Three-terminal semiconductor laser for wave mixing

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We suggest and analyze the concept of a semiconductor laser device that incorporates two basic ideas: (i) dual-wavelength generation of two optical fields on the interband transitions with independent control of each field in a three-terminal ''transistor'' scheme, and (ii) generation of infrared radiation in the 3–300 μm range due to nonlinear wave mixing of the above optical fields in the same laser cavity. Due to inversionless nature of the difference frequency generation and inherently low threshold current, the laser can be capable of continuous room-temperature operation in the mid/far-infrared and THz range.

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The purpose of this paper is to introduce a concept of three-terminal semiconductor laser based on *p-n-p* or *n-p-n* heterostructure (see Fig. 1) designed for generation of radiation at three wavelengths simultaneously: two optical fields at wavelengths corresponding to interband transitions in the visible or near-infrared range, and a third field at wavelength in the mid/far-infrared (IR) range, generated due to nonlinear mixing of the above optical fields. Such a nonlinear mechanism of IR generation avoids problems associated with lasing on the short-lived intersubband transition that become more and more challenging with moving to longer wavelengths. At present, the longest wavelength intersubband lasers operate is 24 μm achieved in quantum cascade lasers at cryogenic temperatures [1].

Moreover, independently on the possibility of IR generation, dual-wavelength operation in the three-terminal scheme can find important applications in integrated optoelectronics, optical communications, optical data processing, and spectroscopy.

The idea of IR generation in semiconductor lasers using resonant nonlinear mixing of self-generated fields has been proposed in our papers [2–4]. Similar scheme was discussed in Ref. [5], in which, however, it was proposed to use nonresonant lattice nonlinearity of a semiconductor crystal.

The advantages of nonlinear self-mixing scheme for the IR generation are as follows:

(1) Low pumping power is needed for the difference frequency generation. There is no need to maintain population inversion and large population of carriers on the excited subband, which was required to overcome modal losses in existing IR lasers. The threshold for IR generation is effectively defined by the threshold for dual-wavelength operation on the interband transitions, which requires considerably lower current densities.

(2) The scheme is scalable to the long-wavelength range beyond the reststrahlen region since the rapidly growing losses is not a killing factor for generation anymore.

In the schemes analyzed in Refs. [2–4], two optical fields with lower and higher frequencies were generated in the same active region on the interband transitions between the ground-state and excited subbands, respectively. Strong electric coupling between two modes and the necessity to achieve lasing from excited states led to an increase in the threshold current and required more complicated design of an active region and a waveguide, as compared to standard diode lasers. In the design discussed in this paper, two optical modes are generated on the interband transitions between ground electron and hole subbands in different active regions and are electrically decoupled.

A sketch of the proposed device is shown in Fig. 1. The laser has two different multiple quantum-well (MQW) active regions, where two optical fields at different frequencies are excited. An important feature is a three-contact ''transistor'' scheme with common gate electrode that is used here instead

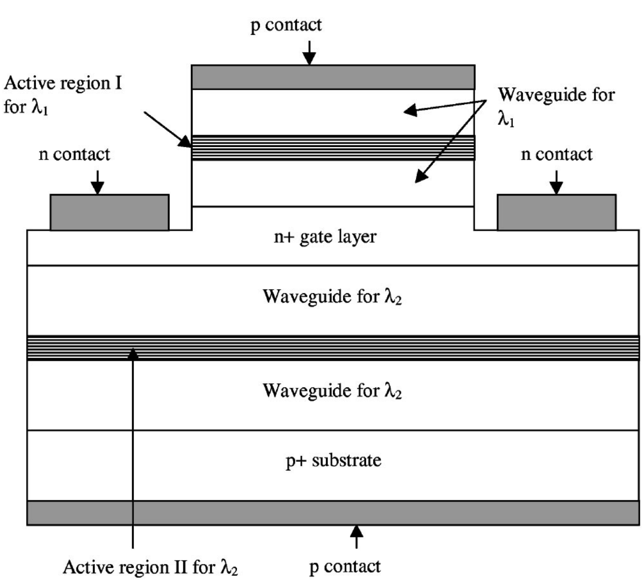

FIG. 1. Generic scheme of a three-terminal laser with electrically independent control of two optical modes generated at wavelengths λ_1 and λ_2. Difference frequency generation can occur in one of the active regions or in between.

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of a two-contact diode scheme usually employed in semiconductor lasers. Such a design permits convenient and largely independent control of intensities of the drive fields by using voltages applied between the common gate layer and each of the two *p* contacts. There are also two separate waveguides that maximize overlap of each mode with corresponding active region. They may have different composition in order to adjust the propagation constants of two optical modes for better phase matching with an IR mode. To achieve lateral confinement of current and optical modes, standard methods can be employed. The device can be implemented in any material system, e.g., in $Al_xGa_{1-x}As$ or $In_xGa_{1-x}As_yP_{1-y}$ compounds.

Note that the three-terminal design has been recently proposed to obtain a dual-wavelength operation of an $In_xGa_{1-x}N$ light emitting diode (LED) [6]. In that work, a strongly doped $p++/n++$ tunnel junction layer was introduced between two MQW segments that were emitting at two different wavelengths. The whole monolithic *n*-*p*-*n*-*p* structure operated as a vertical stack of two LED's with largely independent control of each LED. However, no wave mixing could occur with a suggested design.

To avoid misunderstanding, in the present paper, we do not intend to use the proposed device for the amplification of electric signals as in a real transistor. All we need is a convenient pumping scheme permitting electrically independent two-wavelength operation. Note also that there have been several efforts aimed at monolithic integration of lasers with field-effect transistors; see [7], and references therein. Successful implementation of a field-effect transistor that simultaneously worked as a lateral current injection laser (on one wavelength only) has been reported in Refs. [8,9]. These works did not attempt to make a dual-wavelength laser.

To generate the infrared at a difference frequency, one has to provide a sufficient overlap of the two drive fields. This can be done in several possible ways. The modes can be mixed in one of the active regions indicated in Fig. 1. Alternatively, an additional MQW layer specially designed for the resonant mixing can be inserted between two active regions. Below, we consider one example of the first option in more detail.

Figure 2 shows the layer sequence of an $Al_xGa_{1-x}As$/GaAs structure in which the mixing occurs primarily in one of the active regions. Optical fields are generated on the interband transitions between the ground electron and hole states in active regions I and II at wavelengths 845 nm and 833 nm, respectively. The vertical profiles of intensities of two optical modes at wavelengths, 833 nm and 845 nm are shown in Fig. 3. The mode at 845 nm has a second, slightly lower maximum at the position of active region II, where a considerable overlap with 833-nm mode occurs. Nonlinear mixing of the two modes leads to generation of far-infrared radiation at a difference frequency of 20 meV (in energy units) that corresponds to 62-μm wavelength. The efficiency of difference frequency generation depends on the value of nonlinear susceptibility $\chi^{(2)}$, modal losses for the IR field, and phase mismatch between the polarization wave at a difference frequency and the electromagnetic IR mode of the waveguide. The simplest design is to employ lattice nonlinearity of GaAs crystal. There is, however, a more interesting opportunity to use resonant electronic nonlinearity that is maximized, when all participating fields are close to resonance with corresponding interband and intersubband transitions. This case has been described in detail in our papers [2–4]. Under the optimal conditions, the nonlinear susceptibility associated with electronic nonlinearity can be of the order of resonant linear susceptibility, which provides a higher output power of IR radiation, shortens significantly the required length of a sample and relaxes requirements on the phase matching. There is no specific polarization mode selection associated with wave mixing in this case. Polarizations are mainly determined by the dipole moments of corresponding electronic transitions. If, however, the bulk nonlinearity of a crystal is employed, there is polarization mode selection determined by the symmetry of a crystal.

0.1 μm GaAs contact layer, p+ doped
0.8 μm AlGaAs cladding layer, x = 0.35, p-doped
20 nm AlGaAs layer, x = 0.2, undoped
MQW region for 845 nm wavelength. Five GaAs wells 8 nm each, separated by four AlGaAs (x = 0.2) barriers 10 nm each
20 nm AlGaAs layer, x = 0.2, undoped
0.3 μm AlGaAs cladding layer, x = 0.35, n-doped
0.3 μm AlGaAs gate layer, x = 0.35, n+-doped
0.3 μm AlGaAs cladding layer, x = 0.35, n-doped
30 nm AlGaAs layer, x = 0.2, undoped
MQW region for 833 nm wavelength. Six GaAs wells 6 nm each, separated by five AlGaAs (x =0.2) barriers 10 nm each
30 nm AlGaAs layer, x = 0.2, undoped
1.0 μm AlGaAs cladding layer, x = 0.35, p-doped
GaAs substrate, p-doped

FIG. 2. Principal layer sequence of the $Al_xGa_{1-x}As$/GaAs structure designed for generation at 62 μm due to wave mixing in active region II. Interfaces can be graded.

Such a sharp resonant enhancement of difference frequency generation was demonstrated in Ref. [10] using two external driving fields from CO_2 laser. In the present work we employ the driving fields that are intracavity generated in the same injection-pumped laser structure as a result of lasing on two interband transitions. The energy density of intracavity-generated drive fields can be made very high using reflection coating of the facets. Besides, employing self-generated drive fields provides the possibility of injection current pumping and also removes the problems associated with an external drive (beam overlap, drive scattering and absorption, spatial inhomogeneity), which were inherent in previous work on frequency down conversion in semiconductors.

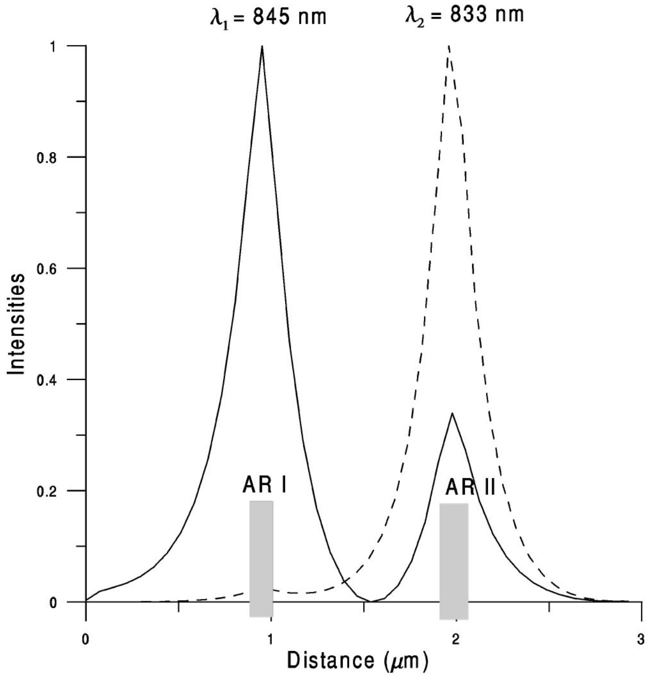

FIG. 3. Vertical profiles of normalized intensities of the optical modes at $\lambda_1=845$ nm (solid line) and $\lambda_2=833$ nm (dashed line) generated in the structure of Fig. 2. The distance is counted from the top of the structure. Wave mixing occurs due to overlap of two modes in active region II. Positions of active region I (AR I) and active region II (AR II) are indicated by shaded rectangles.

Figure 4 sketches a process of wave mixing in active region II. Here E_1 and E_2 are the electric field amplitudes of two optical modes generated in active regions I and II, respectively. The difference between frequencies of two optical fields, $\omega_2-\omega_1=\omega_{\mathrm{IR}}$, is equal to the frequency of a transition hh1-hh2 between the first and the second heavy-hole levels. The first light-hole level and the second heavy-hole level are separated by only few meV at the Γ point and are strongly mixed. The mixing maximizes the product of the dipole moments of two interband and one intersubband transitions that enters Eq. (1) for the far-infrared intensity. It also gives us the possibility to employ for generation of the IR field both the resonance with hh1-hh2 transition and the resonance with hh1-lh1 transition that becomes allowed at high enough hole densities.

The steady-state amplitude, E_{IR} of the IR field is calculated using general expressions derived in Ref. [2] on the basis of density-matrix formalism. An approximate result for the field intensity on the facet of a cavity of length L, which is obtained for the case when homogeneous linewidths of interband transitions, $e1$-hh1 and $e1$-lh1 are equal to the same value γ, the transition hh1-hh2 is homogeneously broadened with linewidth γ_{h12}, and $\omega_{\mathrm{IR}}\gg\gamma$ [actually, $\omega_{\mathrm{IR}}\simeq(3\text{-}4)\gamma$], is given by

$$|E_{\mathrm{IR}}(L)|^2\simeq\left(\frac{\pi\Gamma d_1 d_2 d_{h12}\Delta N}{\mu^2\hbar^2 c\,\gamma_{h12}}\right)^2\frac{|E_1|^2|E_2|^2}{\kappa^2+(\Delta k)^2}\times(1+e^{-2\kappa L}-2e^{-\kappa L}\cos\Delta kL). \qquad (1)$$

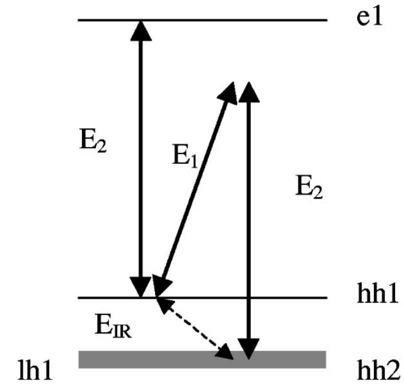

FIG. 4. A scheme of resonant nonlinear mixing of two optical fields E_1 and E_2 in active region II of the structure shown in Fig. 2. Infrared field E_{IR} is generated at wavelength 62 μm resonant to the transition between the ground and excited hole states.

There are also contributions to E_{IR}, that are proportional to $(\gamma/\omega_{\mathrm{IR}})^2$ and population difference on the interband transitions [2]. They become important in the limit of very high temperature of holes, when $\Delta N\simeq 0$. In Eq. (1), Γ is an optical confinement factor for the IR mode, μ the refraction index at IR frequency, c the light velocity in vacuum, d_1,d_2, and d_{h12} are the dipole moments of two interband transitions $e1$-hh1,$e1$-lh1, and the intersubband transition, respectively, ΔN is the volume density of population difference between the lower and upper hole subbands involved in generation, κ the modal losses of the IR field due to absorption and escape from the cavity, $\Delta k=k_2-k_1-k_{\mathrm{IR}}$, where $k_{1,2}$ and k_{IR} are the propagation constants of the optical modes and the IR mode, respectively.

It was assumed in Eq. (1), that the IR field is weak and does not deplete the driving fields.

In the limit of small losses, $L\ll 1/\kappa$, we recover the usual $[\sin(\Delta kL/2)/\Delta k]^2$ dependence of the IR intensity. However, for the present example of a structure, we have an opposite limit: $L\gtrsim 1/\kappa\sim 1/\Delta k\sim 100$ μm. In this case, all the terms containing $\exp(-\kappa L)$ can be dropped. When we substitute the values of parameters relevant for the structure under consideration, assume that the optical field intensity inside the cavity is of the order of saturation value, and use $\Delta N\sim 10^{18}$ cm^{-3},$\Gamma\sim 10^{-3}$, $\gamma\sim\gamma_{h12}$, we obtain the conversion efficiency to the infrared of order 10^{-5} with respect to the *intracavity* optical-field intensity. The corresponding IR intensity is in the microwatt range. This value can be increased by increasing the confinement factor for the IR mode and decreasing modal losses of the IR field in more sophisticated waveguide designs employing, e.g., a semi-insulating substrate or a surface mode. This issue will be considered elsewhere.

When the IR wavelength is increased beyond 100 μm to the tetrahertz range, the linewidth of an intersubband transition in quantum wells becomes comparable to the transition frequency, and the resonance condition does not give an appreciable benefit in the efficiency of wave mixing. It becomes more advantageous to use nonresonant lattice nonlinearity. In quantum dots the homogeneous width of an interlevel transition is believed to be sharper than in quantum wells, and the use of resonant wave mixing is feasible for longer wavelengths.

In conclusion, we have proposed a three-terminal semiconductor laser designed for dual-wavelength operation in the visible/near-infrared range with electrically independent control of two optical fields, and for simultaneous generation in the mid/far-infrared range due to nonlinear wave mixing of the above optical fields. A transistor like scheme provides rich opportunities for implementing various nonlinear optical processes in a compact, inexpensive, injection-pumped semiconductor device. As a dual-wavelength laser source, the three-terminal laser can be employed in many fields of applied optics, such as optical communications, data processing, integrated optoelectronics, and spectroscopy. Probably, the most important feature of the proposed laser is its potential to generate far infrared in the cw regime at room temperature. This is because the threshold current is determined by the threshold of generation on the interband transitions, which is expected to be of the same order as in standard MQW diode lasers.

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