TITLE: Nonlinear Generation of Mid-Infrared Radiation in Quantum Well Laser

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Nonlinear generation of mid-infrared radiation in quantum well laser

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Abstract. A possibility of mid-infrared radiation generation due to lattice nonlinearity in a quantum well laser based on InGaP/GaAs/InGaAs heterostructure is discussed. It is shown that this mechanism can provide radiation power of about 10 mW in the 10 μm wavelength region in a laser which generates two 10 W modes in the 1 μm wavelength range.

Introduction

A semiconductor laser based on GaAs is a promising device in terms of nonlinear optical effects. Indeed, there is an extremely high light intensity inside the laser. Besides, the second order optical nonlinear coefficient of GaAs is six times larger than that of the popular nonlinear crystal $LiNbO_3$. This nonlinearity is responsible for the frequently observed weak green light emission near cleavages in lasers generating 1 μm radiation which is the second harmonic generation. To date the second harmonic generation has been observed in the vertical cavity lasers [1, 2], too. A possibility of the difference mode generation in a quantum well laser emitting two short wavelength modes was discussed in [3]. However, the authors of [3] suggested using the electron nonlinearity of a quantum well containing three electron levels. Probably, this generation is not effective due to the smallness of mode overlapping in the nonlinear region and due to the difficulty in providing the phase matching condition.

In this work we discuss a possibility of the difference mode generation due to the lattice nonlinearity of GaAs in a semiconductor quantum well laser based on InGaP/GaAs/$In_xGa_{1-x}As$ heterostructure, which simultaneously generates two modes in the 1 μm wavelength range. We have suggested a special laser construction able to generate these two modes and to satisfy the phase matching condition which is necessary for effective generation of the difference mode. It has been shown that, if the phase matching condition is satisfied, the difference mode power can be of the order of 10 mW for a 10 μm wavelength region in a laser generating two short-wavelength modes with power 10 W.

1. Laser design

Consider the difference mode generation in a InGaP/GaAs/$In_xGa_{1-x}As$ quantum well laser. In ordinary lasers the waveguide consists of three layers. The central GaAs layer containing one or more quantum wells has a larger refractive index than the neighboring InGaP layers. As a rule, quantum wells generating radiation are situated near the GaAs layer centre. Due to this arrangement and the selection rules for radiative electron transition this laser generates the fundamental TE mode. The phase velocity of this mode is close to the light velocity in GaAs. Such a laser construction is not suitable for difference mode generation, since the dispersion of the refractive index in GaAs prevents phase matching. Indeed, the phase velocity of the difference mode in this case is greater than the phase velocity of the polarization wave corresponding to the difference frequency ($\omega = \omega_1 - \omega_2$) which appears due to nonlinearity.

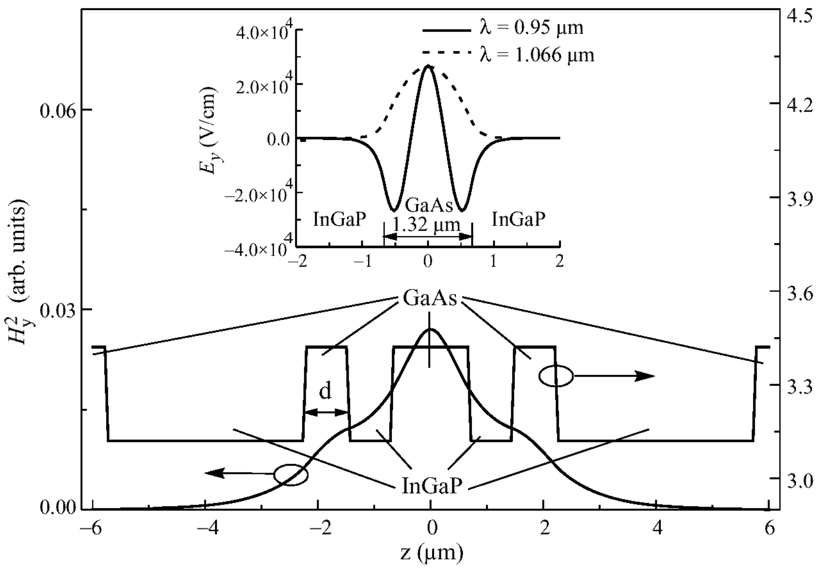

Fig. 1. Dependencies of the real part of refractive index and the square of magnetic field on coordinate for the difference mode. The widths of the lateral GaAs layers equal 0.81 μm and correspond to the power peak in Fig. 2. The value of the imaginary part of refractive index equals 10^{-3}. The dependencies of the electric field on coordinate for two high-frequency modes are shown in the insert. The powers of both high-frequency modes equal 10 W.

To satisfy the phase matching condition, we suggest using the second order mode for the highest frequency (ω_1) generation and the fundamental mode of the waveguide for other high frequency (ω_2) generation. The excited mode phase velocity is greater than the fundamental mode one, if the mode frequencies are equal. Using this peculiarity it is possible to compensate the dispersion of the refractive index and to satisfy the phase matching condition. Besides, in this case it is possible to avoid high absorption of mode with frequency ω_1 in the quantum wells generating mode ω_2, if the latter are situated in the places where the second order mode amplitude is near zero. The electric field distributions across the waveguide for the fundamental mode ($\lambda = 1.067$ μm) and the second order mode($\lambda = 0.95$ μm) are shown in the insert to Fig. 1.

How to excite simultaneously the second order mode for frequency ω_1 and the fundamental mode for frequency ω_2? To this effect we suggest that quantum wells generating frequencies ω_1 and ω_2 should be placed in the centre of the middle GaAs layer and at zero point of the second order mode, respectively. In this case for frequency ω_1 the second order mode has the smallest losses and, therefore, just this mode will be excited. The fundamental and the first order modes for this frequency have substantial losses due to absorption in the quantum wells generating frequency ω_2. For the frequency ω_2 the generation of the fundamental mode is preferable since this mode has the smallest losses and the greatest optical restriction coefficient.

The proposed laser waveguide construction is shown in Fig. 1. Additional lateral GaAs

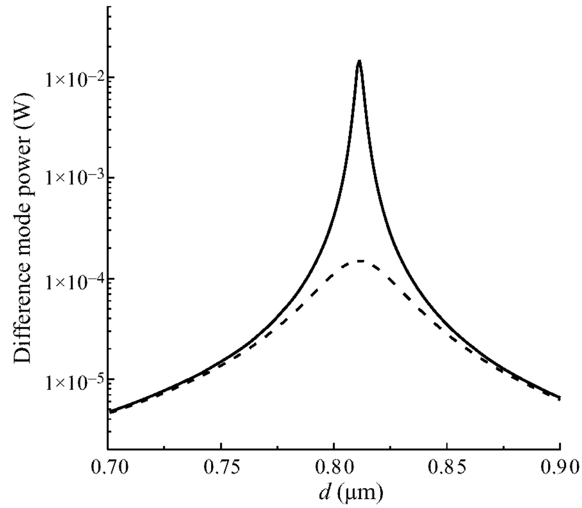

Fig. 2. Calculated dependency of the difference mode power on the width of the lateral GaAs layers. Imaginary part of refractive index equals 10^{-4} (solid line) and 10^{-3} (dash line). Wavelength of the difference mode is 8.66 μm and the ones for high-frequency modes are 0.95 and 1.067 μm. Calculations were carried out for the high-frequency mode powers 10 W and the waveguide width of 100 μm.

layers are necessary to provide low leakage losses of the difference mode. The width of these layers d we will consider as a parameter to satisfy the phase matching condition. Further we will assume that both GaAs lateral layers are of equal width d.

We also assume that a laser structure is grown on the (001) plane and the mirrors are the facets (110) or $(1\bar{1}0)$. In zinc blend-type crystals the optical second-order nonlinear tensor has equal nonzero elements only when three indexes are different $\varepsilon^{(2)}_{xyz}$. The axes x, y, z are directed along [100], [010] and [001], respectively. The electric field vectors of the high frequency modes have nonzero x- and y-components. Therefore, the electrical induction vector for the difference frequency is directed along z and the difference mode is a TM mode. The calculated dependence of the magnetic field squared on the coordinate for the excited TM difference mode is shown in Fig. 1. It is clear from the figure that the fundamental difference mode is excited.

2. Difference mode power

The calculated dependencies of the difference mode power on the width of lateral GaAs layers are shown in Fig. 2. We assume the powers of both short wavelength modes equal to 10 W and the waveguide width equal to 100 μm. The solid line corresponds to the free carrier concentration 10^{17} cm^{-3}. In this case we set the imaginary part of the refractive index for the difference mode ($\lambda = 8.66$ μm) to be $n' = 10^{-4}$ [4]. The real part of the refractive index equals 3.42 in GaAs [4] and 3.12 in InGaP. The dashed line corresponds to free carrier concentration 10^{18} cm^{-3}, in this case we set $n' = 10^{-3}$ [4]. From Fig. 2 it is clear that there are peaks of power when $d = 0.81$ μm. These peaks correspond to the phase matching. With an increase in losses the peak decreases and grows in width. For the considered parameters the maximal power of the difference mode is of order 10 mW for $n' = 10^{-4}$ and 100 μW for $n' = 10^{-3}$. To ensure low leakage losses the widths of the external InGaP layers should be more than 5 μm and 3.5 μm in the first and the second cases, respectively.

Thus the proposed laser is able to generate power of order of ten mW in a 10 μm wavelength range. Note that to decrease the threshold current and improve efficiency it is possible to increase the reflection of mirrors for the short wavelength modes by using of multi-layer dielectric coatings.

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