Bistability in quantum-well lasers

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Since the early sixties there has been a growing interest in using optical nonlinearities of semiconductor materials for optical logic. Amongst a variety of devices particular attention has been given to the operation of inhomogeneously pumped injection lasers showing two stable light-output levels at the same injection current. Recent advances in the techniques for semiconductor-layer growth have made possible the fabrication of lasers with very thin active layers known as quantum wells. The article below presents some preliminary results of an investigation of the optical bistability in inhomogeneously pumped quantum-well lasers.

Introduction

An inhomogeneously pumped semiconductor injection laser may show optical bistability in the form of two stable light-output levels for the same value of injection current. This nonlinear optical effect relies on saturation of the light absorption in a passive region in the device. It offers the possibility of making optical switching devices to be used for modulating light sources and processing information which is being transmitted or manipulated by means of light beams.

In recent years there has been particular interest in the multiple-quantum-well (MQW) laser, where the light is generated in a set of GaAs layers which are thinner than 20 nm and which are sandwiched between layers of Al_xGa_{1-x}As with a larger band gap. In the active layers the motion of electrons and holes perpendicular to the interfaces is quantized. In addition to fascinating physical phenomena, MQW lasers show some practical advantages such as a relatively low threshold current and a short emission wavelength. It is also expected that the nonlinear optical effect due to inhomogeneous pumping is stronger in MQW lasers than in lasers having a thick active layer of 'bulk' GaAs. The ability to make use of this enhanced nonlinearity could lead to the development of highly efficient electro-optic logic elements.

The fabrication of MQW lasers requires advanced growth techniques such as molecular beam epitaxy (MBE), which has become highly developed at Philips Research Laboratories in Redhill, England, or metal-organic vapour-phase epitaxy. MBE is a refined form of vacuum evaporation in which molecular (or atomic) beams from effusion cells impinge upon a heated substrate under ultra-high vacuum conditions. The layer-growth rate for a material like GaAs is

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typically about 1 μm/h, i.e. one monolayer per second, so with beam shutters in front of each cell operating within 0.3 s it is possible to grow very thin layers with interfaces that are 'abrupt' within one monolayer.

In the investigation described in this article, we have performed some preliminary experiments on inhomogeneously pumped quantum-well laser structures in the GaAs/Al_{x}Ga_{1-x}As material system grown by MBE, and the measured light-current characteristics do indeed show hysteresis. It has been possible to demonstrate rapid switching between low and high light-output levels. The mechanism of the optical bistability in MQW lasers was assessed by studying the laser-emission spectrum and the optical absorption spectrum of the passive region.

In this article we first give some details of the MBE-grown laser structures. Next we describe their light-current characteristics and switching behaviour. Finally, the physical processes responsible for the observed bistability are discussed.

**Device structures**

The structure of an inhomogeneously pumped MQW laser device is shown schematically in fig. 1. The epitaxial semiconductor structure was grown by K. Woodbridge using a laboratory-built MBE system with computer-controlled effusion-cell temperatures and shutter operations. The structure has a 200 nm thick waveguiding region of Al_{0.35}Ga_{0.65}As barriers and two 2.5 nm thick quantum wells of GaAs. On both sides cladding layers of Al_{0.65}Ga_{0.40}As were grown. Contact layers of heavily doped n-GaAs and p-GaAs were used to obtain good electrical contacts to the metallizations. A stripe laser, 50 μm wide and 300 μm long, was made by P. J. Hulyer using oxide insulation. The laser operated at a wavelength of 777 nm. Inhomogeneous pumping was achieved by dividing the p contact of the device into two regions with a groove etched through the top metallization and top GaAs contact layer in a direction perpendicular to the oxide stripe. It was thus possible to have a pumped region and an unpumped region within the same Fabry-Pérot cavity.

![Fig. 1. Schematic diagram of the structure of an inhomogeneously pumped MQW laser device.](image)

**Light-current characteristics and switching**

The light-current characteristics were measured in real time by driving one contact segment of the devices with a triangular current pulse, with an overall duration of 800 ns and a repetition rate of 1 kHz, and by detecting the generated light with a fast avalanche photodiode. For the inhomogeneously pumped devices curves with a hysteresis were obtained as shown in fig. 2 for a typical MQW device. As current is first
injected the light output increases slowly. At higher current the light output increases steeply when the laser operation switches on. If in this state the current is decreased slightly, the laser remains 'on'. When the current is still further decreased the light output suddenly drops to a low level. It is then necessary to drive the device to a higher current in order to turn it 'on' again. The difference between the threshold current for laser action and the turn-off current was not affected by the maximum current, \( I_{\text{max}} \), to which the device was driven above threshold. This is also shown in fig. 2 for two different maximum current values, \( I_{\text{max}}^a \) and \( I_{\text{max}}^b \).

The hysteresis observed in the light-current characteristics of these structures suggests that it should be possible to cause them to switch between two stable optical power levels. This was demonstrated by driving the devices with a relatively long pulse (\( \approx 500 \text{ ns} \)) to a current \( I_1 \) (fig. 2) within the hysteresis loop, then superimposing shorter (\( \approx 20 \text{ ns} \)) switch-up and switch-down pulses having amplitudes which drove the devices above threshold current and below the turn-off current respectively. Fig. 3 shows typical oscilloscope traces of the monitored device current and the light output as functions of time. Switching is clearly demonstrated with the light output remaining at a high level after the switch-up pulse was removed and the current returned to \( I_1 \). Likewise, the output remained at a low level for the same base current \( I_1 \) after the switch-down pulse was applied. Thus at the current \( I_1 \), the light output is at one of two stable levels according to the sense of the preceding short switching pulse. The same type of hysteresis and switching was observed for a variety of inhomogeneously pumped MQW devices made from the same slice. The rise time of the light output in response to a switch-up pulse was less than 2 ns, our present experimental limit, and the optical power at the threshold current was a few milliwatts (fig. 2). The hysteresis described here with the associated switching behaviour was not observed for homogeneously pumped structures made from the same materials.

This kind of switching is due to the passive region in the laser cavity, and we have observed similar behaviour in conventional double-heterostructure
lasers which do not embody quantum wells. We argue below, however, that the mechanism in quantum wells is different from that in bulk materials, and one of the objectives of our research is to determine whether quantum wells offer advantages in these devices.

Mechanism of the bistability

We believe that the observed hysteresis in the light-current characteristics of the inhomogeneously pumped devices is due to reduction of the optical absorption within the unpumped region as the optical power is increased, as in other devices of this type\cite{1}\cite{5}. The importance of the optical absorption can be illustrated by emission spectra measured from each end of an inhomogeneously pumped device at different currents below threshold; see fig. 4. Since the light absorption within the cavity is stronger at the short-wavelength side, it has the effect of moving the spontaneous-emission peak to longer wavelengths. In our device, the spontaneous emission is generated only within the pumped region. Consequently, for a single pass through the cavity, this absorption has a more pronounced effect on the spectrum from the unpumped end as no light is generated near this facet. This explains why the spontaneous emission peak from the unpumped end occurs at longer wavelengths than that from the pumped end (fig. 4).

As the current is increased, the gain peak moves to higher energy, thus the emission peak moves to shorter wavelengths. Eventually there is sufficient gain in the pumped region to overcome the absorption losses in the unpumped region over some part of the spectrum. Thus an additional peak appears on the long-wavelength side of the spectrum emitted from the pumped end. This peak coincides with the emission peak from the unpumped end at the threshold current, and represents light which is amplified over several round-trips of the cavity, leading to laser action at threshold.

From the fast rise time of the light output in response to a switch-up pulse we infer that the optical bistability is caused by electronic processes rather than thermal processes. In bulk GaAs, experiment has shown that the effect of an increasing optical power on the absorption depends on the photon energy of the light with respect to the band gap of the semiconductor material\cite{6}. For light having a photon energy lower than the original band gap, the absorption increases due to a reduction of the band gap as a result of Coulomb interactions between the increasing number of charge carriers. For light having a photon energy higher than the original band gap, the absorption decreases with increasing optical power as band filling reduces the probability of valence-to-conduction band transitions because of the Pauli exclusion principle. This effect most probably causes the optical bistability in conventional double-heterostructures with an active layer of bulk GaAs.

![Normalized emission spectra from the unpumped end and the pumped end of an inhomogeneously pumped MQW laser device.](image)

**Fig. 4.** Normalized emission spectra from the unpumped end and the pumped end of an inhomogeneously pumped MQW laser device. The relative intensity $Int$ (in arbitrary units) is plotted against the wavelength $\lambda$ of the emission for three values of the injection current $I$ below the threshold current ($I_{th}$) for laser action. The emission peaks for the unpumped end have a lower intensity and are situated at longer wavelengths than those for the pumped end. At increasing injection the maxima shift to shorter wavelengths. At $I = 0.86 I_{th}$ an additional peak appears in the spectrum from the pumped end at about the same wavelength as the maximum for the unpumped end, coinciding with the laser-emission wavelength (arrow) at $I = I_{th}$.

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\[ \text{[5]} \text{S. Tarucha and H. Okamoto, Voltage-controlled optical bistability associated with two-dimensional exciton in GaAs-AlGaAs multiple quantum well lasers, Appl. Phys. Lett. 49, 543-545, 1986.} \]

In MQW devices, however, the absorption at the band edge may be strongly affected by the presence of bound electron-hole pairs known as excitons [7]. At low carrier densities excitons appear much more strongly in MQW systems than in bulk material due to the effects of spatial confinement which increase the probability that the motion of an electron and a hole will be correlated to form an exciton, and increase the binding energy of such an electron-hole pair. Thus large resolved exciton peaks are observed in the absorption spectra of MQW structures even at room temperature. The active region of the device used in this work was sufficiently lightly doped (10¹⁶ cm⁻³) for excitons to be present in unpumped material. At high carrier densities, however, the excitons are screened out by many-body interactions and the absorption saturates, giving rise to a large optical nonlinearity at these energies.

![Fig. 5. Room-temperature absorption spectra of an MQW structure having a hundred 8.5-nm quantum wells, measured with the light propagating perpendicular to the wells. The sample was grown by MBE in the same system as the bistable devices. The absorption A, measured at three different levels of the incident optical power L, is plotted in arbitrary units against the photon energy E. Whereas the absorption increases with increasing power at the low-energy side (= 1.45 eV), it decreases at the energy where excitonic absorption occurs. The data for this figure were provided by A. Miller, of the Royal Signals and Radar Establishment, Great Malvern, England.](image)

Fig. 5 shows the absorption spectrum of an MQW structure having 8.5 nm thick quantum wells, grown by MBE in the same system as the present bistable device structures, measured for three optical-power levels with the direction of light propagation perpendicular to the wells. It can be seen that the exciton peaks present at low power levels are screened out with increasing optical intensity, while the simultaneous effect of band-gap reduction is to bring the continuum absorption edge to lower energies. Thus the net result is that the absorption increases at low energies, but decreases in the vicinity of the exciton peaks. Above the original band edge the absorption may also decrease due to band filling. In our case, the inhomogeneously pumped MQW devices with 2.5-nm wells operate below the original band edge in the region of the excitonic peaks in the absorption spectrum. Thus the decrease in absorption was provided by the excitons and not by the continuum. The subsidiary peak in the emission spectrum of fig. 4, at which the device switches, thus arises from the decreasing losses at the exciton resonance.

An additional effect which could reduce the absorption below the band edge in inhomogeneously pumped MQW structures is the quantum-confined Stark shift of the band edge under the influence of an electric field. This shift arises from the change in the shape of the potential distribution in a quantum well when an electric field is applied across it. The potential changes in such a way that the energy difference between the lowest quantum states of the electrons and holes is reduced [8]. In the unpumped segment of the bistable MQW laser structure there is a built-in field due to the presence of the p-n junction. This field is reduced at high injection current by carriers generated upon absorption of light from the pumped segment. This reduces the Stark shift, so that the absorption edge moves to a higher energy at a higher injection current. We have observed a shift of the absorption edge of this structure of approximately 3-4 meV for an applied bias of 9 V (6.8 x 10⁵ V/cm) whereas the built-in field is only about 1.8 x 10⁵ V/cm. Even if this field is reduced to zero under optical excitation, the resulting shift is less than about 1 meV, which is too small to be responsible for the bistability we observe.

In conclusion, we believe that the bistability of the inhomogeneously pumped MQW devices is due to excitonic saturation. Experiments are planned to investigate this further and to compare the performance of MQW and bulk materials in these switching devices.

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Summary. Hysteresis has been observed in the light-current characteristics of inhomogeneously pumped GaAs-Al₅₀Ga₅₀As laser structures which were grown by molecular beam epitaxy and whose active regions consisted of 2.5 nm thick multiple quantum wells (MQW). Fast switching (< 2 ns) between low and high light-output levels was demonstrated. The observed bistability was due to saturation of the optical absorption in the passive region of these structures at high injection currents. The MQW laser devices operated in the wavelength region of the excitonic absorption and their bistability was ascribed to the decrease of this absorption at higher light intensities.