Measurements of the barrier-well injection bottleneck in a multiple quantum well optical amplifier

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We describe broadband static pump probe measurements of the barrier-well injection bottleneck caused by a complicated interaction between three- and two-dimensional carriers in a 1.5-μm multiple quantum well optical amplifier.

Gain characteristics of multiple quantum well (MQW) lasers and amplifiers are strongly dependent on the dynamics of carrier injection into the wells. This injection process is rather complicated and consists of several parts.1,5 Figure 1(a) shows the energy band diagram of a typical 1.5-μm MQW laser amplifier structure. In most practical structures of this type, the confinement region is wide enough to be considered as a three-dimensional medium so that the injected-carrier flowing through it is dominated by diffusion and by the Coulomb interaction between electrons and holes.5 Following the diffusion, carriers are captured into the wells with a finite quantum mechanical probability6,7 and can contribute to gain. The exact details of the coupling between the three-dimensional carriers in the confinement and barrier regions and the two-dimensional carriers in the quantum wells are not yet known. Approximate models5-7 and some experiments1,5 suggest that for practical structures, the capture probability, measured by means of an equivalent local capture time, is approximately 1 ps.5 The carrier injection process is further complicated by thermally activated escapes from the wells, the flow by diffusion and drift in the barrier regions separating the wells and by tunneling between wells.4,5 Moreover, the carrier flow is also influenced by the carrier contributions to both spontaneous emission (at energy levels of both the barrier and wells) as well as to stimulated emission at energy levels of the quantum well states. Stated in different terms, the finite transport time across the confinement and barrier regions, coupled with the local capture time and the other processes, cause an injection bottleneck for the carriers. This bottleneck has a profound influence on the nonlinear gain characteristics of MQW lasers (and hence on their modulation properties)3,4 on the amplification of high bit rate data streams8 and on four wave mixing with widely separated signals9. The injection process has recently been modeled for amplifiers5 and lasers.2-4 However, these models are rather incomplete. Experimentally, the injection bottleneck was observed using single wavelength ps pump-probe measurements,10 time resolved photoexcited luminescence11 and by fitting models to measured modulation responses and relative intensity noise spectra in lasers. While these experiments reveal many of the relevant details, and in particular the dependence of the injection bottleneck effect on the exact structure of the confinement region,4,10 none accurately describes the details of this bottleneck phenomenon.

In this letter, we propose to examine the injection bottleneck using a broadband pump-probe measurement. The experiment is described conceptually in Fig. 1(b). A forward biased MQW amplifier (for simplicity, only one well is shown) is optically pumped at a wavelength corresponding to an energy level inside the well. This optical signal is strong enough to saturate the gain, namely to cause the removal of carriers by stimulated emission. A second signal, from a tunable laser, is used to probe the gain at all energies (wavelengths) from up in the barrier (λ=1.3 μm) to deep in the well (λ=1.48 μm). The effect of the
pump on the probe signal is detected as a crosstalk signal. Alternatively, the probe signal can be eliminated and a crosstalk signal between the pump and the spontaneous emission spectrum can be detected. The two measurements reveal essentially the same results. Ideally, the experiment would time resolve the crosstalk signal with a sub-ps resolution. However, the present experiment is limited to a static examination. Nevertheless, the measurements are capable of describing many of the details related to the injection bottleneck phenomenon.

The experimental setup is shown in Fig. 2. The pump laser used was a single mode MQW distributed Bragg reflector laser operating at 1.53 μm, close to the amplifier gain peak. The probe signal source was a tunable external cavity laser. The pump and probe signals were TE polarized and coupled to the amplifier using a microlens. The output from the amplifier was filtered by a 1-nm-wide bandpass filter. For the gain crosstalk measurements, the pump was chopped and a monochromator and a lock-in amplifier were used to measure the crosstalk signal. For the spontaneous emission measurement the probe signal was eliminated and an optical spectrum analyzer placed after the filter, was used to record the crosstalk signal. Spontaneous emission and gain spectra were measured with and without the pump over the wavelength range of 1.3–1.48 μm.

Spontaneous emission crosstalk spectra measured over a large range of drive currents are shown in Fig. 3. Each point on the three-dimensional plot was obtained by subtracting the spontaneous emission signal (at a given wavelength) under optical pump injection conditions from the corresponding signal with the optical pump removed. Examination of Fig. 3 reveals several points: (1) The crosstalk level is bias dependent at all wavelengths, since it is proportional to the gain. (2) There is a finite, bias dependent, crosstalk level at wavelengths shorter than 1.36 μm. This signal is due to carriers accumulated in the three-dimensional region because of the injection bottleneck. (3) There is a sharp change of slope, at all bias levels, at the wavelength of 1.36 μm. This change of slope (at a constant wavelength) is clearly seen in the insert of Fig. 3, which is a two-dimensional representation of the crosstalk at four currents and is included for clarity. The wavelength of 1.36 μm, where the slope changes, is identified as the wavelength corresponding to the energy where the three- and two-dimensional regions meet. (4) For wavelengths longer than 1.36 μm, the crosstalk signal increases rapidly as the pump wavelength is approached. This signal is due
to carriers which correspond to energy levels inside the well.

Figure 4 shows a crosstalk measurement as a function of drive current for the three-dimensional region at the wavelength of 1.3 μm which is in the three-dimensional region. The crosstalk signal increases first with current but at 140 mA saturates and eventually drops. This effect is probably the result of two mechanisms that oppose each other. At low drive current, the number of carriers in the three-dimensional region is small and any stimulated emission (in the well) which requires replenishing by carriers from the three-dimensional reservoir causes a large relative change and hence the effect is strong. However, at high currents, the number of carriers accumulated in the three-dimensional region is large (due to the bottleneck effect) so that for a constant pump level at the well, the relative number of carriers removed from the reservoir is small and the effect decreases.

In conclusion, we have presented crosstalk measurements representing the interaction between three- and two-dimensional regions in a MQW optical amplifier. The broadband static pump-probe technique enables to map out details of the gain spectra in the region where the barrier and well regions meet. While the static technique does not reveal the dynamics of the interactions between carriers in the two types of regions, it nevertheless describes many details of the injection bottleneck phenomenon which is an important contributor to gain nonlinearity in MQW lasers and amplifiers.

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