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Stimulated emission from optically pumped quantum dots

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Abstract. **Stimulated emission from optically pumped quantum dot arrays has been studied experimentally at room temperature. We have demonstrated stimulated emission on interband transitions from the ground level in a quantum well ($\lambda \approx 1.31$ μm) and from two excited states ($\lambda \approx 1.21$ and 1.12 μm). The gain coefficient of the transitions has been evaluated using exposed strips of variable length. The gain coefficients thus obtained are rather large, up to 15 – 17 cm^{-1} (at $\lambda \approx 1.31$ μm). A procedure is discussed for measuring large gain coefficients (above 10 cm^{-1}) of active media. The stimulated emission from the excited states is found to be sharply suppressed with increasing strip length.**

Keywords: *quantum dots, stimulated emission, optical pumping.*

1. Introduction

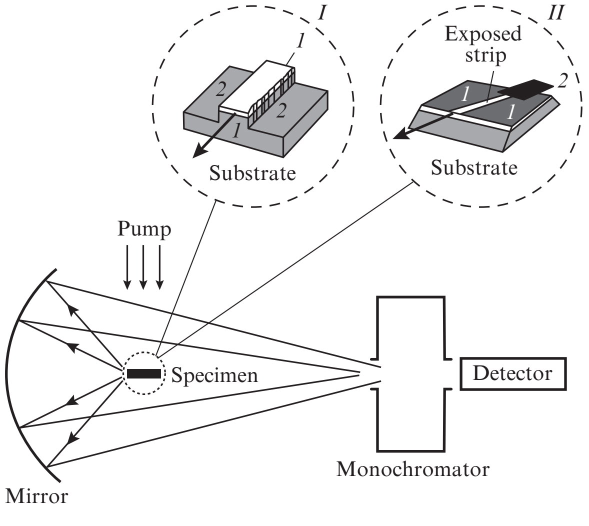
The study of stimulated emission and lasing is directed primarily at creating monochromatic light sources with a high spectral density and low divergence. At the same time, recent years have seen wide research interest in more exotic stimulated emission sources, such as frequency-tunable or frequency-switchable [1] lasers. In this paper, we report an experimental study of such sources and measurements of the gain coefficient of quantum dot (QD) arrays. The configuration we used to optically pump undoped structures makes it possible to study emission characteristics without problems related to losses in waveguides and contact regions (in contrast to electrical pumping).

2. Experimental results

2.1. Stimulated emission of a QD array

We studied undoped structures grown by molecular beam epitaxy on a GaAs substrate. The structures consisted of five rows of QDs in a 0.2-μm-thick GaAs waveguide sandwiched between a 1.5-μm-thick Al$_{0.8}$Ga$_{0.2}$As layer (grown on the substrate) and a 0.1-μm-thick Al$_{0.3}$Ga$_{0.7}$As layer (top layer). The InAs QDs were covered with an InGaAs layer in order to obtain an emission wavelength $\lambda = 1.3$ μm, corresponding to the transition from the ground electronic state of the QDs.

Emission spectra were measured using an LS-2137 electro-optically *Q*-switched, frequency-tunable Nd : YAG laser as a pump source. It generated pulses at wavelengths from 400 to 2500 nm, pulse durations from 6 to 8 ns and a pulse repetition rate of 10 Hz. The experimental setup used is shown schematically in Fig. 1. Specimens were pumped along the normal to the film surface, and the emission emerging from their end face was focused by a spherical mirror onto the entrance slit of a monochromator and measured using a photodetector. In our experiments, we investigated stimulated emission from narrow strips produced by sawing (with rough lateral faces) (Fig. 1, inset *I*) and narrow exposed strips defined by opaque metallic screens (Fig. 1, inset *II*).



Schematic of the experimental setup. Inset *I* schematically shows a specimen prepared by sawing along faces (*2*) and cleaving along faces (*1*). Inset *II* shows a specimen with a narrow exposed strip defined by metallic screens (*1*). Its length can be varied by translating screen (*2*). The arrows in the insets indicate the output beam direction.

First, we used large (~ 10 mm) specimens in order to demonstrate stimulated emission. Figure 2 shows the stimulated emission spectrum of QDs optically pumped at $\lambda = 485$ nm and an intensity $P \approx 3 \times 10^4$ W cm^{-2}. The spectrum was obtained using a specimen ~ 5×10 mm in dimensions, with cleaved faces, without averaging, at the maximum width of the monochromator slits (4 mm). In Fig. 2, three lines are well seen, corresponding to transitions from the three lowest levels

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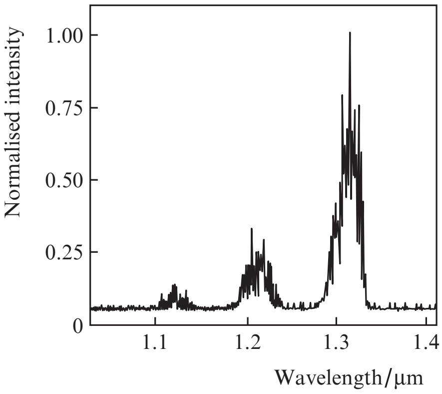

Figure 1. Stimulated emission spectrum of QDs optically pumped at $\lambda = 485$ nm and a pump pulse intensity $P \approx 3\times10^4$ W cm^{-2}.

(ground level and two excited states) of the electrons localised in the QDs. Because the monochromator slits were fully opened in order to obtain the strongest signal, the width of the spectral lines was determined by the resolution of the monochromator.

Note that each stimulated emission line has its own threshold pump power density. Thus, the main emission line ($\lambda \approx 1.31$ μm) has a threshold $P_{\rm th} = (3-5)\times10^2$ W cm^{-2}, and the second excited state ($\lambda \approx 1.12$ μm) has $P_{\rm th} \approx 10^4$ W cm^{-2}. Because of the pump power instability, stimulated emission fluctuations near the threshold are very large and may reach 100%. The threshold behaviour is an indication of stimulated emission. With increasing pump power, stimulated emission power fluctuations decrease.

To produce directional light sources, we fabricated cavities in the form of strips 50–100 μm in width and several millimetres in length by cutting heterostructures. Figure 3a shows the stimulated emission spectrum of such a specimen. Cavities produced by sawing have rough lateral surfaces, with roughness values within 10 μm. Such roughness of the lateral surface ensures high Q for the fundamental cavity mode and low Q for the other modes. The cavity end faces were made by cleaving. The cavities thus produced ensure high directionality of the laser radiation. Using such cavities and pulsed optical pumping at 1.06 μm, we obtained lasing at 1.31 μm and measured the radiation pattern of the specimen. Its angular width was found to be several degrees in the horizontal plane and tens of degrees in the vertical plane. The radiation pattern in the horizontal plane is presented in Fig. 3b. It was constructed for the stimulated emission from one end (facet) (which corresponds to zero angle in the figure). The angular dependence of the stimulated emission is represented in polar coordinates, with the detector signal represented by the radius. The stimulated emission intensity was measured at a distance much greater than the emission wavelength and specimen size.

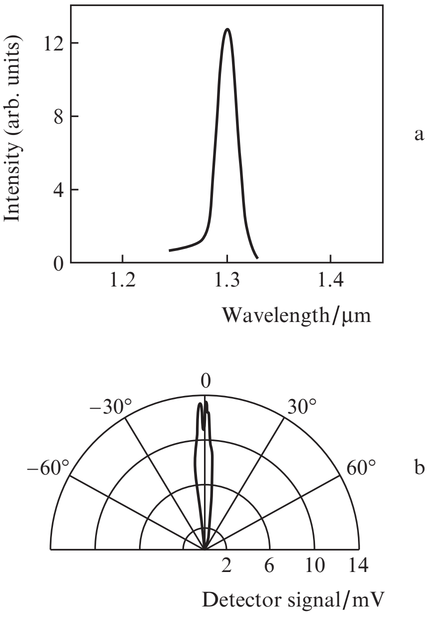

Figure 2. (a) Stimulated emission spectrum of a specimen with a mechanically fabricated cavity and (b) its radiation pattern in the horizontal plane.

2.2. Gain measurement

The gain coefficient was determined by varying the length of narrow exposed strips. The specimens had the geometry shown in inset *II* of Fig. 1. A similar approach was described, e.g., by Negro et al. [2]. It should be kept in mind in such measurements that, in our experiments, such systems had rather large gain coefficients (up to 10 cm^{-1}). It should also be taken into account that, during optical pumping of a narrow strip defined on the film surface by opaque screens, the local temperature may rise considerably (to almost 100 °C). This leads to a slight reduction in the band gap of the exposed material (during an optical pump pulse) and, hence, to an increase in stimulated emission wavelength relative to the interband transition wavelength in the unexposed region. Because of this, the unexposed regions of the specimen around the strip are transparent (nonabsorbing) to the emerging stimulated emission, which is thus free to propagate throughout the specimen and to reflect from its faces.

It is for this reason that the gain coefficient is difficult to determine in such systems. In the case of large gain coefficients, an important point in gain measurements is to avoid reflection from all boundaries, that is, to ensure 'purely' stimulated emission in the medium. It is, however, impossible to avoid all reflections, so the reflected signal should be minimised, which can be achieved via diffuse scattering from the specimen surface. Given these requirements, the following experimental procedure was employed to determine the gain coefficient. We used rather large specimens (~ 10 mm). To avoid specular reflection from the specimen faces, these were made rough and bevelled, with a decrease in film thickness at the edge (Fig. 1, inset *II*). On the specimen surface, opaque screens defined a narrow exposed strip 100–300 μm in width and 0.5 to 7–10 mm in length. Because of the specimen heating, the stimulated emission readily emerged from the specimen even when the edge of the strip was not at the end face. To avoid multiple reflection of the stimulated emission, the strip made an angle with the normal to the specimen surface.

Figure 4 shows the emission spectra obtained as described above for a QD structure at different strip lengths. The in-plane specimen dimensions were ~ 10 mm, and the strip width (defined by opaque screens) was 200 μm. All the specimen faces were rough, with both the film and substrate bevelled at about 45°. The observed stimulated emission line was rather broad, presumably because of inhomogeneities in the specimen. This was verified experimentally as follows: we took samples from different parts of the structure and measured their stim-

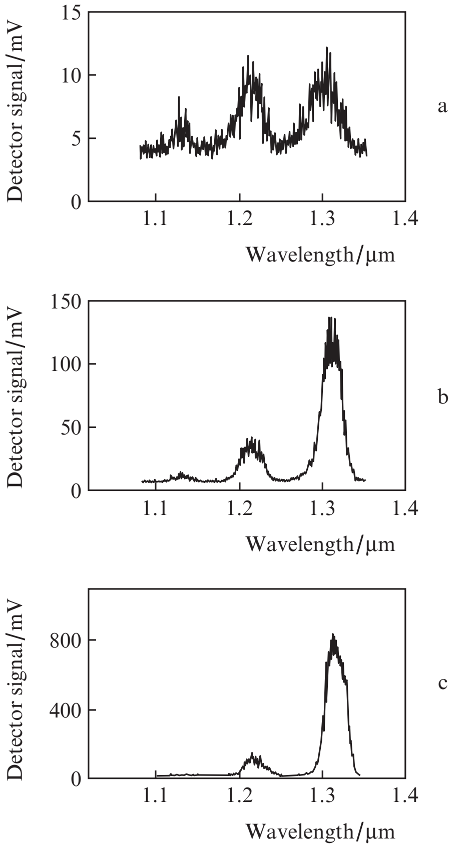

Figure 3. Emission spectra of a specimen at a strip length l = (a) 3.5, (b) 4.5 and (c) 8 mm; spectral resolution of the monochromator, 19 nm.

ulated emission spectra. The stimulated emission frequency was found to vary from sample to sample by 0.5%–2%.

Figure 5 plots the maximum emission intensity against strip length, l, for the three emission lines. The gain coefficient reaches a maximum at l values where stimulated emission is far from saturation (far from the region where the emission intensity increases linearly with l), that is, in the region where the intensity rises exponentially with strip length. Estimates under the assumption that the stimulated emission intensity rises exponentially and that there is no reflection from the specimen faces indicate that the maximum gain coefficient for the emission line at $\lambda \approx 1.31$ µm (Fig. 5a) reaches 26 cm^{-1} at a strip length $l = 3.5$–4 mm and room temperature. For the lines at $\lambda \approx 1.21$ and 1.12 µm (Figs. 5b, 5c), the maximum gain coefficients are 19 and 7 cm^{-1}, respectively.

The assumption that there is no reflection from the specimen faces is in general incorrect. In experiments, there is always such reflection. The reflected signal will be minimal in the case of diffuse scattering from the specimen surface. We attempted to realise this situation. Taking into account diffuse reflection reduces the gain coefficient from 26 to 15–17 cm^{-1}. This value of the gain coefficient was confirmed in the following experiment: We took several samples of different lengths. Stimulated emission was obtained at sample lengths above 0.8 mm and not at smaller sample lengths. This also allows the gain coefficient to be estimated at 15 cm^{-1}.

When evaluating the exponential dependence of the gain coefficient on strip length, one should take into account that different waves pass different paths in the strip. Therefore, strictly speaking, integral relations that take this into account should be used to accurately determine the gain coefficient.

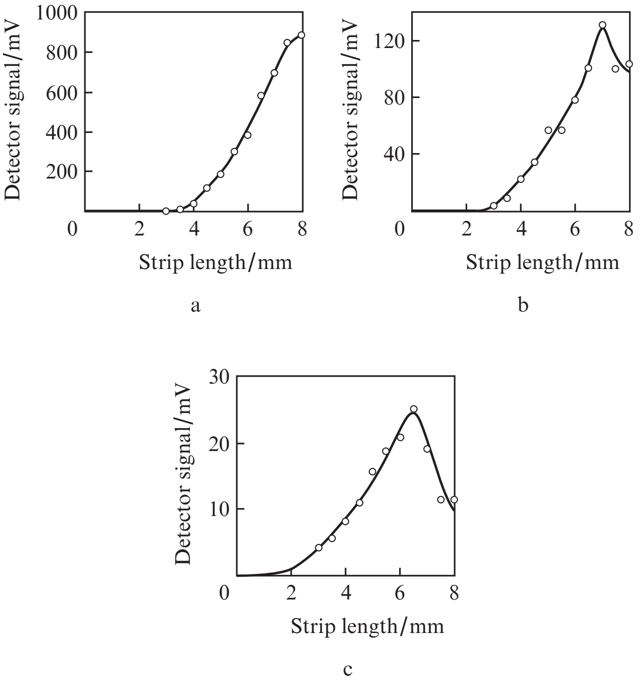

Figure 4. Maximum signal as a function of strip length, λ, for the emission lines at (a) 1.31, (b) 1.21 and (c) 1.12 µm.

At the same time, to estimate the maximum gain coefficient of an active medium, it is sufficient to consider the region where the signal rises exponentially and the major contribution to the emission intensity comes from waves that pass the entire strip length. This can be illustrated by the example below.

Consider the data in Fig. 5a. At strip lengths $l < 3.5$ mm, the signal is very weak. As l increases from 3.5 to 4 mm, the signal rises exponentially. In this range of strip lengths, the gain coefficient is almost constant. At higher l values, emission saturation effects come into play and the gain coefficient drops rather sharply. In this range, one should take into account that there are waves passing exposed regions of different lengths. In this study, we restricted ourselves to estimating the maximum possible gain coefficient.

Our experiments showed sharp suppression of stimulated emission from the excited states with increasing strip length at a constant pump intensity. It follows from the data in Fig. 5 that the stimulated emissions from the three levels in question are not independent. Strong signals at $\lambda \approx 1.31$ µm are accompanied by ‘quenching’ of the other two emission lines, due to interband transitions from excited states of the QDs: first, quenching of the line related to transitions from the third level and then, from the second level. The quenching of the emission from upper electronic levels of QDs is caused most likely by a reduction in hole population in response to the saturation of the transition from the first electronic level. An important role may, in principle, be played by the depopulation of the ground level by the stimulated emission and electron transitions from upper levels to the ground state. The sharp quenching with increasing exposed region length may imply that an additional electron relaxation process from the excited and ground levels of the QDs comes into play. Note also that the continuing rise in the intensity of the stimulated emission from the ground state with increasing exposed region length indicates that the contribution of losses in the waveguide to lasing is still small.

3. Conclusions

Stimulated emission from optically pumped semiconductor QD arrays has been studied experimentally at room temperature. We have demonstrated stimulated emission on interband transitions from the ground level of the QDs ($\lambda \approx 1.31$ μm) and from two excited states ($\lambda \approx 1.21$ and 1.12 μm). The gain coefficient of the transitions has been measured using exposed strips of variable length. The gain coefficient obtained for the ground level is rather large: 15–17 cm^{-1}. A procedure is proposed for measuring large gain coefficients (above 10 cm^{-1}) of active media.

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References

1. Andronov A.A., Nozdrin Yu.N., Okomel'kov A.V., Yablonskii A.N., Marmalyuk A.A., Ryaboshtan Yu.L. *Kvantovaya Elektron.*, **39** (3), 247 (2009) [*Quantum Electron.*, **39** (3), 247 (2009)].
2. Negro L.D., Bettotti P., Cazzanelli M., Pacifici D., Pavesi L. *Opt. Commun.*, **229**, 337 (2004).