PACS numbers: 42.65.Ky; 42.55.Px; 07.57.Hm
DOI: 10.1070/QE2008v038n09ABEH013796

# Generation of difference-frequency radiation in the far- and mid-IR ranges in a two-chip laser based on gallium arsenide on a germanium substrate

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***Abstract*. The possibility of efficient generation of difference-frequency radiation in the far- and mid-IR ranges in a two-chip laser based on gallium arsenide grown on a germanium substrate is considered. It is shown that a laser with a waveguide of width 100 μm emitting 1 W in the near-IR range can generate ~ 40 μW at the difference frequency in the region 5 – 50 THz at room temperature.**

***Keywords***: *terahertz waves, difference frequency, germanium substrate, semiconductor laser, mid- and far-IR ranges.*

Although compact radiation sources in the far- and mid-IR wavelength ranges are required for various applications, the number of their types is small. By now the most significant results have been achieved in the development of quantum cascade lasers based on group III – V semiconductors [1]. However, an extremely intricate energy band diagram of cascade structures and high requirements on the control of their parameters prevent wide applications of these lasers. In addition, they cannot in principle emit in the 7 – 10-THz frequency region due to strong phonon absorption in III – V semiconductors in this range.

This restriction can be eliminated by generating radiation at the difference frequency $\omega = \omega_2 - \omega_1$ in this range obtained in the nonlinear-optical conversion of two fields at frequencies $\omega_1$ and $\omega_2$ in the near-IR range due to the quadratic nonlinearity of the crystal lattice of III – V semiconductors [2]. Note that the highest-power semiconductor lasers generate radiation at ~ 1 μm [3].

We propose to generate difference-frequency radiation by using a two-chip laser with a combined cavity consisting of two single-frequency quantum-well lasers, which are mounted adjacent to each other on one heatsink and generate cw radiation at two near-IR frequencies. Both lasers should emit the fundamental transverse mode, and radiation of one laser will be coupled to the waveguide of another laser (normally to the transverse face of the waveguide). The generation of radiation at the frequency equal to the difference of frequencies of these lasers will occur in the latter laser. Such a design will provide the coupling of a great part of radiation from one laser to the other (~ 40 %) [4].

To obtain efficient lasing at the difference frequency in an absorbing nonlinear medium, the phase velocities of a nonlinear polarisation wave, appearing due to nonlinearity during the interaction of near-IR modes, and of the difference wave should be equal. In addition, absorption by optical phonons and free carriers at the difference frequency should be suppressed.

These conditions cannot be fulfilled for lasers on a GaAs substrate generating fundamental transverse modes in the near-IR range, because the phase velocity of the nonlinear polarisation wave proves to be, as a rule, lower than the phase velocity of the difference wave [5]. As shown in [6], these conditions can be provided by using the fundamental transverse mode at frequency $\omega_1$ and a higher-order transverse mode at frequency $\omega_2 > \omega_1$. However, a disadvantage of the scheme proposed in [6] is a low nonlinear polarisation at the difference frequency, which is proportional to the product of the intensities of almost orthogonal transverse near-IR modes of different orders.

To fulfil these conditions, we propose to use a pure (or weakly doped) germanium substrate in an InGaAs/GaAs/InGaP heterostructure laser which will generate radiation at the difference frequency. The lattice constants of Ge and GaAs are close, and therefore the Ge/GaAs heterojunction can be grown without dislocations. The efficiency of a laser on a germanium substrate was demonstrated in paper [7]. The greatest part of the difference-frequency wave will propagate in a germanium substrate, and therefore its phase velocity will be close to the phase velocity of a plane wave in germanium (the refractive index is ~ 4), which is smaller than the phase velocity in GaAs [the refractive index is ~ 3.5 for near-IR modes and $n(\omega_2) > n(\omega_1)$] in which the nonlinear polarisation wave mainly propagates. It can be shown by direct calculations (Fig. 1) that the effective refractive index $[n(\omega_2)\omega_2 - n(\omega_1)\omega_1]/(\omega_2 - \omega_1)$ for the difference-frequency nonlinear polarisation wave in the laser waveguide of the GaAs/InGaP heterostructure is smaller than the refractive index of Ge in the frequency range up to 50 THz if both near-IR modes are the fundamental $TE_0$ modes. Therefore, it is possible to select a mode at the difference frequency in the frequency range up to 50 THz whose phase velocity coincides with the phase velocity of the nonlinear polarisation wave and for which the condition of efficient lasing at the difference frequency is fulfilled. An advantage of this method is that the overlap integral for these transverse modes is not small (modes are not orthogonal). In addition, because a germanium substrate plays the role of

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Received 17 January 2008; revision received 20 March 2008
*Kvantovaya Elektronika* **38** (9) 855 – 858 (2008)
Translated by M.N. Sapozhnikov

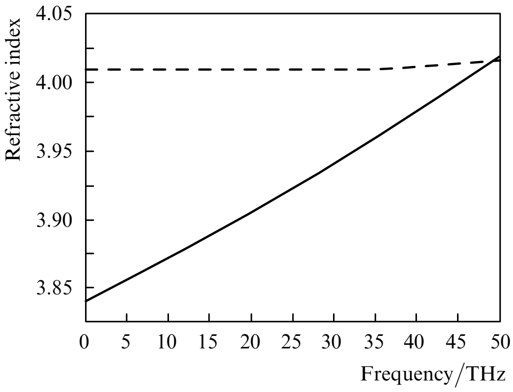


**Figure 1.** Frequency dependences of the effective refractive index for the difference-frequency nonlinear polarisation wave (solid curve) in the laser structure with parameters from Table 1 and of the refractive index of germanium (dashed curve).

a superdimensional waveguide for the difference-frequency wave, absorption at the difference frequency can be efficiently reduced because phonon absorption in germanium is suppressed much stronger than in GaAs, while undoped germanium virtually does not contain free carriers.

If the laser structure with parameters presented in Table 1 is grown in the (001) plane and near-IR modes have the TE polarisation and propagate along the [110] direction, nonlinear polarisation in GaAs is perpendicular to the plane of layers and excites the TM mode at the difference frequency [6]. Indeed, the second-order nonlinear permittivity tensor $\varepsilon_{ijk}^{(2)}$ in materials with the zinc blende structure is symmetric with respect to the permutation of indices in the coordinate system where the $x'$, $y'$, $z$ axes are directed along crystallographic directions [100], [010], and [001], respectively [8]. In addition, only those components of the tensor are nonzero in which all the three indices are not equal to each other. Therefore, this tensor can be described only by one function of frequency $\varepsilon_{x',y',z}^{(2)} = \varepsilon^{(2)}(\omega, \omega_1, \omega_2)$ [2] $\{\varepsilon^{(2)}$ and components of the second-order permittivity tensor [8] are related by the expression $\varepsilon^{(2)} = d_{14} = d_{25} = d_{36}\}$.

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

| Layer number | Layer composition | Conduction type | Carrier concentration/cm$^{-3}$ | Layer thickness/μm |
|---|---|---|---|---|
| 1 | Ge | – | – | 130 |
| 2 | GaAs | n | $10^{18}$ | 0.1 |
| 3 | InGaP | n | $10^{18}$ | 0.8 |
| 4 | GaAs | – | | 0.6 |
| 5 | InGaP | p | $2 \times 10^{18}$ | 0.8 |
| 6 | GaAs | p | $10^{19}$ | 0.2 |
| 7 | Au | – | – | 0.2 |

The vectors of the electric field of near-IR modes in this coordinate system have nonzero $x'$ and $y'$ components $|E_{jx'}| = |E_{jy'}| = E_j/\sqrt{2}$, where $j$ is the number of the near-IR mode at frequency $\omega_j$. Therefore, the electric induction vector caused by the nonlinear interaction of waves is directed along the $z$ axis:

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

Thus, the difference harmonic should have the TM polarisation. We will assume that

$$E_j(x, z, t) = A_j(z)[\exp(\mathrm{i}k_{jk}x - \mathrm{i}\omega_j t) + \exp(-\mathrm{i}k_{jx}x + \mathrm{i}\omega_j t)], \quad (2)$$

where $k_{jx}$ is the $x$ component of the wave vector of the $j$th near-IR mode (in the coordinate system where the direction of the $x$ axis coincides with the wave propagation direction [110] and the direction of the $y$ axis coincides with the $[\bar{1}10]$ direction. Hereafter, we consider the waves at the difference frequency propagating only along the $x$ axis (for which the wave vector $k_y \ll k_x$) because the length of interaction of these waves with the nonlinear polarisation wave is maximal and, therefore, it is these waves that have the maximum intensity. Then, the equation for the $y$ component of the magnetic field of the difference-frequency wave has the form

$$\varepsilon(z,\omega)\nabla \frac{1}{\varepsilon(z,\omega)} \nabla H'_y - \frac{\varepsilon(z,\omega)}{c^2} \frac{\partial^2 H'_y}{\partial t^2} = -2\varepsilon^{(2)}(\omega) \frac{k_x \omega}{c} \times A_1(z) A_2(z)[\exp(\mathrm{i}k_x x - \mathrm{i}\omega t) + \exp(-\mathrm{i}k_x x + \mathrm{i}\omega t)], \quad (3)$$

where $\varepsilon(z,\omega)$ is the permittivity and $k_x = k_{2x} - k_{1x}$. It is obvious that the solution of Eqn (3) can be represented in the form of the double real part of the solution of an equation analogous to (3), whose right-hand side contains only one exponential: $H'_y(x,z,t) = 2\mathrm{Re}[H_y(x,z,t)]$. In the approximation $\alpha L \gg 1$ ($\alpha$ is the absorption coefficient at the difference frequency, $L$ is the laser length), the solution can be sought in the form $H_y(x,z,t) = H_y(z)\exp(\mathrm{i}k_x x - \mathrm{i}\omega t)$. Indeed, the absorption coefficient in the mid- and far-IR ranges for the structure with parameters presented in Table 1 exceeds 10 cm$^{-1}$, while the laser length can achieve 5 mm. Therefore, our approximation is valid for real structures. Then, the equation for $H_y(z)$ can be written in the form

$$\varepsilon(z,\omega) \frac{\mathrm{d}}{\mathrm{d}z}\left[\frac{1}{\varepsilon(z,\omega)} \frac{\mathrm{d}H_y(z)}{\mathrm{d}z}\right] + \left[\varepsilon(z,\omega)\frac{\omega^2}{c^2} - k_x^2\right] H_y(z) = -2\varepsilon^{(2)}(\omega)\frac{k_x\omega}{c} A_1(z)A_2(z). \quad (4)$$

The values of $H_y(z)$ and $\varepsilon^{-1}\mathrm{d}H_y/\mathrm{d}z$ at the interface of layers with different permittivities are continuous. To find the right-hand side of Eqn (4), it is necessary to solve equations for $A_j(z)$:

$$\frac{\mathrm{d}^2 A_j(z)}{\mathrm{d}z^2} + \left[\frac{\varepsilon(z,\omega_j)\omega_j^2}{c^2} - k_{jx}^2\right] A_j(z) = 0. \quad (5)$$

The values of $A_j(z)$ and $\mathrm{d}A_j(z)/\mathrm{d}z$ are continuous at the interface of layers with different permittivities. The boundary conditions for the guided modes are the requirements $A_j(z) \to 0$ for $z \to \pm\infty$. The electric field component $E_z(z)$ of the difference-frequency wave and its power are determined from the equalities

$$E_z(z) = -\frac{1}{\varepsilon(z,\omega)}\left(\frac{ck_x}{\omega} H_y(z) + 2\varepsilon^{(2)}(\omega)A_1(z)A_2(z)\right),$$
$$P = -\frac{cL_y}{2\pi}\int_{-\infty}^{\infty} \mathrm{Re}(H_y(z)E_z^*(z))\mathrm{d}z. \quad (6)$$

Here, $L_y$ is the width of the active region of the laser.

We used in the calculation the frequency and wavelength dependences of the refractive indices of GaAs and InGaP [5], respectively, for near-IR modes:

$$n_{\mathrm{GaAs}}(\hbar\omega) = \left(7.1 + \frac{3.78}{1 - 0.18(\hbar\omega)^2}\right)^{1/2},$$
$$n_{\mathrm{InGaP}}(\lambda) = 9.236 + \frac{0.795\lambda^2}{\lambda^2 - 0.37}, \quad (7)$$

where $\hbar\omega$ is measured in electronvolts and $\lambda$ – in nanometres. The permittivities of the GaAs and InGaP layers in the mid- and far-IR ranges were calculated by the expression from [9] by using data [5, 10]:

$$\varepsilon(\omega) = \varepsilon_\infty + \frac{\omega_{\mathrm{TO}}^2(\varepsilon_0 - \varepsilon_\infty)}{\omega_{\mathrm{TO}}^2 - \omega^2 - \mathrm{i}\Gamma\omega} - \frac{\omega_{\mathrm{p}}^2\varepsilon_\infty}{\omega^2 + \mathrm{i}\gamma_{\mathrm{p}}\omega}, \quad (8)$$

where $\varepsilon_0$ and $\varepsilon_\infty$ are the low-frequency and high-frequency permittivities of a pure semiconductor; $\omega_{\mathrm{TO}}$ is the frequency of a transverse optical phonon; $\Gamma$ is the attenuation coefficient of optical vibrations 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; and $n_{\mathrm{c}}$, $m^*$, and $\mu$ are the concentration, effective mass, and mobility of charge carriers.

The permittivities of Ge and Au were calculated by the interpolation of data from handbook [11]. The dependence of the component of the second-order nonlinear permittivity tensor for GaAs was described by expression (3.47) from [2] and is shown in Fig. 2. The figure also presents the spectral dependence of the power of the difference-frequency wave calculated for the proposed structure for the power of near-IR modes equal to 1 W. The maximum wavelength $\lambda_1$ of the near-IR range modes was fixed in calculations and the difference frequency was changed by varying the wavelength of another near-IR mode. The dependence of the power on the difference frequency exhibits closely spaced resonance peaks. Each of them corresponds to a transverse mode of a superdimensional waveguide in the far- and mid-IR ranges whose phase velocity is equal to the phase velocity of the nonlinear polarisation wave. Indeed, the difference-frequency wave will mainly propagate in the germanium substrate, while the interaction of near-IR modes will take place in the GaAs laser grown on this substrate.

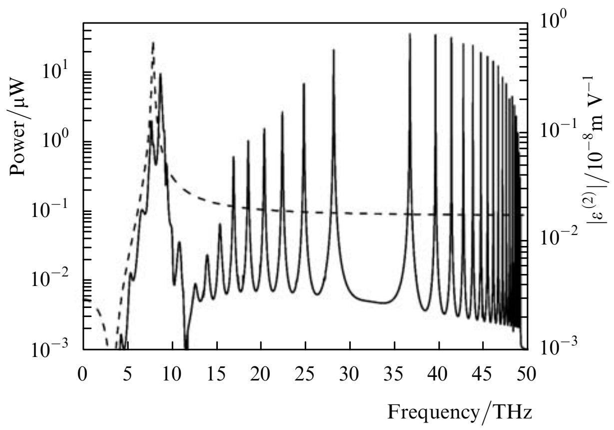


**Figure 2.** Spectral dependences of the radiation power at the difference frequency for the structure with a 130-μm-thick Ge substrate (solid curve) and of the modulus of the component of the nonlinear permittivity tensor $\varepsilon^{(2)}$ of GaAs (dashed curve); $\lambda_1 = 1.13$ μm.

One can see from Fig. 2 that the mid-IR radiation power will be of the same order of magnitude as the power that can be obtained by generating difference-frequency radiation with the help of lasers with transverse modes of different orders [6], although the overlap integral for these modes in the transverse direction is small. This is explained by the fact that the refractive index of Ge considerably exceeds the refractive indices of GaAs and InGaP. As a result, the difference-frequency wave weakly penetrates into the laser structure from the Ge substrate, which leads to a small overlap integral for the difference-frequency wave and the nonlinear polarisation wave (Fig. 3).

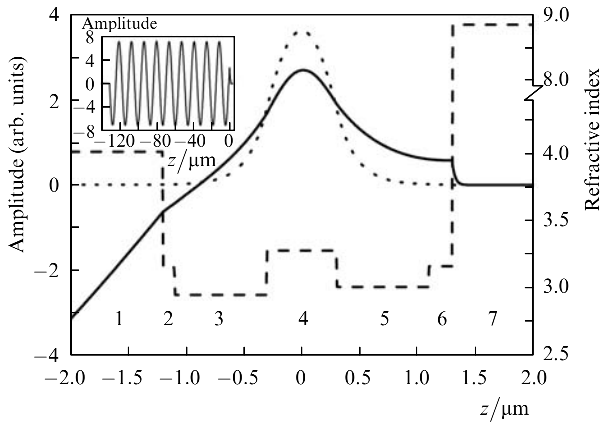


**Figure 3.** Dependences of the magnetic field strength of the difference-frequency wave (solid curve) and the refractive index $n$ (dashed curve) at a frequency of 36.5 THz on the transverse coordinate for the structure grown on a germanium substrate. The dotted curve shows the amplitude of a near-IR mode, the inset shows the distribution of the magnetic field strength of the difference-frequency wave in the entire laser (layers are numbered as in Table 1).

Note the specific features of radiation generation in the 7 – 10-THz range. Absorption in GaAs and InGaP and the quadratic nonlinearity of GaAs drastically increase in this region because they have the common phonon nature [2] (Fig. 2). In addition, the refractive index of these materials strongly changes. Because of this, there exists the frequency region [between the frequencies of transverse phonons in GaAs (8.02 THz) and InGaP (9.2 THz)] where phonon absorption in GaAs drastically decreases, but has no time to increase drastically in InGaP. As a result, nonlinearity in this region is considerably higher than that in the mid-IR frequency range and the refractive index of InGaP exceeds that of Ge. In this case, the difference-frequency wave quite easily penetrated into the laser structure from the substrate, resulting in a considerable increase in the lasing power in this frequency range (Fig. 4).

Our calculations showed that a planar laser with a waveguide of width 100 μm on the Ge substrate emitting 1 W in the near-IR range can generate ~ 40 μW at the difference frequency in the frequency region 5 – 50 THz at room temperature.

***Acknowledgements.*** This work was supported by the Russian Foundation for Basic Research (Grant Nos 07-02-00486-a, 07-02-12177-ofi, 08-02-90054-Bel_a, and 08-02-

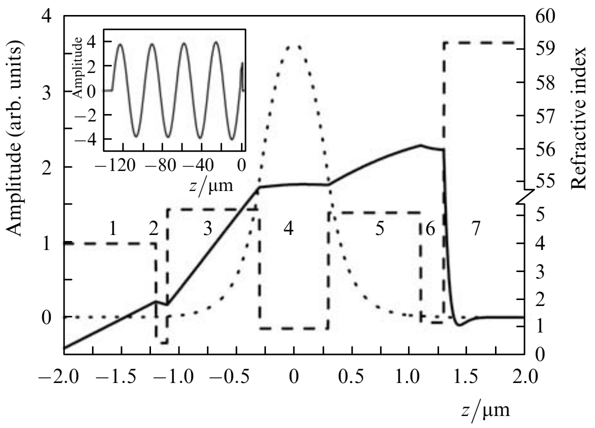


**Figure 4.** Dependences of the magnetic field strength of the difference-frequency wave (solid curve) and the refractive index $n$ (dashed curve) at the frequency 8.6 THz on the transverse coordinate for the structure grown on a germanium substrate. The dotted curve shows the amplitude of a near-IR mode, the inset shows the distribution of the magnetic field strength of the difference-frequency wave in the entire laser (layers are numbered as in Table 1).

97034-p_povolzh'e_a), the Presidium of the RAS (Program 'Terahertz Electromagnetic Waves'), and Grant No. MK-3344.2007.2 of the President of the Russian Federation for the support of young Russian scientists and leading scientific schools.

## References

1. Williams B.S., Kumar S., Hu Q., Reno J.L. *Opt. Express*, **13**, 3331 (2005).
2. Flytzanis C. *Phys. Rev. B*, **6**, 1264 (1972).
3. Slipchenko S.O., Vinokurov D.A., Pikhtin N.A., Sokolova Z.N., Stankevich A.L., Tarasov I.S., Alferov Zh.I. *Fiz. Tekh. Poluprovodn.*, **38**, 1477 (2004).
4. Biryukov A.A., Aleshkin V.Ya., Nekorkin S.M., Kocharovsky V.V., Kocharovsky Vl.V., Zvonkov B.N., Scully M.O. *J. Mod. Opt.*, **52**, 2323 (2005).
5. Madelung O. *Semiconductors: Data Handbook* (New York: Springer – Verlag, 2003).
6. Aleshkin V.Ya., Afonenko A.A., Zvonkov N.B. *Fiz. Tekh. Poluprovodn.*, **35**, 1256 (2001).
7. D'Hondt M., Yu Z.-Q., Depreter B., Sys C., Moerman I., Demeester P., Mijlemans P. *J. Crystal Growth*, **195**, 655 (1998).
8. Grigor'ev I.S., Meilikhov E.Z. (Eds) *Fizicheskie velichiny: Spravochnik* (Handbook of Physical Quantities) (Moscow: Energoatomizdat, 1991).
9. Blakemore J.S. *J. Appl. Phys.*, **53**, R123 (1982).
10. Ferrini R., Guizzetti G., Patrini M., Parisini A., Tarricone L., Valenti B. *Europ. Phys. J. B*, **27**, 449 (2002).
11. Palik E.D. *Handbook of Optical Constants of Solids* (New York: Acad. Press, 1998).