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Soichi Kobayashi (M'80), for a photograph and biography, see this issue, p.427.

Yoshihisa Yamamoto (S'75–M'80), for a photograph and biography, see this issue p. 421.

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Tatsuya Kimura (S'63–M'68–SM'78), for a photograph and biography, see p. 64 of the January 1982 issue of *IEEE J. Quantum Electron.*

Superhigh Differential Quantum Efficiency and Strong Self-Sustained Pulsation in CW DH Laser Diodes

CHI-MING WANG, LI-QING ZHAO, WAN-RU ZHUANG, JING-MING CHANG, CHUN-SHAN CHANG, AND ZHEN-QIU WU

Abstract—**Some experimental results in GaAs DH lasers having a stable, long operating-time, such as nonlinear superhigh differential quantum efficiency, the behavior of light output saturation and sudden growth again in the same filament, strong self-sustained pulsation, and so on, are presented. A model of double filaments caused by the nonuniform distribution of aluminum in the active layer of the laser diode is presented to explain their anomalous behavior qualitatively.**

I. Introduction

THE transient response in laser diodes is an important factor for application to optical communication. At present, the self-sustained pulsations appearing in AlGaAs DH laser diodes interest scientists and engineers. Some mechanisms causing pulsation have been suggested, such as second order mode locking [1], deep-level traps [2], and saturable absorption effect [3]–[5], and so on, but more attention is paid to the latter.

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We also have observed this behavior in AlGaAs DH laser diodes made in our laboratory and found some new phenomena. The devices are made by conventional LPE technology on (100) plan of GaAs substrate. Five layers are grown. They are n-GaAs (buffer layer), N-$Al_{0.35}Ga_{0.65}As$ (Te-doped), p-$Al_{0.05}Ga_{0.95}As$ (Si-doped active layer), P-$Al_{0.35}Ga_{0.65}As$ (Ge-doped), and p-GaAs (Ge-doped cap layer). The thickness of the active layer is about 0.3-0.5 μm. Other parameters are the same as those in [6]. The stripe-geometry structure is formed by proton bombardment with a stripe width of 12 μm. The length of the cavity is about 300 μm. The depth on the proton bombardment is just inside the p-type confined layer. Contacts of Cr–Au–Zn and Au–Ge–Ni are applied to the p-side and substrate side of the chips, respectively. The CW threshold current density J_{th} is about 1000-3000 A/cm^2.

II. *L–I* Characteristics on Laser Diodes

Most laser diodes have a normal *L–I* curve without "kinks," but some are quite different.

Two kinds of anomalous dc *L–I* curves have been measured as shown in Fig. 1. Laser diodes *A* show an anomalous wide flat step, while laser diodes *B* show an anomalous superhigh

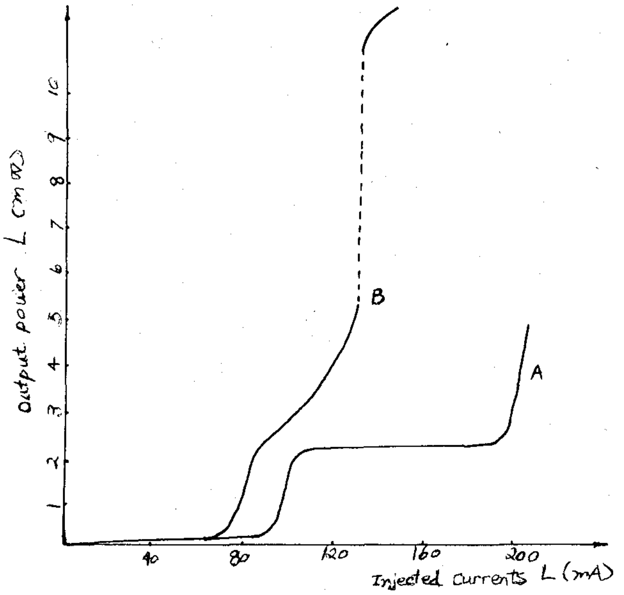


Fig. 1. DH laser L-I characteristics.

differential quantum efficiency at certain values of current. Sometimes, both anomalous characteristics are present together in the same diode. The important fact is that the operating time of these lasers could at least exceed more than several thousand hours.

III. Near-Field Pattern

The near-field pattern in these laser diodes have been observed, especially in diode B, at various operating currents. The space resolution is about 1 μm. As shown in Fig. 2, two filaments lasing in this diode appeared at a certain higher injection current (185 mA). When the operating current is below this value, there is only one filament present. It is interesting that when the operating currents are between 141 and 185 mA, the optical output powers are nearly tending to saturation, which corresponds to the flat step in the L-I curves. However, if we increase the operating current to 195 mA, the second new filament L_2 will grow rapidly and the first filament L_1 will suddenly increase at the same time. Consequently, the total light output suddenly increases. This nonlinear effect results in the superhigh η_{ext} presented in the laser diode.

IV. Polarizing Characteristics

TE and TM polarizing mode radiation have been measured in these diodes. According to Fig. 3, we can see that, for these laser diodes, the light output is predominantly TE polarized. The lower TM mode light output only represents the spontaneous radiation in the laser diode. There are two flat steps present in the TM mode output curve. These behaviors are just the opposite to those in the TE mode output curve. It means the saturation of the spontaneous radiation and lasing in the diode. Obviously the first flat step means lasing in filament L_1. Between B and C, the spontaneous radiation is unsaturated and continuously increases. It means that, at the very beginning from B, the radiation of filament L_2 contributes to the total TM mode output dominantly.

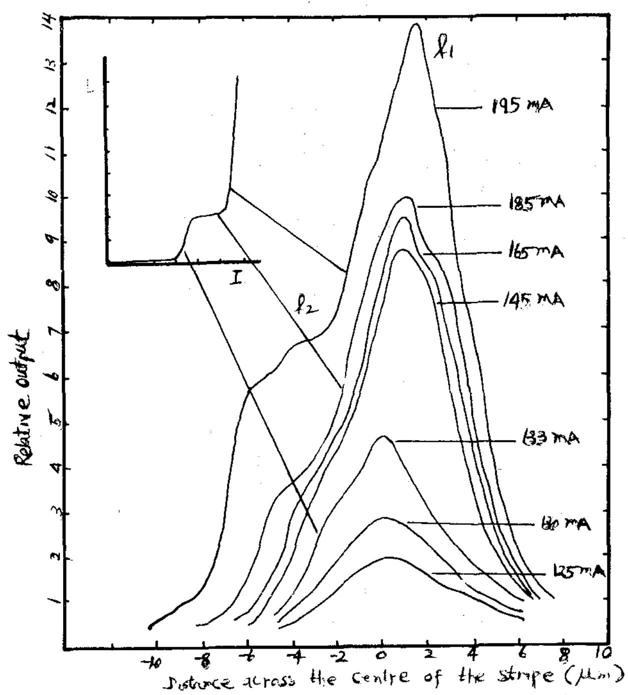


Fig. 2. Near-field pattern of 23-001# laser at different currents.

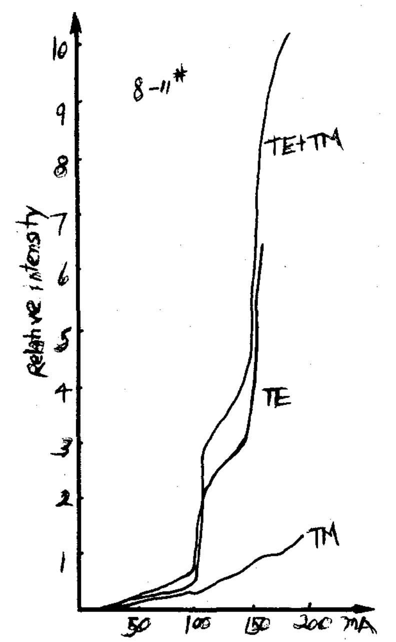


Fig. 3. L-I characteristics with TE and TM polarization.

V. Lasing Spectra

Initially, we measured the lasing spectra in total light output as in Fig. 4. It was made in three current levels that correspond to different operating regions. It is found that at the current corresponding to the first linear operating region there is only one family of modes with a peak wavelength at 8120 Å. But in portion B, another mode family appears on the short wavelength side about 30-40 Å away from the main peak. When the current increases to about 150 mA, which corresponds to the laser diode operating at the superhigh differential quantum efficiency region, the shorter wavelength

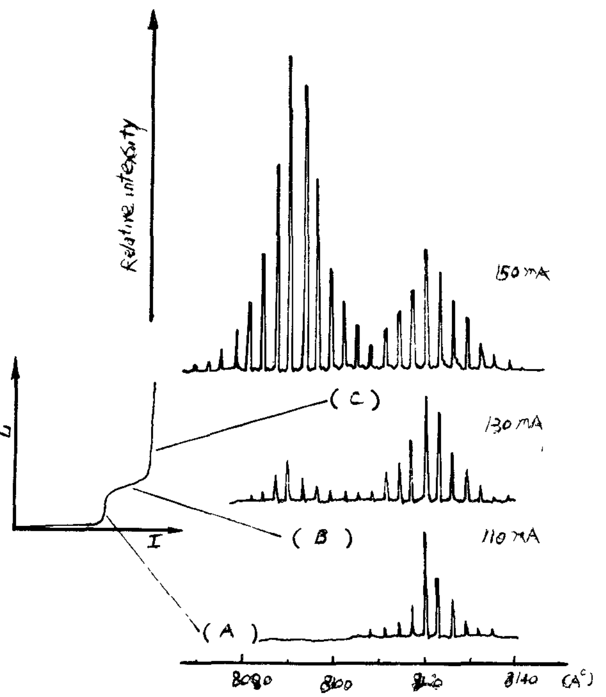


Fig. 4. Spectra of DH 23-173 laser operating at different currents.

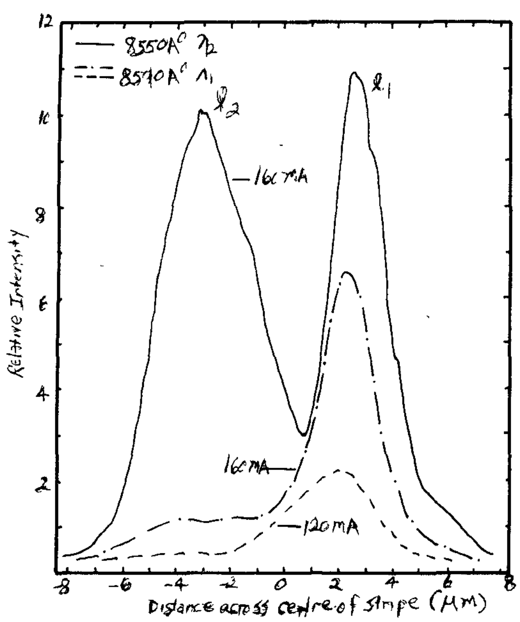


Fig. 5. Near-field with both peak wavelengths.

mode family suddenly increases rapidly. It seems to be dominant in this operating current region. Second, we measure the light output of both peak wavelength distributions across the near-field position at the same current. As shown in Fig. 5, when the operating currents are lower, there is no emission from filament L_2. The light output from L_1 at these operating currents are almost completely of longer peak wavelength. When the filament L_2 lases, it is almost completely of the shorter wavelength group. However, at that current, the spectra family of filament L_1 is complicated. According to these results; we suggest that the energy gap of material in filament L_2 is wider than that in L_1.

VI. Self-Sustained Pulsation

The transient response was observed in diodes having superhigh differential quantum efficiency at different operating currents, as presented in Fig. 6. The time resolution of measurement system is about 1 ns. We found that when the currents are in the first linear operating region, the transient behaviors are just like a normal relaxation oscillation with frequencies of about 0.5-2 GHz, but it increases with the increase of the current. When the diode operates in the region of the flat step, the relaxation oscillation frequency will reach a higher value; it is about 1-2 GHz and the damped out will be faster. When the diode operates at the current region of superhigh differential quantum efficiency a strong stable self-sustained pulsation following the relaxation oscillation readily comes in with a frequency of about 2 GHz.

VII. Transient Response at Different Wavelength Ranges

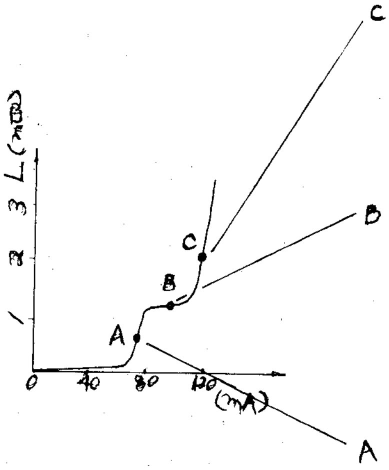
The transient response was observed on another laser diode at different wavelength range, as shown in Fig. 7. The response can be divided into two parts, that is, a fast damped relaxation oscillation, and a slow damped pulsation. The wavelengths λ_1 emitted from relaxation oscillation are in the range of 8264-8270 Å and λ_2 emitted from pulsation are in the range of 8234-8256 Å. The difference of peak wavelength $\Delta\lambda$ is about 30 Å. But in other diodes, $\Delta\lambda$ of 70 Å also can be observed. We believe that the relaxation oscillation must come out in the filament L_1 and the output in the pulsation is contributed predominantly by the filament L_2.

VIII. Discussion

According to our experimental results presented above, we suggest a model of double diodes connected in parallel caused by the nonuniform distribution of Al in the active layer, which can be used to explain these experimental results qualitatively. As shown in Fig. 8, the stripe region of the active layer can be divided into two parts corresponding to filament L_1 and L_2. It is just like two diodes D_1 and D_2 connected in parallel, having respectively forward turn-on voltages V_1 and V_2. When the bias exceeds V_1 but below V_2, only the filament L_1 will be able to lase at a peak wavelength λ_1 corresponding to the energy gap E_{g1}. When the bias exceeds V_2, the filament L_2 will be able to lase at a shorter peak wavelength λ_2 corresponding to E_{g2}. As shown in Fig. 9, when the bias is below V_2, there are only a few electrons injected into diode D_2, while a great number of electrons will be injected into diode D_1. If the electron density injected into the conduction band of diode D_1 is above the threshold density, it will be lasing. But diode D_2 is still an absorption region, including intrinsic and free carrier absorption. So the lasing light emitting from diode D_1 passing through diode D_2 will be strongly absorbed when the difference of the energy gap is not very large.

In this case, the threshold gain equation in $L_1(D_1)$ is given

$$g_{th_1}\Gamma_1 = \alpha_1\Gamma_1 + \alpha_2\Gamma_2 + \alpha_d\Gamma_d + \frac{1}{L}\ln\frac{1}{R} \quad (1)$$



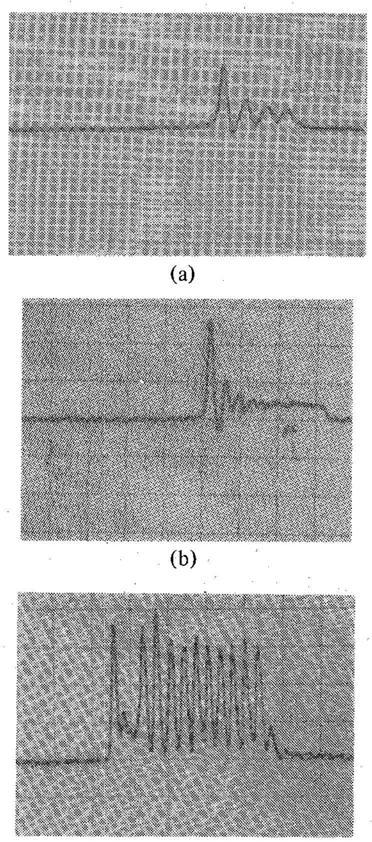

(a)
(b)
(c)

Fig. 6. Transient response and self-sustained pulsation.

where

Γ_1, Γ_2	are the confinement factors, respectively, in L_1, L_2;
Γ_d	is the confinement factor in the other diffraction region;
α_1, α_2	are total losses, respectively, in L_1, L_2;
α_d	is the loss in the other diffraction region;
L	is the length of laser cavity, suppose that it is the same in L_1 and L_2;
R	is the reflection coefficient at the both end surfaces.

The location of electron quasi-Fermi level E_{F1} is determined by the threshold gain g_{th1}. But increasing the bias V to more than V_2, the diode D_2 will begin to lase. At that time, the intrinsic absorption will tend to zero, or rather, tend to have a

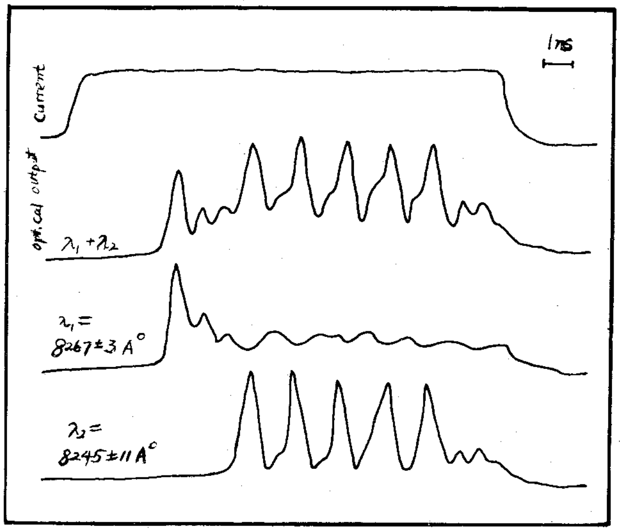


Fig. 7. Self-pulsation of 93# DH laser at different emitting wavelength ranges.

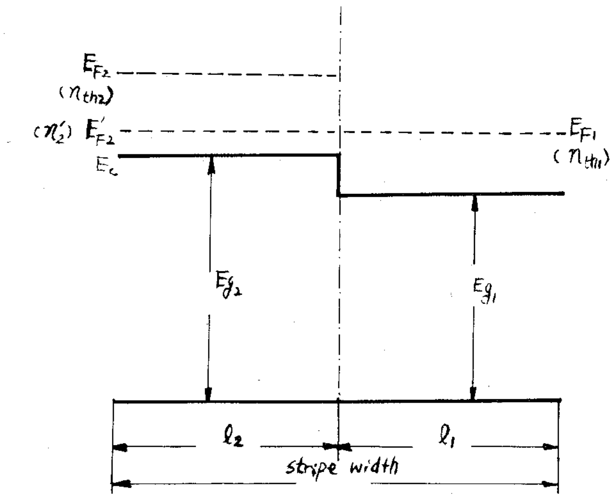


Fig. 8. Energy band diagram in the active layer across the stripe.

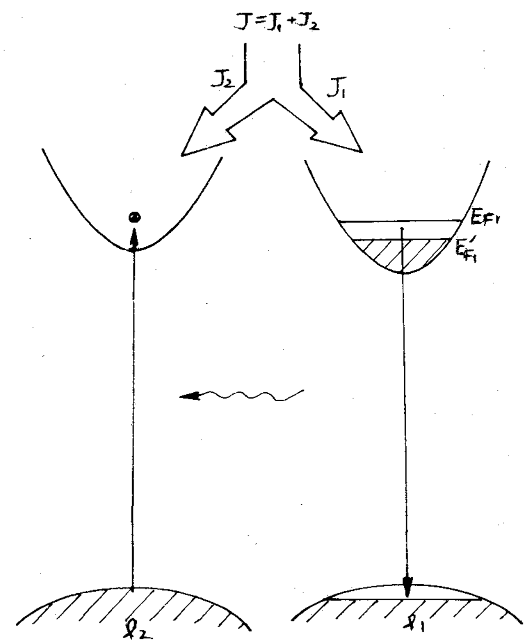


Fig. 9. Energy band structure in the active layer in filaments l_1, and l_2.

negative absorption. It means that α_2 in (1) will drastically reduce to a minimum value α_2', $\alpha_2' \ll \alpha_2$. So does the g_{th1} to g_{th1}':

$$\Delta g_{th_1} = g_{th_1} - g_{th_1}' = \frac{\Gamma_2}{\Gamma_1} \Delta\alpha_2. \tag{2}$$

Therefore, the threshold current of diode D_1 will suddenly lower to a value J_{th1}', and ΔJ_{th1} is determined as follows:

$$\Delta J_{th_1} = J_{th_1} - J_{th_1}'$$
$$= \frac{d}{\eta_i \beta} \Delta g_{th_1} = \frac{d}{\eta_i \beta} \frac{\Gamma_2}{\Gamma_1} \Delta\alpha_2 \tag{3}$$

where

d is the thickness of the active layer,
η_i is the internal quantum efficiency,
β is a constant.

The quasi-Fermi level of electrons in filament L_1 will go to E_{F1}' from E_{F1} as shown in Fig. 9. So the electrons occupied in the states between E_{F1} and E_{F1}' will be suddenly in transition to valence band and that will cause the emission of an additional lasing light power ΔL,

$$\Delta L = \eta_{ext} \frac{h\nu_1}{q} \Delta J_{th_1} \tag{4}$$

where η_{ext} is the external quantum efficiency and ν_1 is the frequency of the radiation from filament L_1.

Since these electrons are just like being stored there before, this makes possible the generation of a superhigh differential quantum efficiency similar in a Q-switch (in fact, it is a light output jump) and giving rise to a nonlinearity in the gain.

The transient behavior of electrons and photons on filament L_1 and L_2 are determined by rate equations, as follows, respectively,

$$\frac{dn_1}{dt} = \frac{J_1}{qd} - \frac{n_1}{\tau_{sp}} - g_1 S_1 + D\nabla^2 n_1 + \mu_n \operatorname{div}(n_1 E) \tag{5}$$

$$\frac{dn_2}{dt} = \frac{J_2}{qd} - \frac{n_2}{\tau_{sp}} - g_2 S_2 + D\nabla^2 n_2 + \mu_n \operatorname{div}(n_2 E) \tag{6}$$

$$\frac{dS_1}{dt} = g_1 S_1 - \frac{S_1}{\tau_{p_1}} \tag{7}$$

$$\frac{dS_2}{dt} = g_2 S_2 - \frac{S_2}{\tau_{p_2}}. \tag{8}$$

Suppose that the thickness of active layer d, the spontaneous recombination lifetime τ_{sp}, the mobility of electron μ_n, and the diffusion coefficient D are the same in L_1 and L_2. S_1, S_2, J_1, J_2, τ_{p1}, and τ_{p2} are the photon density, injection current density, and the photon lifetime in cavity, respectively, in filaments L_1 and L_2.

The relation between injection electron density N and gain g having a linear function, is given by

$$g \propto an \tag{9}$$

where a is a constant.

As mentioned before, the injected electrons always fill in the bottom of the conduction band in filament L_1 before L_2. Filament L_1 always begins to lase at first and emits light having a peak wavelength of λ_1. S_1 will have a normal relaxation oscillation as shown in Fig. 7. The injected electrons will be continuously filling in the conduction band of filament L_2. On the other hand, the light emitting from L_1 passing through L_2 also pumps the electrons from valence band to conduction band. After a relaxation time τ_R, they both will increase the electron density in L_2 to reach the threshold value N_{th}. Then L_2 will begin to lase. The light output will rapidly grow again as shown in Fig. 10. Suppose that the electron transfer from L_2 to L_1 can be neglected, the τ_R is given by

$$\tau_R = \int_{n_2'}^{n_{th_2}} \frac{dn}{\frac{J_2}{qd} - \frac{n}{\tau_{sp}}} = \tau_{sp} L_n \frac{J_2 - J_2'}{J_2 - J_{th_2}} \tag{10}$$

where

$$J_2^1 = \frac{qd}{\tau_{sp}} n_2'$$

and n_2' is the electron concentration in L_2 corresponding to the quasi-Fermi level E_{F2}' just being agreed with E_{F1}.

Because the transient values of photon densities S_1 and S_2 significantly exceed the stable values S_{10} and S_{20} which depend on the photon lifetime τ_{p1} and τ_{p2}, the recombination of the electrons in the bottom of conduction band will exceed in stable values. But the photons are still continuously emitted out of the cavity so this process leads to a stop in the lasing of the diode. When the electron concentration in L_2 is lower than the threshold value n_{th2} by an amount of Δn_2, at that time the total light output will decrease to the lowest level. After that, the injection processes will begin again. The only difference is that the background photons in L_1 and L_2 are much more so the threshold values n_{th1} and n_{th2} will be lower than before and the relaxation time T_p required for L_2 to lase again will be shorter than before and

$$T_p = \int_{n_{th_2}-\Delta n_2}^{n_{th_2}} \frac{dn}{\frac{J_2}{qd} - \frac{n}{\tau_{sp}}}$$
$$= \tau_{sp} L_n \left(1 + \frac{\Delta J_2}{J_{th_2}} \frac{J_{th_2}}{J - J_{th_2}}\right)$$
$$\Delta J_2 = (J_{th2}/n_{th2}) \Delta n_2. \tag{11}$$

As soon as the second light output pulse reaches its maximum, the dropping process will repeat as before. Obviously, the light output from L_2 must be dominant in total output as shown in Fig. 7. It is this periodic process which constituted the self-sustained pulsation in these laser diodes. The pulse frequency f is given by

$$f = \frac{1}{T_p}. \tag{12}$$

However, according to our experimental results, the ratio of $\Delta J_2/J_{th2}$ is so small; therefore

$$f = \frac{1}{T_p} = \frac{J_{th2}}{\tau_{sp} \Delta J_2} \frac{J - J_{th2}}{J_{th2}}. \tag{13}$$

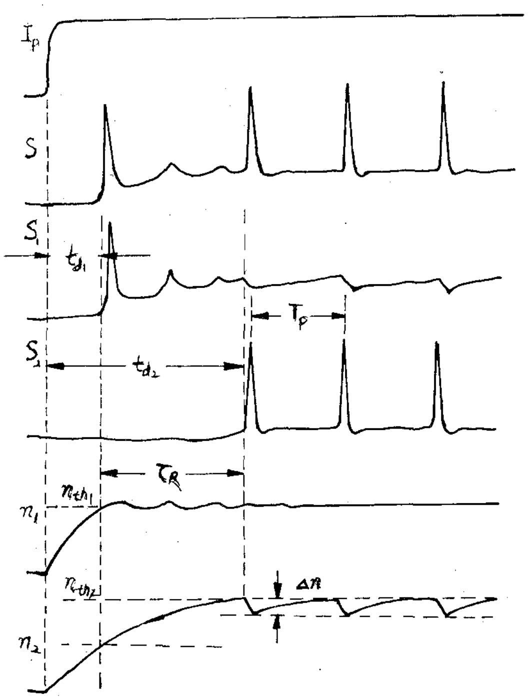


Fig. 10. The transient process of pulsation in DH laser with two filaments having different turn-on voltages.

In general, we suppose the ratio of $\Delta J_2/J_{\text{th2}}$ is about 10^{-2} and $\tau_{sp} = 2.5$ ns. Therefore, when the ratio of $J - J_{\text{th2}}/J_{\text{th2}}$ is in the range of 5×10^{-3}-5×10^{-2}, the frequency f will be in the range of 0.2-2 GHz. It agrees well with our experimental results.

Since the nonuniform distribution of Al can be in two-dimensions the problem is more complex than discussed above. In that case, more diodes will be connected in series and in parallel with each other, and have different forward turn-on voltages. In spite of that the model of two diodes connected in parallel can be used to well explain the behavior observed in our laser diodes qualitatively.

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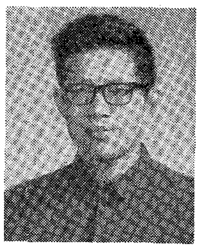

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A Theoretical Analysis on Transmission Characteristics of Semiconductor Lasers

YONG-ZHENG SHAN AND BAO-XIUN DU

Abstract—**In this paper, on the basis of classical control theory transmission characteristics of semiconductor lasers will be analyzed. In the case of small-signals semiconductor lasers is considered as an isolated linear system and the rate equation describing its physical process is linearized; four kinds of transmission functions showing its transmission characteristics have been obtained by using network theory; response characteristics to optical–electrical input signals and corresponding equivalent network are then given according to the transmission functions, and transmission characteristics are, in turn, analyzed and synthesized according to the transmission functions and the equivalent network.**

I. Introduction

A great number of studies on transmission characteristics of semiconductor lasers have already been reported [1]-[3]. However, the analysis for its transmission characteristics often needs to solve complicated rate equations first; this sets forth before us a problem: whether a series of mathematical modes and corresponding equivalent networks can be established in a semiconductor laser system as that in other semiconductor devices. If it can be done, not only will the analysis process be simplified, but also the analysis and synthesis for the transmission characteristics can be brought into the well-established network theory.

In view of the control theory, semiconductor lasers can be considered as a relatively isolated system, merely controlled by external signals through "input" and giving its response to external signals through "output." If this system is a linear system, the excitation function is $M(t)$, and output $Q(t)$, then

$$\sum_{i=0}^{n} a_i Q^{(i)}(t) = \sum_{j=0}^{m} b_j M^{(j)}(t). \tag{1}$$

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Through the Laplace transform, we obtain the equation

$$Q(p) \cdot \sum_{i=0}^{n} a_i p^i = M(p) \cdot \sum_{j=0}^{m} b_j p^j. \tag{2}$$

Hence,

$$Q(p) = G(p) \cdot M(p) \tag{3}$$

where

$$G(p) = \sum_{j=0}^{m} b_j p^j \Big/ \sum_{i=0}^{n} a_i p^i. \tag{4}$$

$G(p)$ represents the transmission characteristics function of the system.

Supposing $p = j\omega$, we get the steady-state frequency response $G(j\omega)$; when we have the inverse Laplace transform of $G(p)$, the impulse response of system $G(t)$ is obtained, and the corresponding equivalent network of the system can be given according to the pole distribution of $G(p)$. Then, the output response characteristics of the system can be controlled by changing the excitation function and the parameters of the system itself, so the system can be synthesized according to the required response characteristics.

Based on the above consideration, in the case of small signal, the rate equations describing the physical process of semiconductor lasers are normalized and linearized in this paper And four kinds of transmission functions showing transmission characteristics of semiconductor lasers are obtained through the Laplace transform. By the use of network theory, and according to the pole characteristics of the transmission function, semiconductor lasers are classified into double-pole systems with equivalent or unequivalent real number poles, or with conjugate complex number poles, and the corresponding equivalent network model is given. According to the transmission function and the equivalent network, transmis-

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