device. Gain (or stimulated emission) is related to the refractive index via the Kramers-Kronig relation, and hence there is an associated change of index in the presence of a sufficiently strong optical input. The resultant change of phase in the Fabry-Perot cavity can give rise to strongly non-linear input-output characteristics and to bistability [5].

To understand the cavity effects in more detail, consider the spectral response shown in Fig 1 for three values of input optical intensity. The figure shows the normalised average intensity in the cavity ($I_{av}/I_s$) as a function of single-pass phase change $\emptyset$, for an amplifier at 95% of lasing threshold. ($I_s$ is a convenient scaling intensity introduced in our previous paper [5].) Whilst the

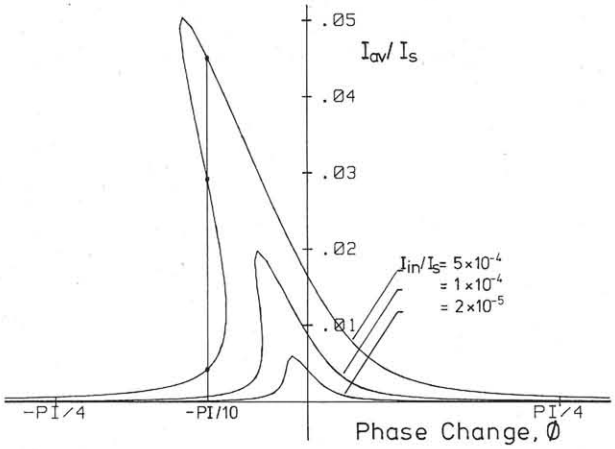


Fig 1 Calculated spectral response of an amplifier at 95% of lasing threshold. The average intensity in the cavity, $I_{av}$, is plotted for three input intensities, $I_s$, as marked. All intensities are scaled to $I_s$, which for 1.5 μm operation assumes the value 8 x $10^5$ W/cm$^2$. The horizontal axis is the phase detuning from a cavity resonance in the absence of an input signal.

initial phase Ø at low levels is determined by the input wavelength with respect to the peak of a Fabry-Perot resonance, the actual phase change experienced by a strong input will be approximately linearly dependent on $I_{av}$. Thus values of $I_{av}$ close to the peak of the resonance will induce larger phase shifts than those further away from the peak, thus resulting in the spectral response shown in Fig 1. The vertical line marked on the figure at Ø = -0.1Π intersects the curve for $I_{in}/I_s = 5 \times 10^{-4}$ in three places. Hence an input wavelength corresponding to this Ø will give OB; the upper and lower intersections turn out to be stable solutions, whilst the intermediate one is unstable. To get an idea of the input power levels required, we note that for an amplifier operating at a wavelength of 1.5 μm the scaling intensity $I_s$ is about 8 x $10^5$ W/cm$^2$. The minimum scaled input to give OB on Fig 1 is about $10^{-4}$, and it follows that for an amplifier whose active area is about 1 μm$^2$ a coupled power level of around 1 μW should be sufficient to observe OB.

In order to calculate the transient response of amplifier OB, we note that the cavity round-trip time is usually about three orders of magnitude less than the electronic recombination time. It is, therefore, a good approximation to assume that the optical intensity in the cavity reacts instantaneously to changes of the electron concentration. This means it is only necessary to solve a single time-dependent rate equation for the electron concentration in order to determine the transient response of amplifier OB. This is discussed in more detail in our time dependent study [4] which shows that the rapid increase in output intensity during switch-up takes place during the evolution of the cavity phase as it changes between steady states. That is, although the observed optical transition is very fast and determined by the cavity round-trip-time, switching times are in fact set by the rate at which the cavity phase changes; which is in turn related to the time taken for carrier recombination.

MEASUREMENTS

Fig 2 shows the schematic diagram of the equipment used. The source was a grating loaded external

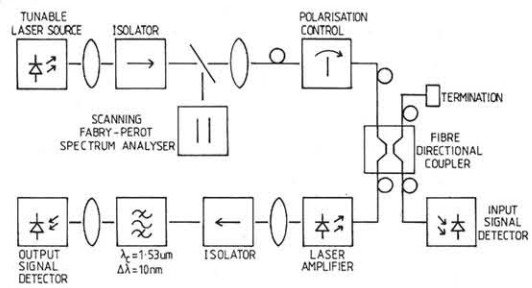


Fig 2 Measurement set-up.

cavity laser [6] built around a 1.5 μm Double Channel Planar Buried Heterostructure (DCPBH) laser made in BTRL. This configuration gives a CW spectral linewidth of about 10 kHz and allows the emission wavelength to be matched to the dominant mode in the amplifier spectrum and continuously varied over a range of 0.7 nm about this point. The Fabry-Perot amplifier was a 200 μm long BTRL InGaAsP/InP DCPBH laser which had a dominant-mode wavelength of 1.54 μm. For all the measurements it was biassed at 14.5 mA which

was about 95% of its lasing threshold current ($I_{th}$). A Peltier heat pump stabilised the amplifier temperature to ±0.02°C. Light was injected into the laser active region using a single-mode fibre which, with a taper and hemi-spherical lens formed on the end, gave a coupling loss of 5 dB. The launched state of polarisation was set at TE using a fibre-birefringence polarisation controller [7] and a fibre directional coupler allowed both the output signal and a representation of the input signal to be monitored with InGaAsP PIN photodiodes. A scanning Fabry-Perot optical spectrum analyser with a free spectral range of 7.5 GHz was used to measure the signal wavelengths and observe the spectral purity of the input signal. Optical isolators were used to control reflections in the system and the output of the amplifier was spectrally filtered to reduce spontaneous noise at the output detector.

During the measurements the input intensity to the amplifier was varied sinusoidally. Initially a very low input power (< -40 dBm:- sufficiently low as to cause little change in material refractive index and hence only a small detuning) was used to estimate the zero-input resonant wavelength. The input wavelength was detuned from this resonance to longer wavelengths to observe non-linearity and bistability. The period of the modulation was varied and the hysteresis in the bistable switching process observed by displaying on an oscilloscope the amplifier output signal plotted against the input optical waveform. We observed an intensity spike in the amplifier output as the device switched from low to high gain. This is discussed in our time dependent study and arises as a result of the cavity phase passing through resonance as it changes. We also saw a rapid reduction in hysteresis as modulation frequencies approached 250 MHz. At this frequency the intensity of the input signal varies between maximum and minimum levels in 2 ns, a time similar to that taken for carrier recombination.

The loops shown in Fig 3 were produced with an input power of 20 μW peak and an input wavelength detuned from resonance by 0.15 nm. A series of

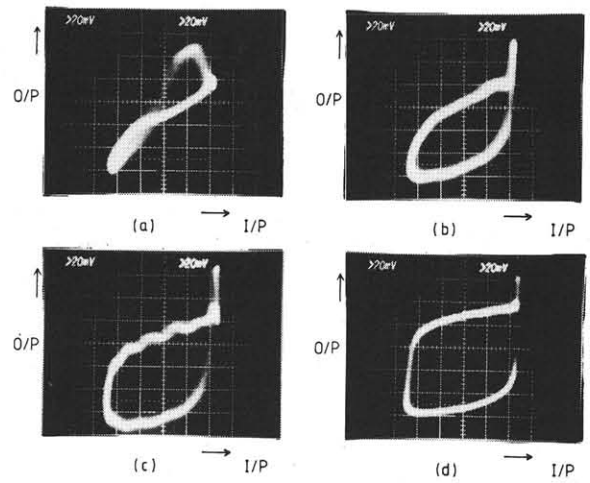


Fig 3 Measured hysteresis curves for input intensity varying sinusoidally with period 4 ns (a), 6 ns (b), 8 ns (c) and 20 ns (d). InGaAsP DCPBH, = 1.53 μm, $J/J_{th}$ = 0.95, detuning 0.15 nm, I/P = 20 μW peak.

similar measurements at an input power of 3 μW peak and with smaller detuning produced closure at a similar input frequency. In this series of photographs the intensity spike is clearly visible and becomes an increasingly significant feature of the transfer characteristic as the input frequency is increased. The measurement bandwidth was ∿ 500 MHz.

COMPARISON WITH THEORY

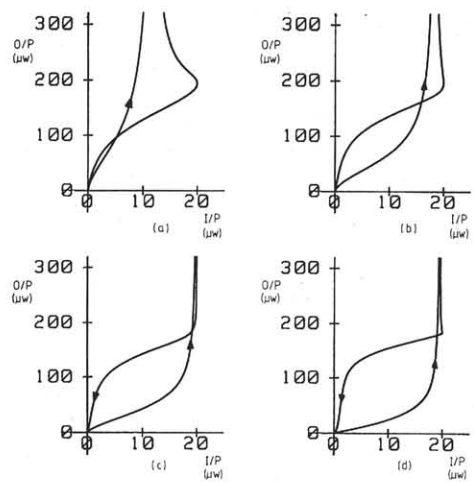


Fig 4 Theoretical hysteresis curves for input intensity varying sinusoidally with period 4 ns (a), 6 ns (b), 8 ns (c) and 20 ns (d). $J/J_{th}$ = 0.95, detuning 0.18 nm, I/P = 20 μW peak.

Using a computer model to analyse the transient response of amplifier OB, the measured results were compared with those predicted from theory. The hysteresis plots of Fig 4 were produced for operating conditions similar to those used in the measurements. The confinement factor was taken as 0.3, facet reflectivities as 0.38, carrier recombination time as 1.7 ns and the line broadening factor as 3.2. The detuning was set at 0.18 nm, which is larger than the measured detuning of 0.15 nm taken for the practical results and was needed to improve the agreement between the two sets of curves. This may be due, at least in part, to an uncertainty in measuring the zero-input resonant wavelength. When comparing the theoretical and measured results the effect of measurement bandwidth is seen in the size and risetime of the intensity spike.

## CONCLUSIONS

These measurements on the non-linearity and optical bistability in InGaAsP Fabry-Perot lasers indicate that switching times are set by the carrier recombination time and that nanosecond switching times will limit the operating speed of these devices. In the case of the device measured, the hysteresis in the switching process ceased to be evident when the repetition rate of the input signal was raised to 250 MHz. In practical terms this would indicate a maximum operating rate of about 400 Mbit/s. Although these measurements relate to the performance of semiconductor laser amplifiers, the results may be significant for other devices which display optical bistability due to non-linearities caused by similar mechanisms [8].

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