5. Spectra of inverse heterojunctions between IV – VI semiconductors of different chemical composition

A few words now about so-called inverse junctions. Experiment and band calculations show that as the chemical composition is changed or under pressure, the inversion of band terms may occur in the vicinity of the narrow gap near the L-points. This comes about when the band gap passes through zero at L-points, having the effect that the electronic terms near the tops and bottoms of the bands reverse symmetry (namely, the even states become odd at the bottom of the conduction band, and vice versa). If two such semiconductors of opposite parity are brought together to form a junction, it can be shown that independent of whether the junction is smooth or sharp, bound electron states appear at the interface. The only requirement is that the work function values on the right and on the left of the junction be less than the gap widths involved. Mathematically, this phenomenon is due to the supersymmetry of the problem and manifests itself in the appearance of the zero mode. The spectrum of the bound states is nondegenerate with respect to 'spin' in the plane of the junction and is similar to that of the Weyl equation for neutrino.

References

1. Pankratov O A, Volkov B A *Sov. Sci. Reviews Sect. A Phys. Rev.* (Ed. I M Khalatnikov) **9** 355 (1987)
2. Volkov B A, Pankratov O A, in *Landau Level Spectroscopy* (Modern Problems in Condensed Matter Sciences, Vol. 27, Eds G Landwehr, E I Rashba) (Amsterdam: North-Holland, 1991)
3. Volkov B A, Idlis B G, Usmanov M Sh *Usp. Fiz. Nauk* **165** 799 (1995) [*Phys. Usp.* **38** 761 (1995)]
4. Volkov B A, Ryabova L I, Khokhlov D R *Usp. Fiz. Nauk* **172** 875 (2002) [*Phys. Usp.* **45** 819 (2002)]
5. Volkov B A, in *Lead Chalcogenides: Physics and Applications* (Optoelectronic Properties of Semiconductors and Superlattices, Vol. 18, Ed. D Khokhlov) (New York: Taylor & Francis, 2003)
6. Abrikosov A A, Fal'kovskiĭ L A *Zh. Eksp. Teor. Fiz.* **43** 1089 (1962) [*Sov. Phys. JETP* **16** 545 (1963)]
7. Volkov B A, Kushnir V P, Pankratov O A *Fiz. Tverd. Tela* **24** 415 (1982)
8. Volkov B A, Kushnir V P *Fiz. Tverd. Tela* **25** 1803 (1983)
9. Volkov B A, Ruchaĭskiĭ O M *Fiz. Tverd. Tela* **40** 57 (1998) [*Phys. Solid State* **40** 50 (1998)]

PACS numbers: 42.55.Px, **42.60.–v**
DOI: 10.1070/PU2003v046n09ABEH001646

New semiconductor laser designs and the exploratory investigation of the terahertz frequency range

A A Belyanin, D Deppe, V V Kocharovskiĭ,
Vl V Kocharovskiĭ, D S Pestov, M O Scully

Owing to advances in quantum and classical electronics and radio engineering, the efficient generation of coherent electromagnetic radiation has been realized in a wide frequency range — from petahertz (ultraviolet) to kilohertz (myriametric waves). The progress towards the hard ultraviolet and soft X-ray ranges (above 10^{16} Hz) is moderated by the short radiative lifetime of excited states participating in allowed transitions in atomic systems, which is inversely proportional to the cube of the transition frequency and falls into the pico- or femtosecond ranges. In this case, the excessive requisite pump power or the necessity of employing inefficient forbidden transitions turns out to be the inevitable limiting factor.

Such limitations are of no fundamental importance in the terahertz range, which corresponds to transition frequencies $\omega/2\pi$ ranging from 0.5 – 1 THz to 10 – 20 THz, i.e., to emission wavelengths λ from 600 – 300 μm to 30 – 15 μm. Nevertheless, it is precisely this range, being at the interface between microwave electronics and laser physics, that is mastered with great difficulty [1 – 4]. For various reasons, the techniques of vacuum and classical solid-state electronics, as well as the conventional schemes of quantum electronics, do not work well here. (In the former case, submillimeter travelling wave tubes (TWTs) and backward wave tubes (BWTs) [3] encounter the problems of low cathode efficiency, complications in e-beam matching with a slow-wave structure, and large losses in vacuum waveguides, while resorting to plasma instabilities in the ballistic transport in semiconductors requires the presently unattainable quality of submicrometer field-effect transistors [5]. In the latter case, molecular (beam) masers necessitate intense cooling and hardly realizable high-quality microresonators, while the inversion on rotational transitions in gas-discharge lasers, sufficient for lasing, is attained only for a limited number of lines [4].) Endeavors to excite terahertz oscillations in a cold plasma, including semiconductor plasmas, or in dipole photoconductor antennas by employing ultrashort (femtosecond) optical pulses are hampered by too low an efficiency ($< 10^{-4}$) of the corresponding 'optical rectification' [6 – 8]. By and large the available sources of coherent terahertz radiation are low-power (from nano- to microwatts, sometimes ranging into the watts), poorly tunable, and actually cover only narrow frequency bands. (Of course, we are not dealing with unique and expensive facilities and instruments relying, for instance, on synchrotrons and free-electron lasers [9] or powerful lasers with parametric mixers based on nonlinear optical crystals, including semiconductor crystals [10, 11].)

This situation is highly unfavorable for a broad range of potential applications of terahertz radiation, including radars, satellite and ground-based communication, security and guidance systems, three-dimensional tomography, diagnostics (biochemical and medical), molecular and solid-state spectroscopy, etc. [1 – 3]. In this connection strong hopes are pinned on semiconductor sources which have proven to be advantageous in the visible and near-infrared (IR) ranges and have recently come under the scrutiny of researchers as sources in the terahertz and far-IR ranges as well. Our work is concerned with precisely this direction of semiconductor laser physics, which potentially leads to the fabrication of compact, monolithic, efficient, and inexpensive laser sources ranging from ten to hundreds of micrometers in wavelength.

Conventional diode heterojunction lasers utilizing interband transitions in narrow-gap semiconductors based, for instance, on lead salts of the Pb(S, Se) or $\mathrm{Pb}_{1-x}\mathrm{Sn}_x\mathrm{Te(Se)}$ type prove to be inefficient and unable to work in the far-IR range for $\lambda > 30$ μm. The achievement of the population inversion in them even in the middle-IR range is associated with cooling down to helium (4 K) or nitrogen (77 K) temperatures and a high threshold current density ranging, respectively, from a fraction of to tens of kiloamperes per square centimeter. Their stability, reliability, and output power (milliwatts) leaves much to be desired [12]. Here, lasers utilizing interband transitions in type-II quantum wells [13] do not seem to hold promise, either.

At present there are only two types of semiconductor lasers that have been approved in practice and exhibited efficient terahertz lasing (at cryogenic temperatures), both being unipolar and reliant on intraband (intersubband) transitions. The first is a germanium p-type laser in strong crossed electric and magnetic fields [14 – 16] which provide the population inversion for 'hot' hole states and pulsed lasing in the submillimeter wavelength range (70 – 200 μm). However, its power is substantial (up to several watts) only at helium temperatures. The second is a quantum cascade n-type laser harnessing multiwell or superlattice heterostructures like AlInAs/GaInAs/InP or AlGaAs/GaAs [17 – 19], which has recently exhibited lasing at wavelengths of 70 μm [20], 24 μm [21], and 16 μm [22] with an output power of about a milliwatt at respective temperatures of less than 50, 100, and 300 K.[1] Also noteworthy are the potentialities of a 'fountain' laser [23] which has been realized only in the middle-IR range to date, and of a laser utilizing transitions in shallow donor impurities like P, Bi, and Sb in silicon [24 – 26], which has been shown to lase only at several narrow lines in the 51 – 59-μm range at helium temperature.

Among numerous, though unrealized, proposals to produce population inversion on intersubband terahertz transitions we note, for instance, the possibility of intervalley transitions in complex quantum wells under conditions of lateral electron transport [27], and the versions of a structure with three-level quantum wells whose lower level is to be depopulated either due to interband induced transitions by way of simultaneous lasing in the near-IR range [28] or due to resonant Auger processes [29]. The attainment of population inversion in all realized and unrealized proposals is primarily hindered by the short (picosecond) lifetime of the upper excited level, which is determined by nonradiative transitions involving mostly phonons. Another general problem is the strong ($\propto \lambda^2$ or λ^3) damping of infrared and particularly terahertz radiation in semiconductors, which stems from the Drude absorption by free carriers (as well as from phonons and diffraction). The Drude absorption may even lead to the fundamental prohibition of lasing, based on free carriers, at relatively long (submillimeter) wavelengths in a series of semiconductors, because overcoming the damping requires a high gain for the field, which necessitates raising the density of inverted electron–hole states, which in turn would strengthen the field damping.

A natural way out of this complex situation is the abandonment of the idea of producing population inversion between the neighboring interband levels and the development of inversion-free nonlinear-mixing schemes. In this case, the terahertz or far-IR radiation would be produced owing to the quadratic nonlinearity of the semiconductor structure due to the generation of the difference frequency $\omega_{12} = \omega_2 - \omega_1$ via mixing of two fields at frequencies ω_1 and ω_2 of the optical range or, to be more precise, of the near- or middle-IR range [30 – 35]. It is remarkable that even the lattice nonlinearity of semiconductor laser materials like InAs and GaAs (the group III – V elements) in the IR range amounts to fractions of a nanometer per volt, i.e., is 2 – 3 orders of magnitude stronger than for conventional nonlinear optical crystals of the KDP type. In principle, the quadratic nonlinearity $\chi^{(2)}$ in structures with quantum wells, wires, or dots can be enhanced further by 2 – 3 orders of magnitude due to the resonance contribution from electrons (holes) if all three nonlinear-mixing, i.e., parametrically coupled, fields are made resonant with the corresponding interband and intraband (allowed) transitions [30 – 32]. The last statement was experimentally verified in the three-wave mixing of external fields in multiwell heterostructures [13, 36 – 39], and such resonance enhancement of three-wave mixing was recently demonstrated in a two-color quantum cascade laser [40] (see also below). For gases, a similar result is well known and has also been proposed as a basis for the generation of terahertz radiation in the resonance mixing of two external laser fields [41].

Figure 1 depicts schematically the nonlinear and active elements, their arrangement, and the profiles of generated modes in a two-color quantum cascade laser based on InGaAs/AlGaAs quantum wells [40], in which the laser radiation simultaneously serves as the optical pump for the intracavity nonlinear generation of radiation at the second harmonic and the summary frequency. This unipolar laser generated radiation at five wavelengths of 9.5, 7.1, 4.75, 4.1, and 3.6 μm simultaneously, which correspond to two original lasing frequencies, their second harmonics, and the summary frequency. The signal at the summary frequency, which arises through the nonresonance, nonlinear wave mixing by the crystal lattice, has a different polarization and is weaker by several orders of magnitude. Typical output powers of the nonlinear signals presently attainable with lasers of this type range into the microwatts and correspond to conversion efficiencies up to 100 μW W^{-2} at a moderate pump level.

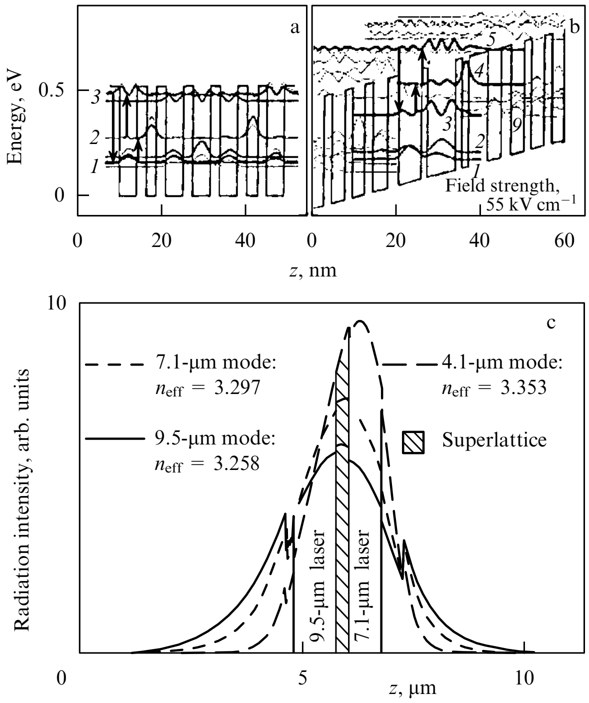

Figure 1. Structure of the superlattice (a) and the active region (b) which provide the generation and nonlinear mixing of 7.1- and 9.5-μm laser modes (c) in a unipolar quantum cascade laser (reprinted from Ref. [40]). The resonance transitions between electron levels are indicated with arrows, and z is the coordinate across the quantum wells.

---

[1] In the middle-IR range (3 – 20 μm), quantum cascade lasers — both pulsed and cw — provide an output power per mode up to a fraction of a watt at cryogenic temperatures, and 1 – 2 orders of magnitude lower at room temperatures (their threshold current density amounts to several kiloamperes per square centimeter).

Of no small importance is the proposal [30 – 34] to harness intracavity laser fields in the three-wave process. It is thereby possible not only to maximize the amplitudes of the fields being mixed and to eliminate the technical problems associated with their input and overcoming of interband absorption in the semiconductor microstructure, but also to retain the compactness (millimeter dimensions) of the oscillator, its monolithic structure, and the capacity for integration into different optoelectronic systems. In this case, the attainment of the terahertz generation threshold formally reduces to the attainment of two-color optical lasing in the near- or middle-IR range, since difference frequency generation is a threshold-free process. Considering its inversionless nature and expecting a relatively low threshold current (tens or hundreds of amperes per square centimeter) of the above two-color (optical) heterolaser, one can hope for the efficient cw generation of terahertz radiation with an output power ranging from several to hundreds of microwatts at room temperature. Among the potential advantages of such an oscillator are the possibility of employing an efficient injection pumping and the fast (picosecond) modulation of terahertz radiation by way of current modulation (which has already shown its worth in heterolasers [13, 42] and quantum cascade lasers [19]), as well as the capability for simultaneous lasing at several wavelengths and the substantial frequency tuning of the long-wavelength radiation by way of a relatively small frequency tuning of the short-wavelength fields being mixed (by changing the pump current and the laser temperature or by applying the external fields). Of course, this approach can be employed to generate radiation not only in the terahertz range, but in the middle-IR range as well. Usually, the resultant long-wavelength mode is TM-polarized and is generated via mixing of the short-wavelength TE modes (see the theory developed in Ref. [30]).

There are several versions of quantum wells which can ensure a strong resonant electronic nonlinearity ($\chi^{(2)} > 1$ nm V^{-1}) in a three-level scheme for obtaining the difference frequency on the intersubband transition in the middle- or far-IR range (3 – 100 μm)[2] and the simultaneous generation of two close fields on interband transitions in the optical and near-IR range (0.3 – 3 μm).

Most favorable are asymmetric quantum wells having, for instance, unequal barriers (Fig. 2) or a stepwise bottom [32 – 34], in which the dipole moments of all (two interband and one intersubband) transitions involved are allowed and their product, which appears in the expression for resonance nonlinearity [30, 33, 43], is rather large. In this case, use can be made of the intersubband transition both for electrons and (heavy) holes, bearing in mind the generation of the difference frequency in the middle- and far-IR ranges, respectively [30 – 32].

Particular attention should be given to the possibility of employing symmetric quantum wells, say, on the basis of GaAs structures: their parameters can easily be selected in such a way that the ground level of light holes lh1 practically coincides with the first excited level of heavy holes hh2 (a four-level scheme) [30, 33, 34]. Then, despite the fact that the transitions between the ground or first excited level of electrons and the first excited or ground state level of heavy holes (e1 – hh2 and e2 – hh1), respectively, are forbidden, the simultaneous lasing on the e1 – hh1 transition (commonly used in heterolasers) and the allowed e1 – lh1 transition, related to light holes, is possible.[3] Expected in this case is the resonance parametric excitation of the far-IR radiation for the allowed hh1 – hh2 transition, which practically coincides with the hh1 – lh1 transition in frequency.

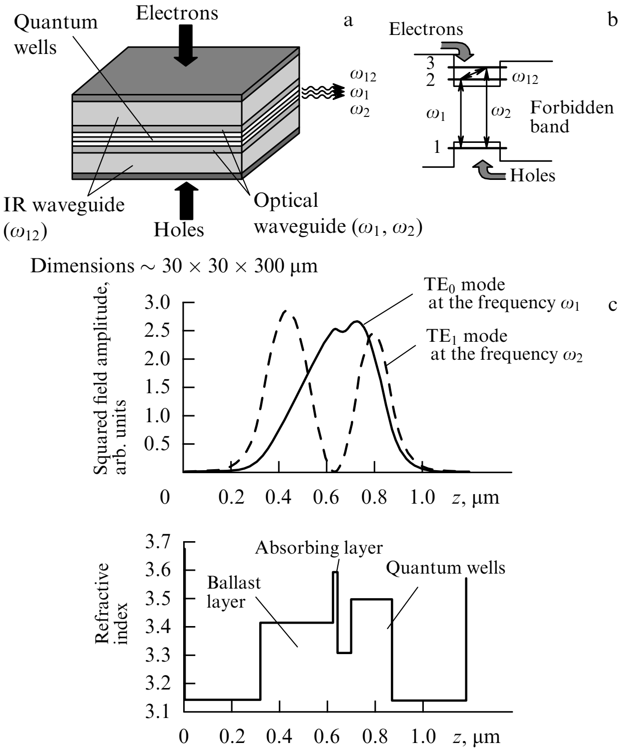

Figure 2. Nonlinear-mixing laser utilizing the electronic nonlinearity of quantum wells: (a) schematics of the laser diode; (b) diagram of operating size quantization levels in an asymmetric quantum well; (c) example of the calculation of optical waveguide structure in the case of GaAs/$Al_{0.12}Ga_{0.88}As/Al_{0.35}Ga_{0.65}As$ stepwise quantum wells, which furnish the generation of radiation at the $\lambda_1 = 0.789$ μm, $\lambda_2 = 0.721$ μm, and $\lambda_{12} = 8.26$ μm wavelengths.

The feasibility of two-color lasing in the near-IR range for injection heterolasers with different symmetric quantum wells embedded in a conventional planar waveguide is well known and has been experimentally borne out [13, 44 – 46]. When the pumping is strong enough, it is also not in doubt for the above quantum wells with two close interband transitions if their dipole moments are comparable in magnitude (see Fig. 2). However, combining the lasing active regions of both optical (near-IR) fields in the common (submicrometer) carrier injection region may be a certain disadvantage in the practical realization: it is expected, and the experiments of Refs [44 – 46] suggest so, that these two fields may, owing to the competition for the carriers, have comparable intensities

---

[2] In the submillimeter range, the broadening of size quantization levels comes practically to the photon energy $\hbar\omega_{12}$, i.e., to the difference between the frequencies being mixed. The resonance enhancement of electronic nonlinearity, therefore, becomes impossible and the decisive role is played by the lattice nonlinearity.

[3] The corresponding calculations of energy levels and transition dipole moments are performed on the basis of the well-known Kane model with the inclusion of mixing of light and heavy holes, which is responsible for the 'repulsion' of the hh2 and lh1 partial levels in the neighborhood of the above resonance.

only in a narrow range of pump currents — on the order of a few percent of the threshold current. [4]

The conditions for obtaining two- or multicolor lasing can be significantly relaxed by fabricating two or several different neighboring p–i–n injection regions to enable independent pumping of different multiwell heterolayers, which provide different frequencies of lasing in the optical or near-IR range. With this separation, different pumping regions and the corresponding quantum wells can be left within a common optical (dielectric) waveguide or spaced apart into the neighboring waveguides between which a strong optical coupling is retained (see Figs 3 and 4).

Both geometries may prove to be also convenient for ensuring spatial phase matching and maximizing the overlap integral for the interacting modes in the three-wave process under consideration. Finally, owing to the geometry of separation of the regions with different laser frequencies, deeper (asymmetric) quantum wells, which are responsible for longer wavelengths and the resonance electronic nonlinearity, can be pumped, not by current, but by the optical radiation from the neighboring higher-frequency wells which can be simple (symmetric) and well-suited for current pumping. Such a mixed method of pumping permits us to restrict ourselves to conventional laser heterostructures with a single p–n junction.

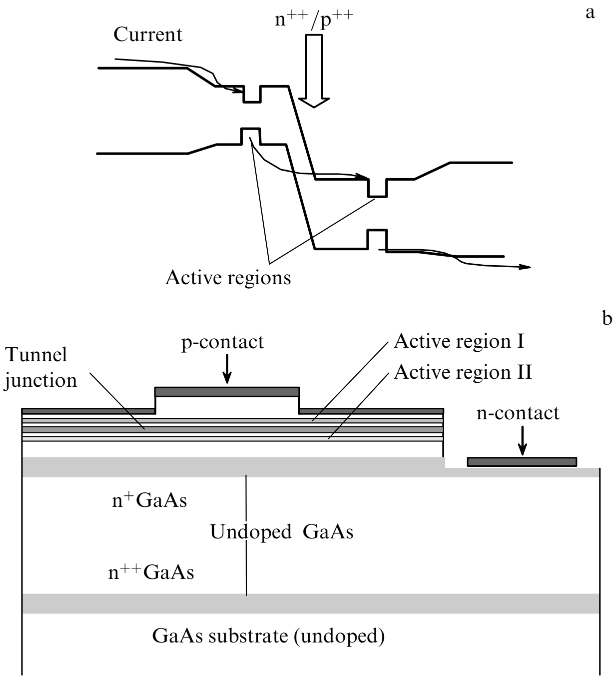

Figure 3. (a) Schematics of current flow in an interband cascade laser with a tunnel junction [48]; a heavily doped tunnel-transparent p^{++}/n^{++} layer leads to successive current flow through the active regions to ensure their pumping and two-wave lasing. (b) Simplified schematics of a two-section GaAs-based laser with a tunnel junction and a side contact, making possible the use of an undoped substrate and a waveguide layer for the terahertz mode. The heavily doped n^{++} layer constitutes the lower wall of the terahertz waveguide. The generation of the difference frequency may proceed both with the use of resonance electronic and bulk lattice nonlinearities.

According to Fig. 3, in the case of a common optical waveguide, the formation of two (or several) adjacent pumping regions corresponding to different active layers is possible due to the placement of a very narrow (tens of nanometers) heavily doped n^{++}/p^{++} tunnel junction between the neighboring regions of different quantum wells. The efficiency of a tunnel junction operating as a backward diode in various optical and near-IR laser structures has been repeatedly demonstrated [47–50]. The proposed interband cascade laser scheme eliminates the problem of wells competing for the pump and makes possible the lasing of two (or several) TE modes that are close in frequency, profile, and amplitude. In this case, the overlap integral optimization and the phase matching of the waves of beats of these modes with the generated terahertz waves are effected by selecting the positions and concentrations of guiding (restricting) layers and doped n^+ and n^{++} layers, which govern, along with the upper metallic contact, the structure and losses of the difference-frequency TM modes. The current injection through the side contact in the additional n^+ layer and the employment of wide undoped layers (between n^+ and n^{++}) in such 'double plasma' waveguides [5], which have been approbated in the intersubband quantum cascade lasers [19, 20, 51], allow us to reduce the losses of terahertz TM modes to an acceptable level of tens of cm^{-1}.

We note one peculiarity in the realization of this scheme characteristic of typical heterostructures, for instance, GaAs/AlGaAs on a GaAs substrate or InGaAs/AlGaAs on an InP substrate, which arises in going over from the long- to short-wavelength part of the terahertz range. Namely, for about $\lambda < 50$ μm it becomes difficult to satisfy the phase matching condition for the least-damped (principal) TM mode and the wave of beats of two close TE modes of equal order (0, 1, 2, ...). Moreover, it is not easy to overcome the damping of the higher-frequency mode (out of these two) caused by the presence of quantum wells that generate the lower-frequency one, unless a reasonable level of pump current is exceeded. Both problems specified above can be solved by a small modification of waveguide design to ensure transfer of the higher-frequency lasing (ω_2) to a higher-order mode, say, TE$_1$ in place of TE$_0$, so that the neighborhood of the node of its electric field coincides with the layer of the wells that generate the lower-frequency mode TE$_0(\omega_1)$. (On the attainment of phase matching due to higher-order modes, see Refs [32, 33, 35, 53] and below.) In this case, instead of a 'double plasma' waveguide in the interband cascade laser, by the way, the use of a conventional surface 'plasma' wave pressed against the upper metal contact is made possible, as is done in intersubband quantum cascade lasers currently in operation at wavelengths of 10–25 μm [19, 54]. For intermediate values of $\lambda \sim 50$ μm, it is also possible to manage without the lower heavily doped n^{++} layer (see Fig. 3); all one needs to do is to displace the contact n^+ layer slightly deeper into the structure and increase the degree of its doping, so that the terahertz TM mode is largely sandwiched between the layer and the upper metal contact and its losses remain at a level of $\lesssim 100$ cm^{-1}.

Referring to Fig. 2c, the above way of attaining the phase matching in the mixing of the principal TE$_0(\omega_1)$ and higher

---

[4] This circumstance is of no particular significance when use is made of a broadband optical pump which covers the frequency range between ω_1 and $2\omega_2 - \omega_1$.

[5] To make the second (lower) part of the terahertz waveguide metallic, like Ref. [52], is usually not a good solution for the technology and for our purposes: in this case, it is difficult to satisfy the condition of phase matching with the nonlinear wave of beats of short-wavelength modes in a medium with a positive dispersion typical for semiconductors.

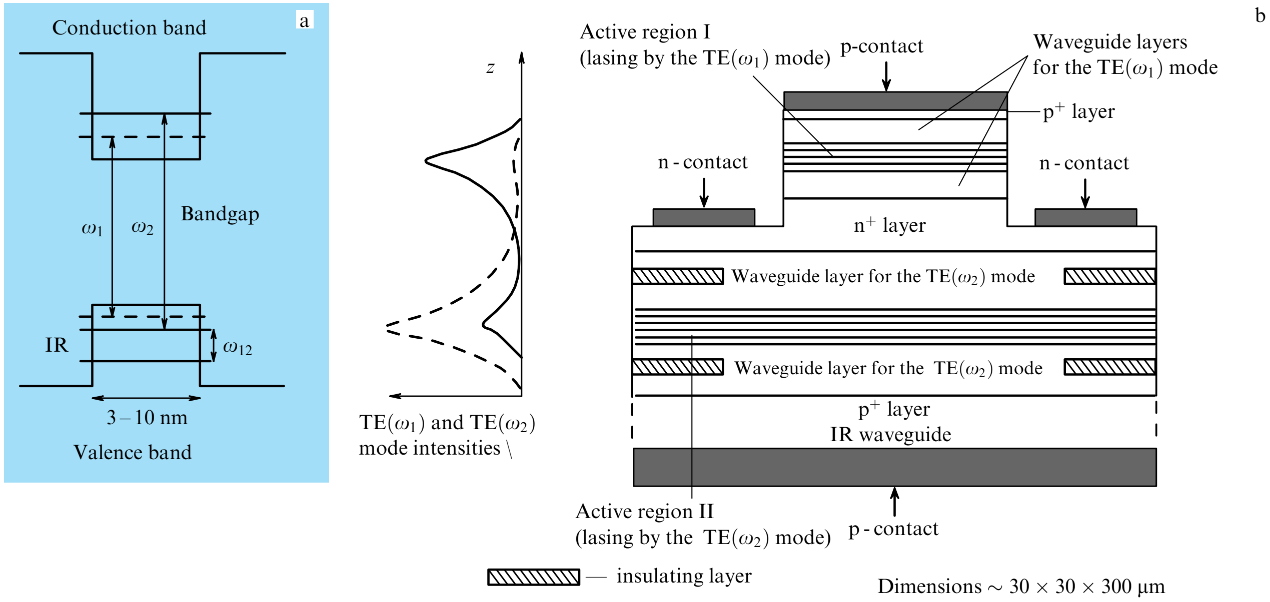

Figure 4. Semiconductor transistor laser for multifrequency optical (near-IR) and infrared (terahertz) generation: (a) combined system of levels in the quantum wells (dashed line — active region I, solid line — active region II); (b) schematics of a transistor laser and optical mode profiles. The insulating layers form the current channel for the injection pumping.

$\mathrm{TE}_1(\omega_2)$ modes can also be realized in a conventional heterostructure with a single type of 'three-level' quantum wells. But now the suppression of principal mode excitation at the higher frequency, $\mathrm{TE}_0(\omega_2)$, is ensured, not by the adjacent quantum wells generating the $\mathrm{TE}_0(\omega_1)$ mode, but by a special absorbing semiconductor layer whose energy gap width is selected approximately in the middle between $\hbar\omega_1$ and $\hbar\omega_2$. The ballast layer in Fig. 2c ensures that this absorption layer is made coincident with the node of the $\mathrm{TE}_1(\omega_2)$-mode field. At room temperature, this version is appropriate only when the frequency difference $\omega_2 - \omega_1$ is large enough, i.e., for the generation of the difference mode ω_{12} actually in the middle-IR range. In this case, its waveguide can be completely dielectric (Fig. 2a), like in the corresponding intersubband cascade lasers [19, 22, 55].

In both cases under discussion, the magnitude of the overlap integral of the three interacting modes $\mathrm{TE}_0(\omega_1)$, $\mathrm{TE}_1(\omega_2)$, and $\mathrm{TM}_0(\omega_{12})$ for electronic nonlinearity (for which the location of 'three-level' quantum wells is of significance) proves, as a rule, to be much higher than its magnitude for lattice nonlinearity, since the $\mathrm{TE}_0(\omega_1)$ and $\mathrm{TE}_1(\omega_2)$ modes are nearly orthogonal and the nonuniformity of the $\mathrm{TM}_0(\omega_{12})$ mode is smooth on their scale. However, the contribution of lattice nonlinearity in an interband cascade laser with a tunnel junction can be increased many-fold by making the tunnel junction doping so heavy that the difference (terahertz) mode profile in its neighborhood becomes strongly nonuniform and the contribution from one (upper) half of the profile of the higher $\mathrm{TE}_1(\omega_2)$ mode is suppressed in the overlap integral. As calculations suggest, in the mixing of modes of one type — the principal $\mathrm{TE}_0(\omega_1)$ and $\mathrm{TE}_0(\omega_2)$ modes or the higher-order $\mathrm{TE}_1(\omega_1)$ and $\mathrm{TE}_1(\omega_2)$ modes — the contribution of lattice nonlinearity for the difference TM_0 (or TM_1) mode in the long-wavelength part of the terahertz range proves to be decisive for typical heterostructures, even though the number of 'three-level' quantum wells in use is greater than 10.

Reverting to the problem of the independent pumping of two adjacent layers of different quantum wells with close basic transition frequencies ω_1 and ω_2, which is encountered in obtaining two-color lasing, we dwell on the promising transistor laser scheme [33, 34] (Fig. 4). Here, a dielectric waveguide of its own is made for each of the modes being mixed. At the center of each waveguide is an active layer of quantum wells (or quantum dots), which coincides with the corresponding domain of one of the two p – n junctions in the transistor. (The separated but strongly coupled dielectric waveguides can also be employed in the scheme of an interband cascade laser with a tunnel junction, see Fig. 3.) Applying bias voltages across the p – n junctions ensures independent control of the excitation conditions and intensities of both modes. At the same time, the realization of a relatively strong optical coupling between the adjacent waveguides, resulting in a substantial modification of their partial modes, ensures a large magnitude of the overlap integral of the normal modes. The latter may be either principal or higher-order ($\mathrm{TE}_{0,1,2}$) modes, depending on the losses, optical coupling, and optical confinement factors. Modifying their transverse profiles (along the vertical z-axis in Fig. 4) makes it possible to efficiently vary the difference of their longitudinal propagation constants (by varying the composition and the thickness) and attain its coincidence (phase matching) with the propagation constant for the difference mode: $k_{12} = k_2 - k_1$. By the way, comparing this expression with the resonance condition $\omega_{12} = \omega_2 - \omega_1$ shows that the phase matching in a weakly stratified semiconductor heterostructure, which normally possesses positive dispersion and does not exhibit significant anisotropy, is impossible to attain without participation of surface waves (plasmons), because the group velocity of waves in a bulk semiconductor in the near- or middle-IR range differs from the phase velocity of waves in the far-IR or terahertz range.

According to calculations performed for typical heterostructures based, say, on $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ or $\mathrm{In}_x\mathrm{Ga}_{1-x}\mathrm{AsP}$, the main obstacle which may prejudice the use of the proposed transistor laser to obtain terahertz radiation with a relatively high power is the necessity of doping the structure for the realization of current pumping, leading to significant Drude losses caused by free carriers, particularly in the long-wavelength part of the spectrum. In order to reduce these losses, the laser may be grown on a semi-insulating substrate (like the cascade laser with a tunnel junction in Fig. 3) and all three contacts, including the contact on the lower p^+ layer in Fig. 4, may be brought out to the top.

For those semiconductor structures in which this measure would not permit employing the current pumping, the terahertz (or submillimeter) mode absorption can be reduced only by complete elimination of doping and by going over to external optical pumping which produces carriers only in quantum wells, i.e., pumping represented by photons with energies lower than the energy gap width of barriers and waveguide layers. Should such pumping be effected with femtosecond laser pulses propagating parallel to the heterolayers, in the structure with 'three-level' quantum wells it is possible to attain efficient difference-frequency generation of ultimately short (containing only a few periods of field oscillation) pulses of the middle- or far-IR range due to the mixing of resonantly coupled spectral components of the optical pump pulse. Obtaining few-cycle terahertz radiation pulses is also possible in superradiant two-color lasers with continuous pumping [56, 57].

At present, technological and experimental studies are being actively pursued on the above and other similar schemes for the intracavity difference-frequency generation of infrared and terahertz radiation reliant on the electronic and/or lattice nonlinearity of semiconductor heterolasers with injection, optical, and mixed pumping. In the nearest future, one would therefore expect the realization of this new kind of compact radiation sources, continuously operating at room temperature and possessing an output power up to a fraction of a milliwatt in the terahertz range and up to many milliwatts in the middle-IR range.

This work was partly supported by grants from RFBR No. 02-02-17536, NSh-1744.2003.2, ONR, AFOSR, DARPA, the Research Corporation, the Welch Foundation, the Texas Advanced Research Program, and the TAMU Telecommunication and Informatics Task Force Initiative.

References

1. Miles R E, Harrison P, Lippens D (Eds) *Terahertz Sources and Systems* (NATO Science Series, Ser. II, Vol. 27) (Dordrecht: Kluwer Acad. Publ., 2001)
2. Mittleman D (Ed.) *Sensing with Terahertz Radiation* (Springer Series in Optical Sciences, Vol. 85) (Berlin: Springer-Verlag, 2003)
3. Van der Weide D *Opt. Photonics News* **14** (4) 48 (2003); Negirev A A, in *Vakuumnaya SVCh Elektronika* (Vacuum Microwave Electronics) (Ed.-in-Chief M I Petelin) (Nizhnii Novgorod: IPF RAN, 2002) p. 93
4. Svelto O *Principles of Lasers* 2nd ed. (New York: Plenum Press, 1976) [Translated into Russian (Moscow: Mir, 1984)]
5. Dyakonov M, Shur M S, see [1] p. 187; Knap W et al. *J. Appl. Phys.* **91** 9346 (2002); *Appl. Phys. Lett.* **80** 3433; **81** 4637 (2002)
6. Hu B B, Zhang X-C, Auston D H *Phys. Rev. Lett.* **67** 2709 (1991); Li M et al. *Proc. SPIE* **3616** 126 (1999); Bespalov V G et al. *Opt. Spektrosk.* **93** 158 (2002) [*Opt. Spectrosc.* **93** 148 (2002)]
7. Kersting R et al. *Phys. Rev. Lett.* **79** 3038 (1997)
8. Matsuura S, Tani M, Sakai K *Appl. Phys. Lett.* **70** 559 (1997); Chen Q et al. *Opt. Lett.* **25** 1122 (2000)
9. Colson W B, Pellegrini C, Renieri A (Eds) *Laser Handbook* Vol. 6 *Free Electron Lasers* (Amsterdam: North-Holland, 1990); Colson W B *Nucl. Instrum. Meth. Phys. Res. A* **407** 26 (1998)
10. Shi W et al. *Opt. Lett.* **27** 1454 (2002); *Opt. Photonics News* **13** (12) 57 (2002)
11. Shikata J et al. *IEEE Trans. Microw. Theory Tech.* **MTT-48** 653 (2000); Imai K et al. *Appl. Phys. Lett.* **78** 1026 (2001)
12. Tacke M *Infrared Phys. Technol.* **36** 447 (1995); Hodges M, Schiessl U P *Proc. SPIE* **3628** 113 (1999)
13. Kapon E (Ed.) *Semiconductor Lasers* (San Diego: Academic Press, 1999)
14. Andronov A A et al. *Pis'ma Zh. Eksp. Teor. Fiz.* **30** 585 (1979) [*JETP Lett.* **30** 551 (1979)]; *Opt. Quant. Electron.* **23** (2 Spec.) S205 (1991); Shastin V N *Opt. Quant. Electron.* **23** (2 Spec.) S111 (1991)
15. Gousev Yu P et al. *Appl. Phys. Lett.* **75** 757 (1999)
16. Bründermann E, Chamberlin D R, Haller E E *Appl. Phys. Lett.* **76** 2991 (2000)
17. Faist J et al. *Science* **264** 553 (1994)
18. Faist J et al., in *Intersubband Transitions in Quantum Wells: Physics and Device Applications II* (Semiconductors and Semimetals, Vol. 66, Eds H C Liu, F Capasso) (New York: Academic Press, 2000) p. 1
19. Capasso F et al. *Phys. Today* **55** (5) 34 (2002); *Opt. Photonics News* **12** (5) 40 (2001)
20. Köhler R et al. *Nature* **417** 156 (2002)
21. Colombelli R et al. *Appl. Phys. Lett.* **78** 2620 (2001)
22. Faist J et al. *IEEE J. Quantum Electron.* **QE-38** 533 (2002)
23. Gauthier-Lafaye O et al. *Appl. Phys. Lett.* **71** 3619 (1997); **74** 1537 (1999)
24. Orlova E E et al. *Phys. Status Solidi B* **210** 859 (1998); *Physica B* **302–303** 342 (2001)
25. Pavlov S G et al. *Phys. Rev. Lett.* **84** 5220 (2000); in *Towards the First Silicon Laser* (NATO Sciences Series, Ser. II, Vol. 93, Eds L Pavesi, S Gaponenko, L Dal Negro) (Boston, Mass.: Kluwer Acad. Publ., 2003) p. 331; Shastin V, ibid, p. 341
26. Hübers H-W et al. *Physica B* **308–310** 232 (2001); *Appl. Phys. Lett.* **74** 2655 (1999)
27. Aleshkin V Ya et al., in *Nanofotonika* (Nanophotonics) (Nizhnii Novgorod: IFM RAN, 2002) p. 236; Aleshkin V Ya, Andronov A A *Pis'ma Zh. Eksp. Teor. Fiz.* **68** 73 (1998) [*JETP Lett.* **68** 78 (1998)]
28. Vorob'ev L E *Pis'ma Zh. Eksp. Teor. Fiz.* **68** 392 (1998) [*JETP Lett.* **68** 417 (1998)]; Singh J *IEEE Photonics Technol. Lett.* **8** 488 (1996)
29. Vorobjev L E et al., in *Proc. of the 7th Intern. Symp. Nanostructures: Physics and Technology, St. Petersburg, 14–18 June 1999* (St. Petersburg: A F Ioffe Physicotechnical Institute, 1999) p. 423
30. Belyanin A A et al. *Phys. Rev. A* **63** 053803 (2001)
31. Belyanin A A et al. *Nanotechnology* **12** 450 (2001); *Proc. SPIE* **4605** 363 (2001)
32. Belyanin A A et al. *Izv. Ross. Akad. Nauk, Ser. Fiz.* **66** 247 (2002) [*Bull. Russ. Acad. Sci. Phys.* **66** 262 (2002)]; in *Nanofotonika* (Nanophotonics) (Nizhnii Novgorod: IFM RAN, 2002) p. 120
33. Belyanin A et al. *Phys. Rev. A* **65** 053824 (2002)
34. Belyanin A A et al. *Izv. Ross. Akad. Nauk, Ser. Fiz.* **67** 262 (2003) [*Bull. Russ. Acad. Sci. Phys.* **67** (2003)]
35. Aleshkin V Ya, Afonenko A A, Zvonkov N B *Fiz. Tekh. Poluprovodn.* **35** 1256 (2001) [*Semicond.* **35** 1203 (2001)]
36. Sirtori C et al. *Appl. Phys. Lett.* **65** 445 (1994)
37. Capasso F et al., in *Intersubband Transitions in Quantum Wells: Physics and Device Application II* (Semiconductors and Semimetals, Vol. 66, Eds H C Liu, F Capasso) (New York: Academic Press, 2000) p. 85
38. Liu et al., in *Nonlinear Optics: Materials, Fundamentals and Applications*, OSA Technical Digest, Vol. 56 (Washington DC: Optical Society of America, 2000)
39. Knurgin J B, in *Nonlinear Optics in Semiconductors II* (Semiconductors and Semimetals, Vol. 59, Eds E Garmire, A Cost) (San Diego: Academic Press, 1999)
40. Owschimikow N et al. *Phys. Rev. Lett.* **90** 043902 (2003)
41. Korsunsky E A, Kosachiov D V *J. Opt. Soc. Am. B* **17** 1405 (2000)
42. Chow W W, Koch S W *Semiconductor-Laser Fundamentals: Physics of the Gain Materials* (Berlin: Springer-Verlag, 1999)
43. Belyanin A A et al. *Phys. Rev. A* **64** 013814 (2001)
44. Tokuda Y et al. *Appl. Phys. Lett.* **49** 1629 (1986); Ikeda S, Shimizu A *Appl. Phys. Lett.* **59** 504 (1991)

45. Chen T R et al. *Appl. Phys. Lett.* **60** 2954 (1992); Kaneko Y et al. *J. Appl. Phys.* **87** 1597 (2000)
46. Aleshkin V Ya et al., in *Nanofotonika* (Nanophotonics) (Nizhnii Novgorod: IFM RAN, 2003) p. 315
47. Schmid W et al. *Electron. Lett.* **34** 553 (1998)
48. Kim J K et al. *Appl. Phys. Lett.* **74** 3251 (1999); **77** 3137 (2000)
49. Ozden I et al. *Appl. Phys. Lett.* **79** 2532 (2001)
50. Malyarchuk V et al. *J. Appl. Phys.* **92** 2729 (2002)
51. Rochat M et al. *Appl. Phys. Lett.* **73** 3724 (1998); Ulrich J et al. *Appl. Phys. Lett.* **77** 1928 (2000)
52. Rochat M et al. *Appl. Phys. Lett.* **78** 1967 (2001)
53. Oster B, Fouckhardt H *IEEE Photonics Technol. Lett.* **13** 672 (2001)
54. Sirtori C et al. *Opt. Lett.* **23** 1366 (1998)
55. Sirtori C et al. *Appl. Phys. Lett.* **75** 3911 (1999)
56. Belyanin A A et al. *Izv. Ross. Akad. Nauk, Ser. Fiz.* **66** 365 (2002) [*Bull. Russ. Acad. Sci. Phys.* **66** 394 (2002)]
57. Belyanin A A et al. *Laser Phys.* **13** 161 (2003)