3-6 AN UNIDIRECTIONAL LASER AMPLIFIER BY HOT ELECTRONS IN SEMICONDUCTOR

M. Yamanishi, T. Minami, and T. Kawamura
Department of Electrical Engineering, University of Osaka Prefecture
Mozu-Umemachi, Sakai, Osaka 591

It is desired that a laser has unidirectional characteristics when it is used as a stable amplifier without self-oscillations. But, there have been only a few lasers with unidirectional gain i.e. those caused by the travelling wave pumping of Doppler-broadened transitions[1)2)] in a gas laser and caused by the combination of a conventional laser to a saturable absorber.

Here, we propose a new unidirectional-semiconductor-laser, based on non-symmetrical distribution of electrons in the k-space. Consider an optically pumped laser, as shown in Fig. 1, where electrons and holes are drifted to the direction of a signal photon. The distributions of carriers are non-symmetrical, as shown in Fig. 2. In general, when an electron recombines to a hole the momentum of the system is conserved: $\vec{k}_c-\vec{k}_v=\vec{\beta}$ (β = the wavenumber of photon). In this case, the transition probability from the state-a to the state-b is larger than that from the a′ to the b′. Therefore, the gain for the forward photon of Fig. 1 will be larger than that for backward one.

ONE DIMENSIONAL ANALYSIS: Deriving an analytical form for transition matrix elements, which include effects of photon wavenumber, from k.p perturbation theory[3)] and assuming the displaced F-D distributions for mobile carriers as follows[4)]:

$$f_c=1/1+\exp\{\hbar^2(\vec{k}_c-m_c\vec{v}_e/\hbar)^2/2m_c\kappa T_e-\mu_c\},\qquad f_v=1/1+\exp\{\hbar^2(\vec{k}_v-m_v\vec{v}_h/\hbar)^2/2m_v\kappa T_h+\mu_v\} \qquad (1),$$

where T_e and T_h are electron-temperature and hole-temperature, respectively and they are not always equal to lattice temperature, the gain coefficient for stimulated emission can be written as an analytical form which include the effects of the β which have been neglected in usual treatments[5)]. But, only numerical examples are illustrated because of the complex form of the expression.

Under the condition of $v_e=10^7$ cm/sec, there are significant differences in the gains for forward photons and for backward ones, as shown in Fig.3 for GaAs. For the virtual high refractive index i.e. the virtual high values of the β's (a practical methode for realizing these high refractive index will be mentioned in latter), there are much larger differences in gains, as shown in Fig. 4.

PERIODIC WAVE GUIDES: a periodic wave guide, as shown in Fig. 5, may be used to realize the effective high refractive index by space harmonics. Assuming the pitch of corrugation d is smaller than half the wave-length, there is no power transfer from a guided mode to radiation modes, and consider only the lowest order TE mode. By Floquet's theorem, the field quantities of the guided mode are given as the infinite sum of space harmonics[6)]. The energy, associated with the lowest order TE mode , is written as the collection of harmonic oscillators:

$$W=(1/2)\sum_\beta\{\dot{q}_\beta^\dagger\dot{q}_\beta+\omega_\beta^2 \times q_\beta^\dagger q_\beta\}\sum_{m}\int\varepsilon(x)\,|a_{\beta m}(x)|^2 d\vec{r} \qquad (2)$$

where $a_{\beta m}$ is the amplitude of vector potential of m-th space harmonic. Therefore, the field of guided wave can be quantized and the vector potential is given in a operator form as follows:

$$A=\sum_\beta(\hbar^2/2E_\beta S\varepsilon_0)^{1/2}\left[b_\beta\sum_m a'_{\beta m}\exp\{i(\beta_m z-\omega_\beta t)\}+b_\beta^\dagger\sum_m a'_{\beta m}\exp\{i(\omega_\beta t-\beta_m z)\}\right] \qquad (3)$$

$$(\beta_m=\beta+2\pi m/d\ ,m=\text{integer})$$

where b_β and $b_\beta^\dagger$ represent the annihilation and creation operator of guided-mode-photon, respectively, β_m is the wave number of m-th harmonic , and S is the cross sectional area in y-z plane. By perturbation theory, the gain coeffeicient of the guided mode is obtained as follows:

$$g=e^2tM^2m_cm_v/(8\pi^3m_0^2\varepsilon_0|m_v-m_c|E_\beta)\sum_m\{a'_{\beta m}(x=0)\}^2\sum_{\Delta k_x}\{\sin(\alpha_m-t)\Delta k_x/(\alpha_m-t)\Delta k_x+\sin(\alpha_m+t)\Delta k_x/(\alpha_m+t)\Delta k_x\}^2$$

$$\times\int(f_c-f_v)\,\delta(E_e-E_h-E_\beta)\,d\vec{k}/v_{g\beta}$$

M: matrix element

$$(\Delta k_x=(\pi/t)n,\ n=\text{integer})\quad v_{g\beta}:\text{group velocity} \qquad (4)$$

where the term of the summation on Δk_x represents the uncertainty of the x-component of the momentum of the guided-mode-photon and the integration represents the conservation of z-component of the momentum and of the energy in the system. If the pitch d is enough small (for example, 0.1 μ), the β_m's for higher space harmonics take sufficient large values. Under the condition that the normalized amplitude of m-th space harmonic $a'_{\beta m}$ becomes considerable value in the wave guide with small pitch, one may expect an unidirectional amplification..Numerical examples on the periodic wave guide will be presented.

The operation of the above device will be disturbed by band-to-impurity transitions and exciton recombinations. But, a pure semiconductor can be used because the proposed device does not need a p-n junction. Also, the recombination probability,due to exciton recombination, may be small under high electric field since the excitons are impact-ionized by the drifting carriers[7]. The electron-lattice and electron-electron collisions will disturbe the momentum conservation, but the influence of the collisions for higher space harmonics will be smaller than that for fundamental component because of the large values of β'_ms for higher harmonics.

The corrugation pitch of the order of 0.1μ will be realized by the ion milling technics[8] in near future. This proposed device will have great potentiality in its applications to optical information processing device and optical IC element. Preliminary experiments are in progress.

References

1) N.Skribanowitz et al: Appl. Phys. Letters 19, 161 (1971).
2) N.Skribanowitz et al: ibid 20, 428 (1972).
3) E.O.Kane: J. Phys. Chm. Solids 1, 82 (1956).
4) E.M.Conwell: High Field Transport In Semiconductors, Academic Press (1967).
5) C.H.Gooch: GaAs Lasers, Wiley-Interscience (1969).
6) F.W.Dabby et al: Optics Com. 6, 125 (1972).
7) A.R.Hartman et al: Proc. 10th Conf. Phys. Semiconductors 202 (1970).
8) H.L.Garvin: Private communication (presented at Kodak Microelectronics Seminar, Dec 1972).

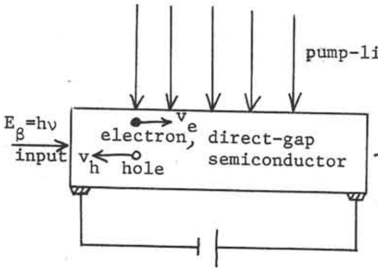

FIg. 1

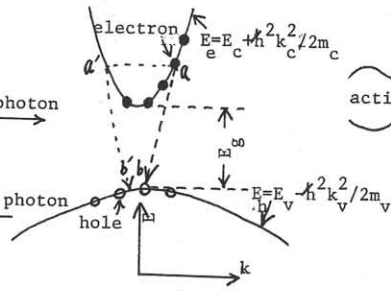

Fig. 2

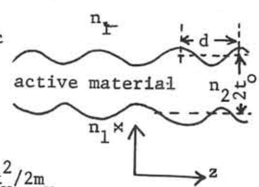

Fig. 5

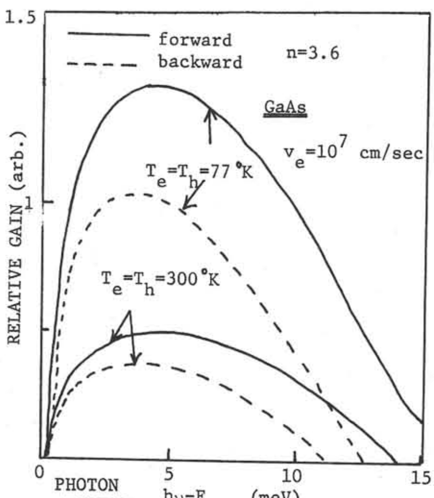

Fig. 3 (quasi-Fermi-level from band edge: μ_c=5 meV, μ_v=11.8 meV)

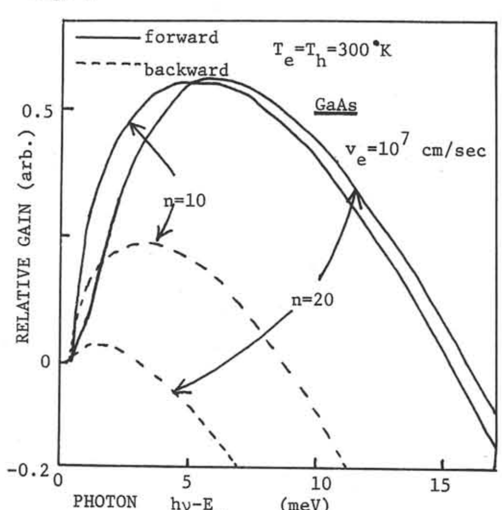

Fig. 4 μ_c=5 meV, μ_v=11.8 meV