AN ACOUSTIC WAVE EFFECT ON THE HETEROSTRUCTURE LASER GENERATION

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Abstract

A new principle of the diode laser frequency tuning has been developed and implemented. According to this, the laser frequency is tuned by alternating strain in the active region of an InGaAsP/InP laser heterostructure emitting in a wavelength range of 1.3–1.8 μm. The strain is induced through the excitation of bulk ultrasonic waves in these heterostructures by means of a specially developed technique. Data on the influence of the alternating strain, induced by the bulk ultrasonic waves, on the spectral characteristics of laser radiation are presented. Estimates based on these data show that the frequency tuning range amounts to ΔF=110 GHz for an acoustic wave with the frequency f = 6.5 MHz and a power of about 1 W.

Introduction

Tunable diode lasers can be the key devices for not only sensitive at high resolution diode laser spectroscopy, but for many other applications. Recently a simple and reliable method is offered by the wavelength tuning through variation of the pumping current in multistage lasers [1]. Frequency tuning in diode lasers for high-resolution laser spectrometers is usually achieved by using thermal effects [2] or by varying the working current [3]. However, any of known methods fails periodic tuning of frequency, that is they does not result in controlled frequency modulation of radiation,

On the other hand, it is known, that the elastic deformation can essentially change optical properties of a material. Due to the photoelastic effect, it results in change of permittivity. In case of elastic waves there is a spatial modulation of permittivity.

Traditionally known acoustooptic interaction results in diffraction of light on an acoustic wave. Such interaction is realized in the case, when the aperture **a** of optical radiation is essential more than length $\mathbf{L_s}$ of a sound wave **a >> $\mathbf{L_s}$.** Therefore light takes a sound wave, as a running diffraction lattice. The Doppler effect, caused by the conservation laws of energy and pulse at such interaction, results in shift of light frequency on a sound frequency. This shift is constant value about hundreds MHz

For the first time we offer to investigate a **untraditional** situation, when the sound wave propagates across a thin semiconductor layer representing an optical resonator, that is **a << $\mathbf{L_s}$**. Light propagating along a layer, should take the ultrasonic strain, as some parameter varied in time. In a dielectric layer it should be permittivity varied in time with frequency of a sound. In a semiconductor the alternating elastic strain, due to deformation potential, can results in time modulation of the band gap. For what of objects such effects can be of interest? First of all they are nano-dimention laser heterostructures. One can expect, that the band gap modulation of the active region of the structure in the presence of the sound can result in change of the generation conditions. So one can expect change of radiation spectral characteristic, in particular, radiation frequencies: the sound intensity should determine the amplitude of frequency tuning, period of a sound wave - period frequency modulations of laser radiation. Change of the refraction coefficient of the laser resonator at the presence of the sound should also effect the spectral characteristics of the radiation.

This paper presents the first results of our investigation of the straining action of bulk ultrasonic waves on the InGaAsP/InP laser heterostructures and the related changes in the radiation characteristics.

Methods

We have studied InGaAsP/InP laser heterostructures of separate confinement with two strained quantum wells (Fig. 1). The heterostructures were grown by metalorganic vapor phase epitaxy (MOVPE) on

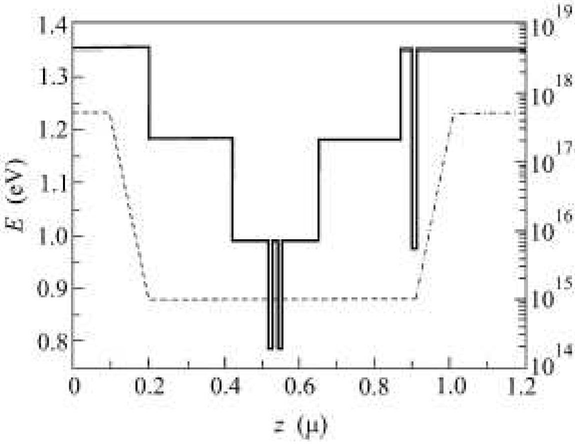


Fig. 1. A schematic energy band diagram of InGaAsP/InP laser heterostructures of separate confinement (KR-1168 type) emitting at λ = 1.58μ m (solid curve). Dash and dot – dash curves show the calculated doping profile for silicon(donor) and zinc (acceptor), respectively (z is the structure growth coordinate).

n-InP substrates. Neither the active region nor the waveguide layers were intentionally doped. The doping profile of the wide-bandgap emitters and the contact layer is presented in Fig. 1. The MOVPE-grown heterostructures were coated with insulating SiO_2 layers, in which 100 µm-wide mesastrips were formed by photolithography. Then, SiO_2 mirrors (with a reflection coefficient of $R > 0.95$) and antireflecting layers ($R < 0.04$) were deposited onto the resonator edges. Finally, the laser diodes were fixed on copper heat exchangers with the aid of indium-based solder

The experiments were performed with the laser heterostructures operating at room temperature in the pulsed regime with a pulse duration up to 3µs at a wave-length of 1.48µm. The threshold current was ~35 mA; the working current was varied from this threshold up to a threefold value. The radiation spectrum half-width was 0.25–0.4 nm.

The investigation was carried out using a specially designed experimental setup schematically depicted in Fig. 2. A collimated and focused beam of the laser radiation was detected by fast-response photodiodes with different photocurrent buildup times τ_d (5 or 60 ns). using one of the two schemes. In the first case, the focused radiation beam was directly detected by a photodiode. In the second case, the collimated beam was passed via a Fabry–Perot etalon (FPE) and then focused and detected by a photodiode in the focal plane. This scheme employed an optical etalon with deposited metal mirrors and an 0.6 – 1 mm-wide air gap. According to calculations, a dynamic dispersion range of this etalon at a wavelength of 1.48 µm was 18.25 Å. Measurements using the FPE scheme allow changes in the spectral characteristics of laser radiation to be analyzed. The output signal of a photodiode was amplified by an amplifier with a bandwidth of up to 5 MHz and displayed on a wide-band (100 MHz) oscilloscope. The signal modulated with a frequency of the ultrasound was measured using an amplifier with a bandwidth of 400 MHz.

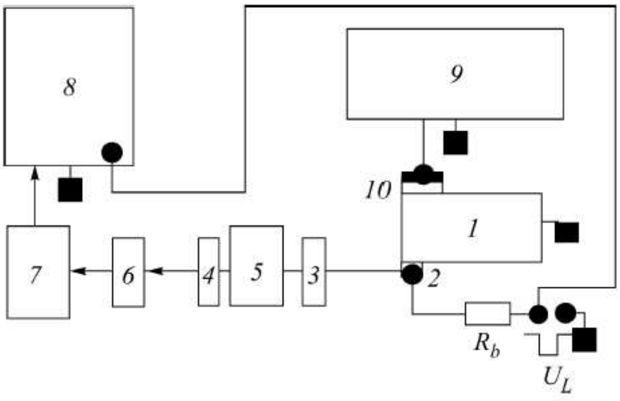


Fig. 2. A schematic diagram of the experimental setup: (*1*) metal substrate; (*2*) laser heterostructure; (*3*,*4*) focusing lenses; (*5*) Fabry–Perot etalon; (*6*) photodiode; (*7*) amplifier; (*8*) oscilloscope; (*9*) microwave oscillator; (*10*) piezoelectric ceramic transducer.

In order to study the effect of elastic strain on the laser generation regime and the radiation spectral characteristics, we have developed a method of exciting of bulk acoustic waves in laser heterostructures in a frequency range from 6.5 to 200 MHz. The bulk longitudinal ultrasonic waves with an intensity of up to 100 W/cm^2 were excited using piezoelectric ceramic resonator plates in a frequency interval of 6.5–10 MHz (Fig. 2).

Results and Discussions

Investigation of the laser radiation intensity as a function of the working current gave the following results (Fig. 3). Direct detection of the radiation (curve*1*) showed a normal threshold character of the process, with a slower monotonic increase in the intensity at a current above the threshold (the working current was varied from this threshold up to a threefold value).

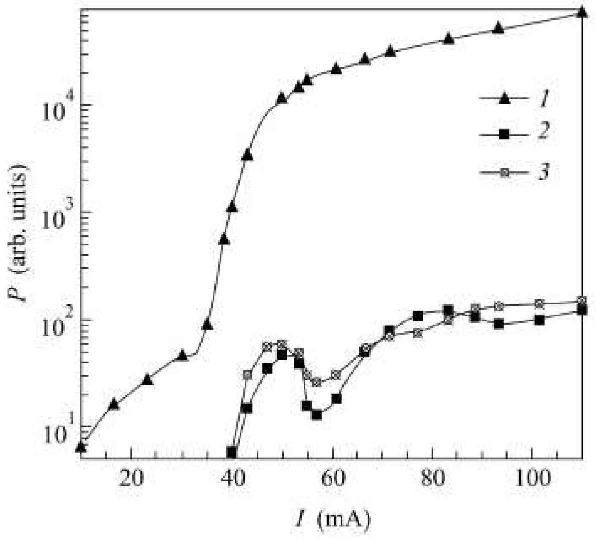


Fig. 3. Plots of the photodiode response signal intensity versus working current of a laser diode: (*1*) direct detection;(*2*) dispersion curve at the FPE output; (*3*) FPE output signal in the presence of an ultrasonic wave ($f = 6.5$ MHz).

Measurements using the FPE scheme revealed oscillating variation of the signal level with the working current (curve *2*). Since the FPE transmission depends on the signal frequency, this signal behavior is evidence that variation of the working current is accompanied by change in the laser radiation frequency. Indeed, independent spectroscopic measurements of the laser radiation wavelength in the regime of variable working current revealed a shift of the laser emission line. Thus, the position of the laser frequency on the dispersion curve of the FPE transmission can be controlled by varying the working current.

The effect of the acoustic-wave-induced straining was studied in two experimental configurations. The first configuration, employing a photodiode detector with a relatively slow response (τ_d = 60 ns) and an amplifier with a relatively narrow bandwidth (~5 MHz), ensured increased dynamic range and was used for "rough" measurements. The second configuration with a fast-response photodiode (τ_d = 5 ns) and a wide-band amplifier (~400 MHz) revealed a frequency-modulated component related to the ultrasound-induced straining.

In the first configuration, ultrasonic excitation of the laser heterostructure led to the following effects. In the regime of minimum transmission, the ultrasonic wave caused an increase in the FPE transmission, whereby the photodiode response increased by a factor of 1.5–2 (Fig. 3, curve *3*). At a maximum of the dispersion curve, the ultrasound produced a reverse effect and decreased the FPE transmission. Both these effects possessed an integral character: the signal increment was virtually constant during the laser pulse (τ_L = 2.5–3 μs) and the acoustic pulse.

Let us qualitatively analyze the obtained results. An elastic wave is essentially the alternating strain. If the strains with opposite signs lead to the corresponding shifts of the light frequency ($\pm \Delta F$) or changes in the emission direction, introduction of the acoustic wave in the regime of minimum FPE transmission would drive the system away from the minimum and, hence, increase the transmission. By the same token, the system occurring at the maximum of the dispersion curve will exhibit the reverse effect, whereby a change in the emission frequency or direction under the action of the acoustic wave will cause a decrease in the FPE transmission—in agreement with what was observed in experiment.

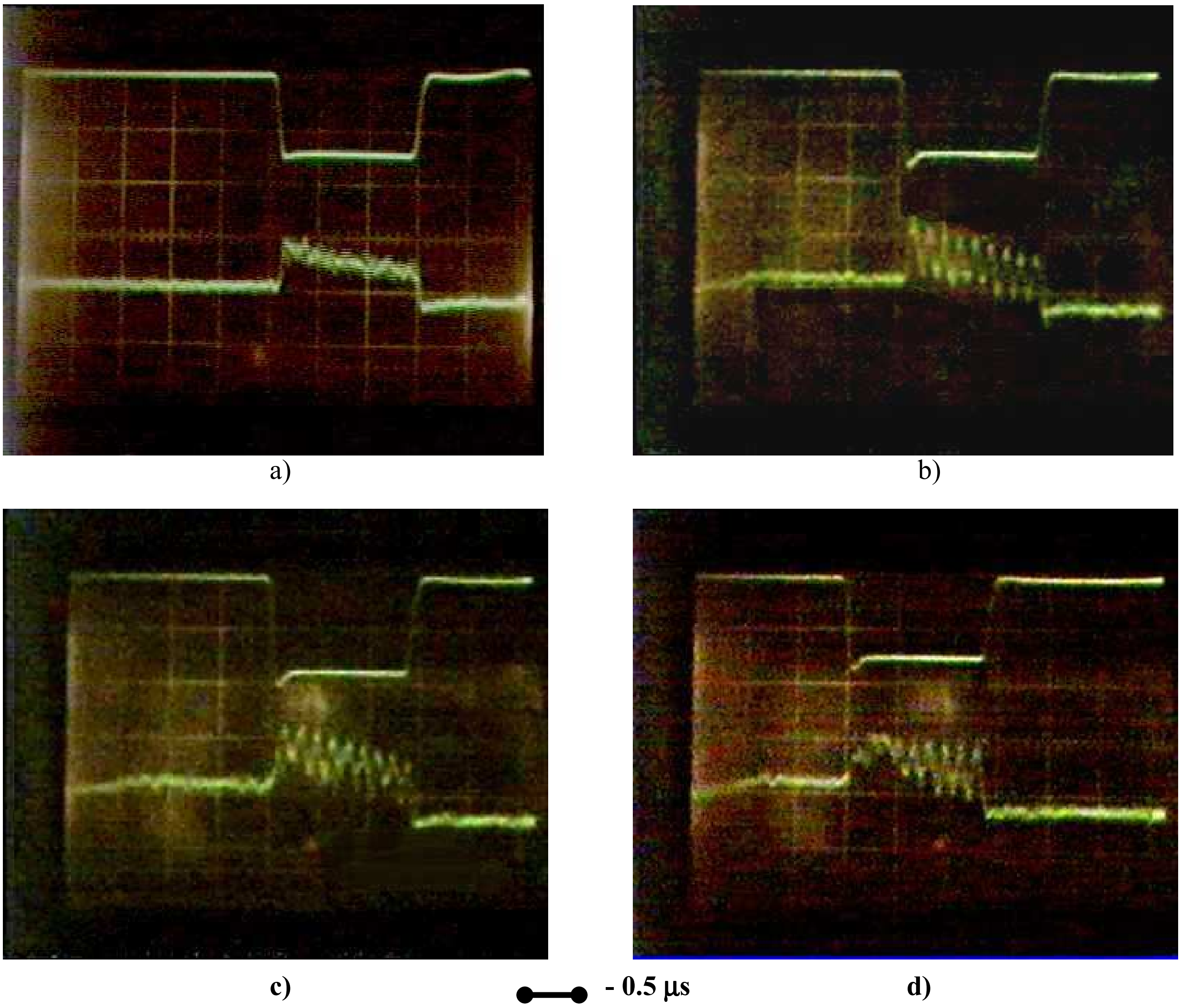
Thus, the observed effects may result from changes in both frequency and direction of the heterolaser emission. However, we have established that the latter factor is insignificant. Taking into account that the acoustic wavelength in our experiments was about 400μm and the optical resonator aperture in the wave propagation direction was about 1μm, it can be readily shown that the laser beam deviations caused by the refractive index gradient do not exceed $20''$, which is beyond the sensitivity limits of our experimental setup. This conclusion is experimentally confirmed by the fact that the position of the signal maximum in the focal plane of the lens was the same for the acoustic generator switched on and off. As for the first factor (frequency shift), the possible mechanisms can be related to changes in both electron parameters of the heterostructure and the optical properties of the laser resonator. Determination of the absolute and relative magnitudes of these contributions requires further experimental and theoretical investigations.

Using the dispersion curve of the etalon transmission (Fig. 3, curve *2*) and the experimental data on variations of the laser radiation intensity (Fig. 3, curve*3*) in response to the acoustic wave introduction (f = 6.5 MHz), we have estimated a change in the laser wavelength $\Delta\lambda$ under the action of bulk ultrasonic waves. For an acoustic power of ~1 W (at an intensity of ~100 W/cm^2), $\Delta\lambda/2$ = 3.5–4 Å per half period (or 7 - 8 Å per period), which corresponds to a frequency shift of ΔF = 110 GHz.

As was noted above, the optical signal increment was virtually constant during the laser pulse and the acoustic pulse, although we might expect the FPE transmission to be modulated by the ultrasound frequency. We believe that the main possible factors which could explain the observed behavior are (i) unsatisfactory frequency characteristics of the detection channel and (ii) a too large radiative recombination time (τ_L) of the laser heterostructure as compared to the acoustic wave period T_S. However, the latter reason is invalid since both published data and our measurements show that $\tau_L << T_S$.

In order to visualize the anticipated modulation of the laser radiation frequency by the ultrasonic wave, we have performed fine measurements in the aforementioned configuration with reduced dynamic range and improved frequency characteristics of the detection channel. The results of these measurements are presented by oscillograms in Fig. 4. The upper sweep represents the working current pulse. The lower sweep shows laser radiation pulses measured for a working current amplitude slightly above the threshold ($I = 1.4 I_{th}$). In the absence of the acoustic wave, the radiation pulse has a nearly rectangular shape (Fig. 4a) to within a pulse top ringing caused by thermal fluctuations of the FPE tuning. Switching on the ultrasound (Fig. 4b) leads to an almost 100% modulation of the laser pulse amplitude with a frequency equal to that of the acoustic wave. Obviously, the observed output signal modulation reflects changes in the FPE transmission in response to the frequency modulation of the transmitted laser radiation. The ultrasound pulse coincides with the working current pulse. On decreasing the current pulse delay, which leads to a partial overlap of these pulses, we observe the corresponding partial modulation of the laser pulse (Fig. 4d).

As was noted above, an increase in the working current is accompanied by a growth of the laser line-width. In our opinion, this circumstance, together with thermal fluctuations of the FPE tuning, accounts for a decrease in the stability of modulation of the


a)

b)

c)

d)

Fig. 4. Oscillograms showing the working current pulse (top, 33 mA/div) and the laser radiation pulses (bottom) measured with the acoustic wave (a) switched off and (b–d) switched on, for the ultrasound frequency *f* = 6.5 MHz.

FPE transmission observed upon increase in the working current (Fig. 4c). This implies that laser structures with a narrower line-width should be used in order to observe the modulation effects in a wider range of working currents.

To summarize, we have studied changes in the laser radiation characteristics under the action of the alternating strain induced by the longitudinal ultrasonic waves with an intensity of up to 100 W/cm^2

It is unambiguously established that an ultrasonic wave introduced into a laser heterostructure produces modulation of the laser frequency with a period equal to that of the acoustic wave. Estimates based on the experimental data show that the amplitude value of frequency modulation is about 110 GHz.

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