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CONTROL OF LASER RADIATION PARAMETERS

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Stimulated-emission wavelength switching in optically pumped InGaAs/AlGaInAs laser heterostructures

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***Abstract*. We report stimulated near-IR emission in optically pumped InGaAs/AlGaInAs heterostructures and stimulated-emission wavelength switching from 1.9 to 1.5 and then to 1.2 μm with increasing optical pump intensity. The wavelength switching behaviour of the heterostructures depends on their geometry (band-gap profile) and the competition between stimulated emissions at different frequencies in different parts of the system.**

Keywords: *stimulated emission, semiconductor heterostructures, optical pumping, lasing frequency switching.*

1. Introduction

This paper reports on the observation of stimulated emission in optically pumped InGaAs/AlGaInAs heterostructures. We demonstrate frequency switching of stimulated IR emission in response to changes in the optical pump intensity. We interpret this behaviour as follows: variations in the photoexcited carrier concentration lead to stimulated emission in different regions of the heterostructure, which differ markedly in the band gap (by virtue of the composition gradient).

It is well known in the physics of heterostructure lasers [1, 2] that, with increasing pump intensity, the output wavelength of heterostructure lasers decreases owing to the broadening of their gain band and stimulated emission on transitions from higher levels of the quantum well. We observed stimulated-emission wavelength switching by almost 50 %. Such switching occurred only in heterostructures with special design features. Multicolour heterostructure lasers utilising such effects may be of interest for certain applications.

2. Experimental results

In our experiments, photoexcitation was provided by 1.064-μm Nd : YAG laser pulses (pulse duration, about 80 ns) and by an optical parametric oscillator (OPO) at $\lambda = 0.75$ and 1.65 μm at room temperature (pulse duration, ∼5 ns; repetition frequency, 10 Hz). From the quantum-well structures grown in this study, rectangular samples one to several millimetres in size were prepared by cleaving. The samples were optically pumped along the normal to their plane, with the beam spot diameter exceeding the sample size. The output radiation (propagating in the quantum-well plane) was focused onto the entrance slit of a monochromator, and its intensity was measured by photodetectors at different wavelengths. If necessary, appropriate filters were mounted in front of the detectors, which made it possible to check the radiation wavelength. The experimental setup was described in detail elsewhere [3].

All of the observed effects were obtained using heterostructures with a carrier concentration $n = (2 - 3) \times 10^{18}$ cm^{-3}, grown on 350-μm-thick InP substrates. The thickness of the Al$_{0.48}$In$_{0.52}$As cap layers was approximately 500 Å. Note that the chemical composition of the cap layer is not very essential for the effects in question because its band gap is wide compared to the pump photon energy and, hence, it absorbs little or no pump radiation. The presence of surface layers is only essential for producing an optical waveguide, reducing the surface recombination rate and protecting the heterostructure layers. The thickness of the layers between the substrate and waveguide structure and between the waveguide and cap layer in our samples was approximately 500 Å. Figure 1 schematically shows the band-gap profiles across the heterostructures studied (1 – 3).

Figure 2 presents emission spectra of heterostructure 1 pumped at 0.75 μm. The sample had the form of a rectangular plate 3×4 mm^2 in area, with cleaved edges. At very low pump powers, we observed a spontaneous emission near 1.9 μm, corresponding to radiative interband transitions from quantum wells. Above a certain threshold, optical pumping gives rise to a 1.9-μm stimulated emission. As the pump intensity is raised from 1.6 to 10 kW cm^{-2} [spectra (*1*) – (*4*)], the 1.9-μm stimulated emission intensity increases (Fig. 2a). Further raising the pump power [spectra (*4*) – (*7*)] reduces the intensity of this emission (Fig. 2b). At pump intensities above ∼22 kW cm^{-2}, an emission line emerges at 1.54 – 1.55 μm and grows progressively stronger. At a pump intensity of 86 kW cm^{-2} [Fig. 2b, spectrum (*7*)], the switching reaches completion, and the spectrum is

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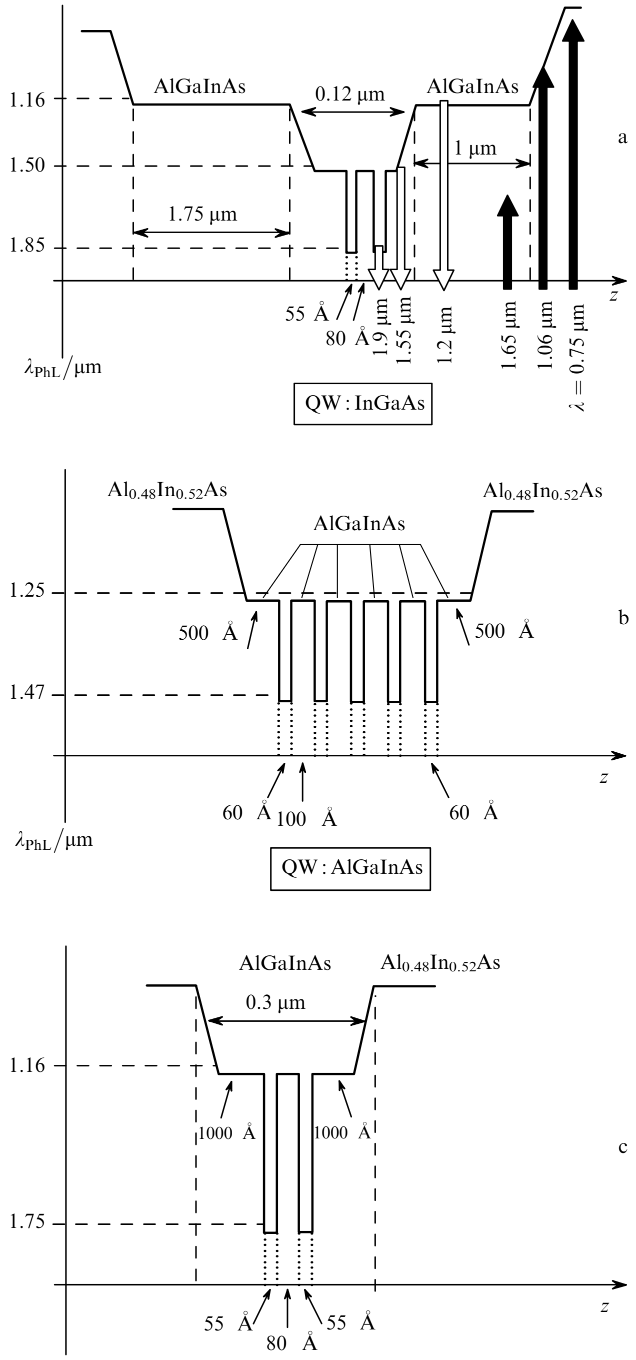

Figure 1. Band-gap profiles across heterostructures (a) 1 (the heavy arrows represent the pump photon energies, and the open arrows represent the stimulated-emission photon energies), (b) 2 and (c) 3. Plotted on the vertical axis is the peak photoluminescence (PL) wavelength of the heterostructure (at a low pump intensity).

dominated by the 1.54-μm stimulated emission, whereas the 1.9-μm signal, due to weak spontaneous emission, is essentially indiscernible. Further increasing the pump intensity gradually quenches the 1.5-μm stimulated emission and gives rise to an emission at 1.2 μm (Fig. 2c).

Thus, raising the 0.75-μm pump intensity leads to two stimulated-emission wavelength switchings in the heterostructure: from 1.9 to 1.5 and then to 1.2 μm. Similar behaviour was observed under pumping with 1.06-μm

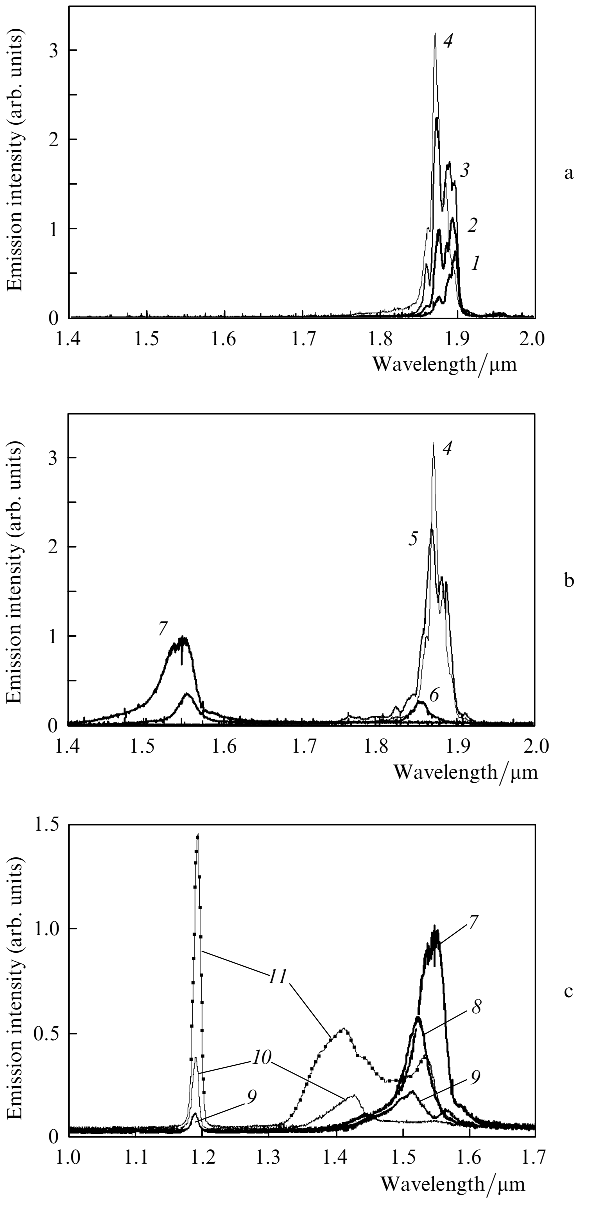

Figure 2. Emission spectra of heterostructure 1 pumped at 0.75 μm with a power density of (*1*) 1.6, (*2*) 3.0, (*3*) 5.4, (*4*) 10, (*5*) 21, (*6*) 24, (*7*) 86, (*8*) 112, (*9*) 152, (*10*) 250 and (*11*) 380 kW cm^{-2}.

Nd : YAG laser pulses. Therefore, wavelength switching is possible at different pump wavelengths; a necessary condition is that the pump photon energy exceed the corresponding band gap in the heterostructure.

In both cases, pump absorption launches carriers to energy levels that lie in the conduction band 1.2 μm above the level involved in the direct optical transition. The carriers then relax from these 'initial' levels to lower levels, emitting optical phonons. Pumping at a sufficient intensity creates population inversion for the lowest level, giving rise to stimulated emission. With increasing pump intensity, the carrier concentration rises at all the levels, and a situation may occur where the population inversion condition is fulfilled for some of the higher levels, leading to stimulated emission from these levels, accompanied by an increase in the amount of photons in the active layer and the corresponding increase in radiative transition probability. If the stimulated emission probability becomes comparable to the optical phonon emission probability, most of the photoexcited carriers relax directly to the valence band, emitting photons (rather than phonons). As a result, the population of the lower levels decreases, which quenches the stimulated emission from them.

To verify this wavelength switching mechanism, we carried out an experiment in which optical pumping was performed at $\lambda = 0.75$ μm. As would be expected, stimulated emission was observed only at 1.9 μm, with no switching up to high pump powers.

Theoretically, there is another explanation of the observed effect, related to an increase in free-carrier absorption, which is known to have a maximum at lower frequencies. A situation is in principle possible where low-lying energy levels retain population inversion, but raising the pump intensity 'turns on' strong free-carrier absorption (this possibility was pointed out by R.A. Suris). To clarify this issue, additional experiments were performed. When stimulated emission takes place, its line in the spectrum always has flat wings due to weak, broadband spontaneous emission. From the variation in its intensity, one can deduce whether the population of the transitions in a given spectral region decreases or increases. Such experiments showed that, when an increase in the pump intensity quenched stimulated emission (e.g. that at 1.9 μm), the intensity of the associated spontaneous emission (on the sides of the stimulated-emission line) also decreased. This implies that the number of particles at long-wavelength transitions decreases. If the observed quenching of stimulated emission were due to an increase in free-carrier absorption (which reduces the gain coefficient to zero), the concentration of particles and, consequently, the spontaneous emission intensity would increase with pump intensity. Therefore, the observed stimulated-emission wavelength switching is related not to an increase in free-carrier absorption but to the competition between different stimulated emissions, as described above.

The band-gap profile across heterostructure 2 is shown schematically in Fig. 1b. Its main distinction from heterostructure 1 is the substantially smaller width of the outer barrier layers. Figure 3 shows the emission spectrum of heterostructure 2 pumped with 1.06-μm Nd : YAG laser pulses. Stimulated emission (a sharp rise in the output power of the heterostructure starting at a threshold pump intensity) was observed at different pump intensities, but only around 1.53 μm, which corresponds to transitions from the quantum wells to the valence band (Fig. 1b). Near 1.28 μm, we observed weak spontaneous emission, without stimulated emission even at high pump intensities, whereas the 1.53-μm emission intensity was found to increase with pump intensity until breakdown of the sample. Thus, heterostructure 2 exhibited no stimulated-emission wavelength switching.

Similar behaviour was exhibited by heterostructure 3, whose band-gap profile is shown in Fig. 1c. Under pumping with 1.06-μm Nd : YAG laser pulses at a power density of 67 kW cm^{-2}, the spontaneous emission spectrum of this heterostructure showed three bands [Fig. 4, spectra (*1*)]. At a pump intensity of 100 kW cm^{-2} [spectra (*2*)], the spectral regions displayed in Figs 4a and 4b contained narrow stimulated emission lines. At the threshold pump power for these emissions, we observed large output power fluctuations, which exceeded by severalfold the pump power fluctuations. The stimulated emission intensity was highest for the topmost level. At the same time, in the spectral region displayed in Fig. 4c only spontaneous emission occurred, with no stimulated emission (no narrowing of

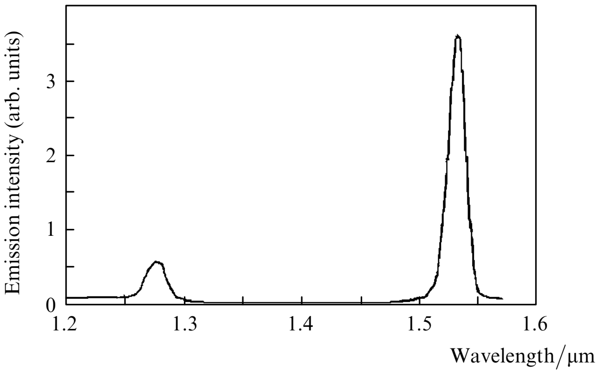

Figure 3. Emission spectrum of heterostructure 2 pumped with 1.06-μm Nd : YAG laser pulses.

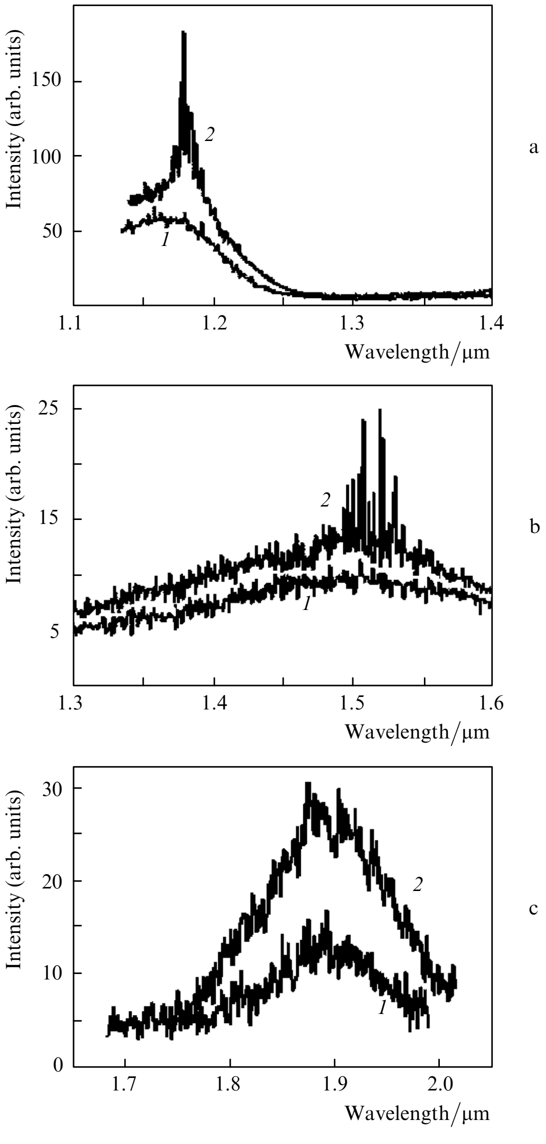

Figure 4. Emission spectra of heterostructure 3 pumped with 1.06-μm Nd : YAG laser pulses at a power density of (*1*) 67 and (*2*) 100 kW cm^{-2}; spectra (a – c) were measured with different photodetectors.

the spectrum). Thus, the behaviour of the emission spectrum in this case differs qualitatively from that for heterostructure 1.

3. Conclusions

The observed suppression of stimulated emissions in heterostructure 1 and the associated wavelength switching with increasing optical pump intensity take place only at high photoexcited carrier concentrations, when at different pump intensities there is a competition between stimulated emissions at different wavelengths, determined by the band-gap profile. This effect would be expected to occur in structures that have a variety of band gaps. The corresponding transition frequencies can be selected so that they will coincide with those in the spectrum of interest (for example, with two or three frequencies in the spectrum of a gas).

Heterostructures 2 and 3 exhibited two-frequency generation, corresponding to different regions of the heterostructure, with no stimulated-emission wavelength switching.

Injection laser diodes similar in parameters to our heterostructures were investigated by Lyutetskiy et al. [4], but they detected neither wavelength switching nor two-frequency generation. We think that the best conditions for the described wavelength switching effect are offered by optically pumped lasers, where both electrons and holes are produced in the active region on the same side of the heterostructure. In laser diodes, holes and electrons are created on the opposite sides, so the stimulated-emission wavelength switching effect of the type in question may be suppressed.

Note that in our experiments we used quantum-well heterostructures that were designed for laser diodes and were not optimised for our experimental conditions. From this point of view, stimulated-emission wavelength switching was achieved under ordinary conditions, so it appears to be a rather general result. We believe that, by optimising the composition and band-gap profile of such heterostructures, even more impressive results can be obtained. A multistep band-gap profile might ensure stimulated-emission wavelength switching in a predetermined sequence.

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