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Intracavity terahertz difference-frequency generation in an InGaAs-quantum-well two-frequency InGaAsP/InP laser

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***Abstract*. The scheme of a semiconductor quantum-well laser is proposed for the simultaneous generation of TE_0 and TM_0 modes with different frequencies in the near-IR region. The possibility of efficient terahertz difference-frequency generation by this laser is considered. It is shown that for the 100-μm-wide active region of the laser and for the 1-W near-IR modes, the laser power at the difference frequency in the 1 – 8-THz region can achieve $\sim$ 1 μW at room temperature.**

Keywords: *generation, nonlinearity, difference frequency, polarisation, semiconductor laser, terahertz frequency range.*

Terahertz radiation can be produced by generating the difference frequency $\omega = \omega_1 - \omega_2$ during the nonlinear-optical conversion of two fields at near-IR frequencies ω_1, ω_2 [1] due to the quadratic nonlinearity of the crystal lattice of A_3B_5 semiconductors [2]. Because the wave intensities in the cavities of semiconductor lasers are large, it is reasonable to perform the difference-frequency generation directly in them [3]. In this case, it is necessary to solve two problems: to design a semiconductor laser generating simultaneously two frequencies and to fulfil the phase-matching condition upon the difference-frequency generation. A two-chip laser can be used to generate simultaneously two frequencies [4]. However, this laser is more difficult to fabricate than a one-chip laser, and it does not allow frequencies to be generated so close that the laser amplification bands are overlapped. The authors of [5] managed to realise stable generation of two frequencies in a one-chip laser at the liquid nitrogen temperature for TE_0 and TE_1 modes when the quantum well (QW) generating the long-wavelength radiation was located in the TE_1-mode node. This QW position is necessary to avoid absorption of short-wavelength radiation in it.

In this paper, we propose a new scheme for generating simultaneously two frequencies in a semiconductor laser. To avoid absorption of the shortest-wavelength radiation in the QW generating the long-wavelength radiation, we propose to use modes with different polarisations – TE_0 and TM_0 modes. According to the selection rules [6], the mode polarisation is determined by the type of the upper hole subband in the QWs generating this mode. Thus, the QW with the upper subband of heavy holes generates a TE mode, and the QW with the upper subband of light holes generates predominantly a TM mode.

The type of the upper hole subband can be controlled with the help of QW deformation in its growth plane. If the well is stretched in the growth plane and its thickness is not very small, the upper hole subband will be produced by the states of light holes. If the QW is not deformed or squeezed in the growth plane, the upper hole subband will be formed by the states of heavy holes. Probably, the QW deformation can be most easily controlled in the $InP/In_xGa_{1-x}As$ heterostructure in which a solid solution serves as a quantum well. The lattice constants of the solid solutions $In_{0.53}Ga_{0.47}As$ and InP coincide [7].

When the fraction of indium in the $In_xGa_{1-x}As$ solid solution increases, its lattice constant also increases. In this connection, in this paper we propose the design of a semiconductor InP laser with a waveguide $In_{0.77}Ga_{0.23}As_{0.5}P_{0.5}$ layer, matched with the substrate by the lattice constant, and with two different QWs (located at the centre of the waveguide layer) for the simultaneous generation of TE_0 and TM_0 modes in the near-IR region. The quantum wells will generate two fundamental modes with different frequencies and polarisations. The active region for the generation of the TE_0 mode will be a 5-nm-thick $In_{0.57}Ga_{0.43}As$ quantum well ($\hbar\omega_1 \approx 0.819$ eV) and for the generation of the TM_0 mode – a 9-nm-thick $In_{0.4}Ga_{0.6}As$ quantum well ($\hbar\omega_2 \approx 0.831$ eV).

The phase-matching condition needed for the efficient difference-frequency generation consists in the equality of phase velocities of the difference mode and the nonlinear polarisation wave appearing during the interaction of two near-IR modes due to the nonlinearity. This condition is achieved for two fundamental modes by selecting the thickness of the waveguide $In_{0.77}Ga_{0.23}As_{0.5}P_{0.5}$ layer. Note that it can be done due to the small dispersion of the refractive index of $In_{0.77}Ga_{0.23}As_{0.5}P_{0.5}$ in the $\sim$ 1.5-μm emission region of this laser [8]. In the terahertz frequency range, InP has a rather large second-order nonlinearity, exceeding by 12 times that of GaAs [2, 8]. The use of the semiinsulated substrate in the proposed laser will significantly reduce absorption at the difference frequency by free carriers because the difference mode will mainly propagate in the substrate playing the role of a superdimensional waveguide.

If the laser structure with the parameters presented in Table 1 is grown in the (001) plane and the near-IR modes

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Table 1. Parameters of the layers of the laser heterostructure.

Layer number	Layer composition	Conductivity type	Carrier concentration/ cm^{-3}	Layer thickness/μm
1	InP (substrate)	semiinsulating	–	150
2	InP	n	10^{18}	0.1
3	$In_{0.77}Ga_{0.23}As_{0.5}P_{0.5}$	–	–	0.8
4	InP	p	2×10^{18}	4
5	InP	p	10^{19}	0.2
6	Au	–	–	0.2

propagate along the [110] direction, the nonlinear polarisation in the $In_{0.77}Ga_{0.23}As_{0.5}P_{0.5}$ layer has both the longitudinal and perpendicular components with respect to the layer plane and excites at the difference frequency the TE or TM mode, respectively. Indeed, in materials with a zinc blende structure, the nonlinear second-order permittivity tensor $\varepsilon^{(2)}_{x'y'z} = \varepsilon^{(2)}(\omega)$ (in the coordinate system, where the axes x', y', and z are directed along the crystallographic directions [100], [010], [001], respectively) belongs to the point group $\bar{4}3m$ for which three coefficients ($d_{14} = d_{25} = d_{36}$) are nonzero [9]. In the near-IR region in this coordinate system, the electric field vectors in the TE_0 mode have nonzero x' and y' components ($|E_{1x'}| = |E_{1y'}| = E_1/\sqrt{2}$) and all the three components ($|E_{2x'}| = |E_{2y'}| = E_2/\sqrt{2}$ and E_{2z}) are present in the field of the TM_0 mode. Therefore, in the coordinate system, where the x axis is along the [110] direction of the wave propagation, the electric induction vector caused by the nonlinear interaction of waves has the components directed along the axes y and z:

$$D^{(2)}_y = 2\varepsilon^{(2)}E_{2z}\sqrt{E^2_{1x'} + E^2_{1y'}} = 2\varepsilon^{(2)}E_{2z}E_1, \quad (1)$$

$$D^{(2)}_z = 2\varepsilon^{(2)}(E_{1x'} + E_{2x'})(E_{1y'} + E_{2y'}) = \varepsilon^{(2)}(E_1 + E_2)^2. \quad (2)$$

Thus, the difference harmonic can have both the TE and TM polarisations.

The difference in polarisations of near-IR modes makes it possible to suppress absorption of the z component of the electric field directed perpendicular to the structure layers at the frequency ω_2 in the QW generating the frequency ω_1. By placing the QW generating the frequency ω_1 in the node of the x component of the electric field directed along the wave propagation, it is possible to suppress absorption of the x component at the frequency ω_2, which provides stable two-frequency generation in the laser proposed. Indeed, in this case the fundamental TM_0 mode has only one y component of the magnetic field directed along the structure layers and perpendicular to the mode propagation direction. The components of the magnetic [$H_{2y}(z)$] and electric [$E_{2x}(z)$] fields are related by the expression:

$$E_{2x}(z) = -\mathrm{i}\frac{c}{\varepsilon(z,\omega_2)\omega_2}\frac{\mathrm{d}H_{2y}(z)}{\mathrm{d}z}, \quad (3)$$

where c is the speed of light in vacuum; $\varepsilon(z,\omega)$ is the permittivity of the structure layers at the frequency ω. Therefore, in the antinode of the $H_{2y}(z)$ component, the $E_{2x}(z)$ component has a node, and the overlap integral of the fields E_1 and E_2 is significantly smaller than the overlap

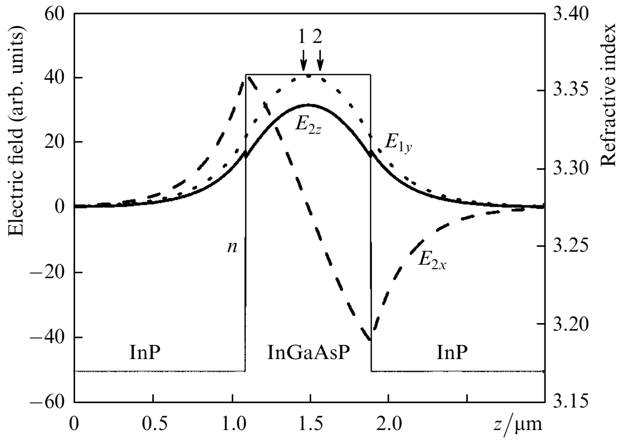

Figure 1. Dependences of the refractive index on the coordinate z for the photon energy $\hbar\omega_1 = 0.819$ eV and electric fields E_{1y}, E_{2z}, E_{2x}. The arrows show the position of the first and second quantum wells – $In_{0.57}Ga_{0.43}As$ (1) and $In_{0.4}Ga_{0.6}As$ (2). The parameters of the structure are borrowed from Table 1.

integral of the fields E_1 and E_{2z} (Fig. 1). One can show that $|D^{(2)}_y| \gg |D^{(2)}_z|$ and, hence, we will consider below only the TE polarisation of the difference wave.

We assume that

$$E_1(x,z,t) = A(z)[\exp(\mathrm{i}k_{1x}x - \mathrm{i}\omega_1 t) + \exp(-\mathrm{i}k_{1x}x + \mathrm{i}\omega_1 t)], \quad (4)$$

$$E_{2z}(x,z,t) = B(z)[\exp(\mathrm{i}k_{2x}x - \mathrm{i}\omega_2 t) + \exp(-\mathrm{i}k_{2x}x + \mathrm{i}\omega_2 t)], \quad (5)$$

where k_{1x} and k_{2x} are the x components of the wave vectors of near-IR TE_0 and TM_0, respectively. Hereafter, we neglect the laser boundaries in the y direction because the laser width in this direction ($\sim$ 1 mm) is much larger than the laser width in the z direction and the wavelengths of electromagnetic waves considered in the problem.

The equation for the y component of the electric field of the difference wave has the form

$$\frac{\partial^2 E'_y}{\partial z^2} + \frac{\partial^2 E'_y}{\partial x^2} - \frac{\varepsilon(z,\omega)}{c^2}\frac{\partial^2 E'_y}{\partial t^2} = -\varepsilon^{(2)}(\omega)\frac{\omega^2}{c^2} \times A(z)B(z)[\exp(\mathrm{i}k_x x - \mathrm{i}\omega t) + \exp(-\mathrm{i}k_x x + \mathrm{i}\omega t)], \quad (6)$$

where $k_x = k_{2x} - k_{1x}$. It is obvious that the solution of Eqn (6) can be represented as the doubled real part of the solution of the equation similar to (6), the right-hand side of which has only one exponential: $E'_y(x,z,t) = 2\mathrm{Re}[E_y(x,z,t)]$. In the approximation $\alpha L \gg 1$ (α is the absorption coefficient at the difference frequency and L is the laser length), the solution can be sought for in the form $E_y(x,z,t) = E_y(z)\exp(\mathrm{i}k_x x - \mathrm{i}\omega t)$. Indeed, in the terahertz frequency range the absorption coefficient in the structure with the parameters from Table 1 exceeds 5 cm^{-1}, and the characteristic length of the laser can achieve 5 mm. Therefore, our approximation is applicable to real structures. Then, the equation for $E_y(z)$ can be written in the form:

$$\frac{\mathrm{d}^2E_y(z)}{\mathrm{d}z^2}+\left[\varepsilon(z,\omega)\frac{\omega^2}{c^2}-k_x^2\right]E_y(z)$$

$$=-\varepsilon^{(2)}(\omega)\frac{\omega^2}{c^2}A(z)B(z). \quad (7)$$

At the boundary of the layers with different permittivities, the functions $E_y(z)$ and $\mathrm{d}E_y/\mathrm{d}z$ are continuous. To determine the right-hand side of equation (7), it is necessary to solve the equations for $A(z)$ and $B(z)$:

$$\frac{\mathrm{d}^2A(z)}{\mathrm{d}z^2}+\left[\frac{\varepsilon(z,\omega_1)\omega_1^2}{c^2}-k_{1x}^2\right]A(z)=0, \quad (8)$$

$$B(z)=-\frac{ck_{2x}}{\varepsilon(z,\omega_2)\omega_2}F(z), \quad (9)$$

where

$$\varepsilon(z,\omega_2)\frac{\mathrm{d}}{\mathrm{d}z}\left[\frac{1}{\varepsilon(z,\omega_2)}\frac{\mathrm{d}F(z)}{\mathrm{d}z}\right]+\left[\frac{\varepsilon(z,\omega_2)\omega_2^2}{c^2}-k_{2x}^2\right]F(z)=0.$$

At the boundary of the layers with different permittivities, the functions $A(z)$ and $F(z)$, $\mathrm{d}A(z)/\mathrm{d}z$ and $[\varepsilon(z)]^{-1}\mathrm{d}F(z)/\mathrm{d}z$ are also continuous. The boundary conditions are the requirements $A(z)$, $F(z)\to 0$ at $z\to\pm\infty$ for the fields of waveguide modes. The power of the difference wave is determined from the equality:

$$P=\frac{c^2k_xL_y}{2\pi\omega}\int_{-\infty}^{\infty}|E_y(z)|^2\mathrm{d}z, \quad (10)$$

where L_y is the active region width of the laser.

The frequency dependences of the refractive index of InP and $In_{0.77}Ga_{0.23}As_{0.5}P_{0.5}$ for the near-IR modes used in calculations were borrowed from handbook [8]. The permittivities of InP and $In_{0.77}Ga_{0.23}As_{0.5}P_{0.5}$ layers in the terahertz frequency range were calculated by the expression from [10] by using data [8, 11]:

$$\varepsilon(\omega)=\varepsilon_\infty+\frac{\omega_{\mathrm{TO}}^2(\varepsilon_0-\varepsilon_\infty)}{\omega_{\mathrm{TO}}^2-\omega^2-\mathrm{i}\Gamma\omega}-\frac{\omega_{\mathrm{p}}^2\varepsilon_\infty}{\omega^2+\mathrm{i}\gamma_{\mathrm{p}}\omega}, \quad (11)$$

where ε_0 and ε_∞ are the low-frequency and high-frequency permittivities of the undoped semiconductor material; ω_{TO} is the frequency of the transverse optical phonon; Γ is the attenuation coefficient of optical phonons of the lattice; $\gamma_{\mathrm{p}}=q/m^*\mu$; $\omega_{\mathrm{p}}^2=4\pi n_{\mathrm{c}}q^2/m^*\varepsilon_\infty$ is the square of the plasma frequency; n_{c}, m^*, and μ are the concentration, effective mass, and mobility of the charge carriers, respectively.

The permittivity of the Au film was calculated by interpolating data from [12]. In numerical calculations we assumed that the components of the tensors of the nonlinear second-order permittivities of $In_{0.77}Ga_{0.23}As_{0.5}P_{0.5}$ and InP are equal and their frequency dependence is described by expression (3.47) from paper [2]. The frequency dependence of $\varepsilon^{(2)}$ is plotted in Fig. 2.

The results of calculations of the power and distribution of the electric field of the difference wave in the presented structure for the 1-W near-IR modes are shown in Figs 2 and 3. The minimal frequency ω_1 for the near-IR modes was fixed in calculations, the change in the difference frequency being achieved by changing the frequency of another near-IR mode. The dependence of the power on the difference frequency exhibits many resonance peaks. Each of them corresponds to the transverse mode of a superdimensional waveguide for which the phase velocity is equal to the phase velocity of the nonlinear polarisation wave. Indeed, the difference wave will propagate mainly in the InP substrate, while the near-IR modes will interact in the $In_{0.77}Ga_{0.23}As_{0.5}P_{0.5}$ layer grown on the substrate. One can see from Fig. 2 that the difference-wave power has a maximum at the frequency 2.6 THz, which is caused by the absorption minimum at this frequency in the structure under study. At frequencies below 2.6 THz, the increase in absorption with decreasing the frequency is related to the absorption by free carriers in doped layers of the structure. At frequencies above 2.6 THz, the increase in the absorption with increasing the frequency is caused by radiation absorption by optical phonons. In addition, when the frequency increases, $\varepsilon^{(2)}$ decreases.

The calculations showed that in a planar InP/InGaAsP/InGaAs laser with a 100-μm-wide active region for the 1-W

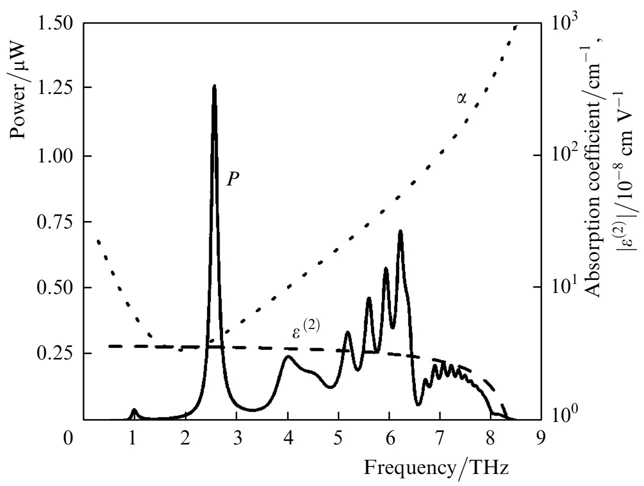

Figure 2. Dependences of the radiation power P at the difference frequency ($\hbar\omega_1=0.819$ eV), the modulus $\varepsilon^{(2)}$ of the nonlinear susceptibility of InP, and the absorption coefficient α of the structure on the difference frequency. The parameters of the structure are borrowed from Table 1.

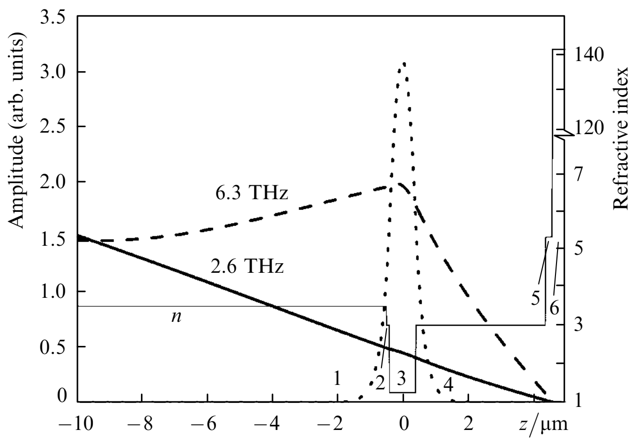

Figure 3. Dependences of the electric field strength of the difference wave with the frequency 2.6 or 6.3 THz and the refractive index n at the frequency 2.6 THz on the coordinate z. The dashed curve shows the amplitude of the near-IR mode in arbitrary units. The layers are numbered in accordance with Table 1.

powers of the near-IR modes, the difference-wave power can achieve ~ 1 μW in the frequency range from 1 to 8 THz at room temperature.

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