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Coupled Mode Analysis of Phase-Locked CSP Laser Arrays

(位相이 固着된 CSP레이저 어레이의 結合모우드 解析)

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要 約

本 論文은 位相이 固着된 CSP레이저 어레이에 관한 것이다. 에미터들의 수와 간격에 의하여 이산모우드의 집합으로 계산한 결과로 결합강도에 따라서 파장과 이득이 갈라짐을 보았다.

CW동작에서 80mW 이상의 안정된 출력을 얻었고 이때 최고차 모우드가 발진하였다. 그리고 강한 hole burning현상을 30mW 이상에서 관찰되었다.

에미터간격 S=3.5μm일 때 가장 안정된 발진모우드를 얻었고 S>7μm에서 결합력이 없었다.

Abstract

A phase-locked Channel-Substrate-Planar (CSP) laser arrays is described. Arrays of emitters with weak coupling are operated in a set of discrete modes determined by the number and spacing of the emitters. The interactions between emitters lead to a splitting of the wavelength and gain which are calculated from the coupling strength. Phase-locked arrays has exhibited to CW output-power as high as 80 mW and the highest order mode will have preferred oscillation. A strong hole burning is occurred at p=30 mW. The most stable lasing mode is occurred at element spacing S=3.5μm and there is no coupling at S > 7 μm.

I. Introduction

There has been intense interest in the use of phase-locked injection laser arrays for application that require high optical power (>100mW) in a coherent beam [1].

A veriety of approach have been utilized to achieve this objective arrays of index-guided lasers that operate in A single-longitudinal mode have been demonstrated [2], [3] as well as array of gain-guided lasers that have delieved output powers as high as 2.5W CW [4], [5].

Operation in a single narrow beam to powers as high as 20 mW has been observed [6], but its control still remains a problem. In an effort to understand the operation of phase-locked arrays, analysis based on conventional multi-slit diffration theory [7] have been extensively applied.

This approach relies on the assumption of a known phase relationship between individual emitters to solve for the far-field patterns of the arrays.

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More recently, coupled-more analysis has been successfully applied to model phase-locked arrays [8],[9],[10]. But they didn't consider to the effect of gain-loss relationship on the lasing modes. So, based on the new understanding, more complete analysis of array structures including gain and loss [11] has resulted in some understanding of the selection of array modes for the first time.

Therefore, in this paper we present an analysis of phase-locked CSP-DH laser array with uniform element spacing to utilize a coupled-mode theory.

As a necessary result to the solution of the coupled-mode equations, we can solve for the splitting of the oscillation wavelength and gain of the individual emitter as a function of the coupling strength.

II. CSP-DH Laser Array Structure

A schematic cross-section of the CSP-DH laser array structure is shown in Fig. 1 and Table 1.

Before LPE growth, the substrate is patterened and etched with 10 grooves ~50μm width, the n-$Al_{0.33}Ga_{0.67}As$ cladding layer is grown so that the distance form the active layer to the tops of the mesas separating the grooves is d_t=0.3 μm to properly confine the lasing filiaments to the groove waveguides.

The active layer was grown ~0.08 μm thick which is much smaller than the channel width 2t (2.8 μm) and the leakage of light to the substrate is not large.

A single broad area contact was utilized and typically was ~ 60μm width to confine the

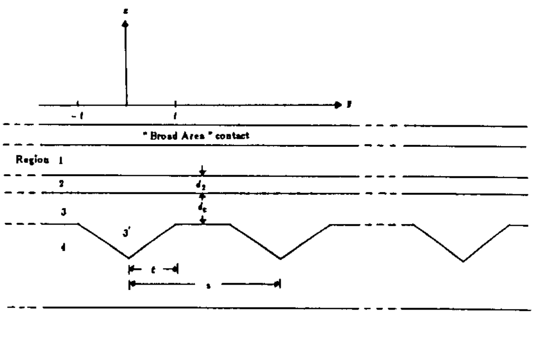

Fig. 1. The structure of csp-dh laser array.

Table 1. The basic structure with material parameters of CSP-DH laser.

Optical Constants			
Region	Material	Refractive Index	Absorption coefficient (cm^{-1})
1	p-$Al_{0.33}Ga_{0.67}As$	3.41	5
2	$Al_{0.07}Ga_{0.93}As$	3.62	-
3	n-$Al_{0.33}Ga_{0.67}As$	3.41	5
4	n-GaAs Substrate	3.64	2500

current distribution so that all of channels were pumped. This contact configuration minimized the edge effects that occurred during LPE growth. The emitter-to-emitter spacing was determined by the desire to maximize coupling strength and mode stability between the elements.

III. Coupled-Mode Analysis

To begin the discussion of the coupled-mode analysis of a laser array, it is necessary to write the wave function of the array in terms of the wave functions of the individual elements.

The singel element will be described by a field distribution $\Psi^i(x,y,z)$ where the superscript pertains to the ith device.

If the individual lasers are separated by a distance S, the overall array aperature size is a multiple of the spacing. For example, the aperature size of the n-element is a value of n x s.

Because the elements are identical, the fields satisfy the condition

$$\Psi^1(x,y+s_1,z) = \Psi^n(x,y+s_n,z) \qquad (1)$$

The optical field of the single element satisfies the wave equation [11]. The individual elements are assumed to be identical and to have the form

$$\Psi^m(x,y,x) = u^m(x,y)\ v^m(y)\ e^{-\gamma_m z} \qquad (2)$$

where $u^m(x,y)$ descrives the transverse profile while $v^m(y)$ governs the lateral mode profile and γ_m is the two-dimensional propagration constant. The index m pertains to the allowed m th element.

Because $u^m(x,y)$ has a y dependence, we are interested in index-guided lasers where there is usually a perturbation to the structure in the lateral direction.

In particular, we analyzed a phase-locked array consisting of CSP-DH structure as shown in Fig. 1. And material parameters for the single element are listed in Table 1.

The wave function $v^m(y)$ satisfies

$$\frac{d^2 v^m(y)}{dy^2} + [\gamma_m^2 - \gamma_{0\,m}^2(y) + k_0^2 \Gamma^m(y) k_v^m(y)] \, v^m(y) = 0 \qquad (3)$$

Where $\Gamma^m(y)$ is the complex optical confinement factor of the active layer, and $k_v^m(y)$ is the perturbation of the active layer dielectric constant from its passive values due to injected carriers.

The quality $\gamma_{0\,m}(y)$ can be written as following

$$\gamma_{0\,m}(y) = \alpha_e(y) + j\, k_0\, n_e(y) \qquad (4)$$

where $\alpha_e(y)$ and $n_e(y)$ are effective absorption coefficient and effective index of refraction in the lateral direction. The index m is dropped from $\alpha_e(y)$ and $n_e(y)$ expressions because we will assume identical array elements. In Fig. 2, we show $\alpha_e(y)$ as a function of the lateral position and optical power for a CSP-DH laser element similar to the types we have used for the fabrication of arrays. The dielectric variation of the active layer for the single element m is

$$k_v^m(y) = 2n_2\, \Delta n_2^m + j\, \frac{n_2 g^m(y)}{k_0} \qquad (5)$$

where $g^m(y)$ is the local gain coefficient at location y. And Δn_2^m is given by the AD HOC relation[12]. This equation simply ties the index change at a point in the active layer to the gain at that position using a linear relationship.

In reality, we show the index change is tied to the magnitude of the gain changes as shown in Fig. 3.

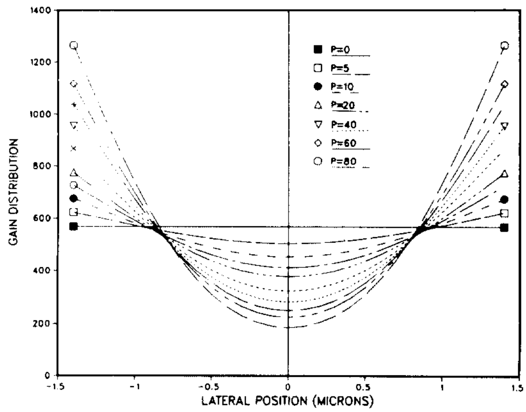

Fig. 3. The optical gain variation as a function of lateral distance.

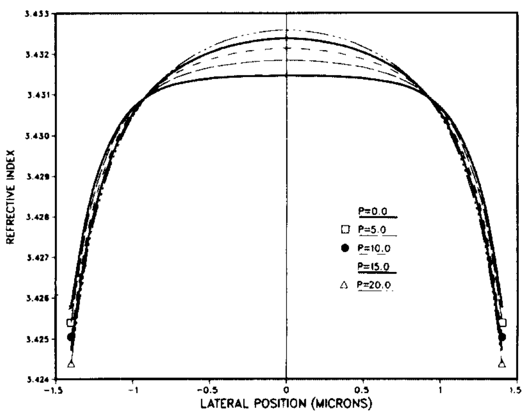

Fig. 2. The refractive index variation as a function of lateral distance.

Including both the effective complex propagation constant and the perturbation of the active layer dielectric constant by the injected carriers, the total dielectric variation of the single element m along y can be written [13],

$$k^m(y) = [n_e^m(y)]^2 - [\alpha_e^m(y)/k_0]^2 + 2\Gamma^m(y) n_2\, \Delta n_2^m - j[2n_e^m\, \alpha_e^m(y)/k_0 - \Gamma^m(y) n_2 g^m(y)/k_0]. \qquad (6)$$

In our individual CSP-DH laser model, the active region gain $g^m(y)$ and refractive index $n_e^m(y)$ are independent the outer region, $|y|>t$ while a central region, $|y|<t$ are dependent of lateral positions as shown in Fig. 2 and

Fig. 3. Because variations of the two terms in the imaginary-part of k^m are y dependent so that both the real and imaginary parts of the dielectric constant are y dependent.

For a uniform spacing array the coupling coefficient are equal, therefore they are determined by the overlap wave functions [13]. Since the fields of the individual elements decay exponentially outside the substrate grooves, so coupling coefficients become

$$C_{nm} = \frac{\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} (k-k_m) u^m u^m v^m v^n \, dxdy}{\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} (u^m u^n v^m v^n) \, dxdy} \tag{7}$$

where k is dielectric constant of waveguide system and k_m is dielectric constant of m-th waveguide.

Because the array elements are identical, we can normalize the field to unity,

$$\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} (u^n v^n)^2 \, dxdy = 1 \tag{8}$$

At Fig. 1, the value of k and k_m can be written as

$$k - k_m = \begin{cases} 0 & \text{for } x,y \in R_1,\ R_2, R_4 \\ k_v(y) & \text{for } x,y \in R_2 \\ k_3 - k_4 & \text{for } x,y \in R_3{}' \end{cases} \tag{9}$$

Here, we only consider the coupling coefficient for the nearest lasers and assume that $n = m-1$, then

$$C_{m-1}, m = \int_{-t}^{t} \int_{-\infty}^{\infty} (k-k_m) u^m u^{m-1} v^m v^m - 1 \, dxdy \tag{10}$$

We have solved the complex wave equations numerically using a multi-point boundary value differential equation solver closys[15]. Then we have calculated the coupling coefficient as

$$C(s) = C_r(s) + j\,C_i(s) = a(s)\, e^{j\,\theta(s)} \tag{11}$$

Where a(s) and θ(s) are the amplitude and phase of the coupling coefficient respectively.

From Fig. 4 we show the calculated values of $c = c_r + j\, c_i$ as functions of laser separation distance S and optical output power.

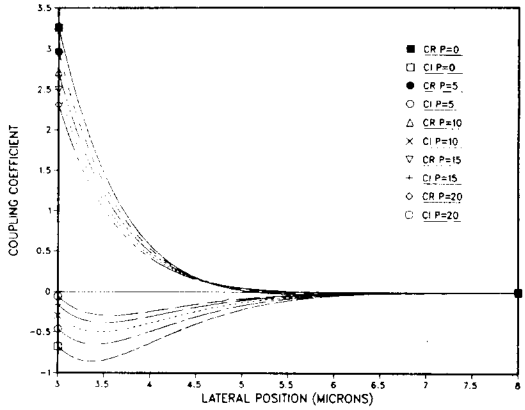

Fig. 4. The coupling coefficient $c = c_r + jc_i$ for csp-dh laser array as a function of element separation.

IV. Splitting of Gain and Wavelength

In a passive CSP-DH structure, the coupled-mode analysis gives only a splitting of the progration constant which relates the possible mode oscillation wavelengths.

In an active structure, both the gain and refractive index distribution affect mode characteristics; the wavelength splitting and the gain splitting of the individual laser modes. The gain splitting is important because it determines which array mode oscillates. The value of the gain of the various array mode can be calculated from the splitting of the complex progagation.

Hence, the array modes have propagation constants[13],

$$\gamma_p = \gamma[1 - ck_0^2/\gamma^2 \cos(p\pi/(N+1))]. \tag{12}$$

The wavelength and gain coefficient of the p-th array mode are determined from the complex coupling coefficient C and from the unperturbed single element parameters.

In general, the value of $\beta \gg \alpha$ thus equation (12) can be simplified as

$$\gamma_p = \alpha + j\beta - (k_o/n_E)\,[c_i - jc_r]\,\cos(p\pi/N+1) \qquad (13)$$

Here, $n_E = \beta/k_o$ is the mode effective index of refraction. And C_r and C_i represent the real and imaginary components of the coupling coefficient. Then the mode oscillation wavelength is

$$(\lambda_p - \lambda_0)/\lambda_p = -c_r/n_e^2\,\cos(p\pi/N+1) \qquad (14)$$

For $C_r > 0$, the wavelength of the P=1 (fundamental) mode is smaller than that of the single element laser while for P=N (the highest-order) mode, the array mode wavelength increases relative to the single element.

According to our calculation, the wavelength splitting between the P=1 and P=10 th mode is as large as 1.8 Å at $\lambda_0 = 0.83$ μm.

While the new CSP-DH laster model gain splitting for the P-th array mode is

$$G_p = G + (2k_0 c_i/n_e)\,\cos(p\pi/N+1) \qquad (15)$$

For $C_i > 0$, P=1 (in-phase) mode is favored while for $C_i < 0$, P=N (out-phase) mode lases. The difference in modal gain for the array modes is linearly dependent on the magnitude of the imaginary-part of the coupling coefficients.

For example, P=1 mode of a 10 element laser array has $G_1 - G = -4.2$(/cm) while P=10 mode has $G_{10} - G = +4.2$(/cm) at $d_2 = 0.08$ μm, dt=0.3 μm, S=3.5 μm and P=5mW.

Thus, the highest-order array mode will lase because it has the largest gain coefficent.

V. Observation of Array Modes

The CSP-DH laser array considered here have lateral waveguides that are strongly developed by both the real and imaginary parts of the dielectric constant.

Since adjacent elements are linked by the optical fields through the lateral dielectric function, The coupling coefficients as given by Eq. (7) will be complex (See Fig. 4). The nature of the complex coupling coefficients is dependent on both the refractive index and gain variations as shown in Fig. 2 and Fig. 3.

In this analysis, the propagation constant of the identical individual ellements will split into a series of complex numbers that represent the propagation constants of the individual array modes for phase-locked operation.

The imaginary part of splitting affects the array mode gain while the real part characterizes the lasing wavelength as given by Eq. (14) and (15).

From Fig. 2, we see that the CSP-DH laser has effective refractive index such that the modes will be strongly index-guided laser. Thus, the wave functions will have very little phase variation in the lateral direction which means that the fields are almost real values.

The evanescent fields will have exponential decay which greatly affects the coupling coefficients. In fact, the magnitude of the coupling coefficients will decay exponentially with respect to element spacing as shown in Fig. 5 which is the amplitude variation of coupling coefficients vs. separation distance.

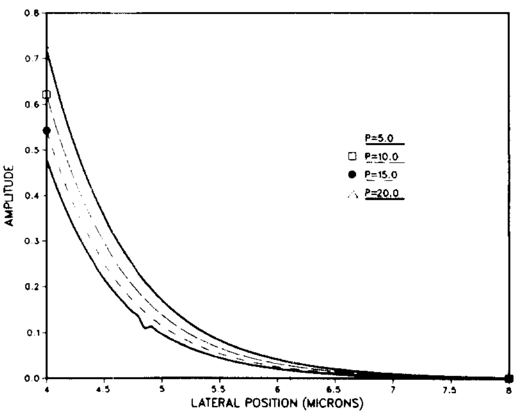

Fig. 5. The amplitude variation of coupling coefficient as a function of element separation.

The optical gain variation as a function of lateral distance is shown Fig. 3. We can show that at optical power P=30 mW, there is strong hole b rning at y=0.

From Fig. 4, when element spacing S=3.5 μm, we obtained the most stable oscillation frequency mode which was good agreement with experimental observation. As illustrated, if we increase optical power, the values of complex coupling coefficients are smaller.

This is the same reason as shown in Fig. 2, because the width of the refractive index is narrowing while increasing power.

But the coupling will be small when element spacings are larger than approximately 7 μm. Thus, models using only nearest neighbor coupling appear to be rather accurate.

VI. Conclusion

In this paper, we have presented a theoretical and experimental study of phase-locked index-guided CSP-DH laser array with uniform element spacing. The model predicts splitting of the wavelength and gain that can be calaulated by the coupling strength. The imaginary-part of coupling coefficient affects the array model gain while the real-part of coupling coefficient characterizes the lasing wavelength.

In a CSP-DH array mode, the analysis predicts that the highest-order array mode will have the largest modal gain so that it will reach threshold all other array modes, and the fundamental mode will have the lowest gain hence, it will not lasing. This is consistent with experimental observation.

Physically, the highest mode has fields with differential phase-shifts of 180° between neighboring elements, so losses are minimized and far-field pattern will be two-lobed beams.

On the other hand, the fundamental mode has fields with 0° phase-shift, which produces single-lobe in the far-field pattern, consequently will not have a null field value in the lossy regions, so it will have higher absorption losses. These are good agreement with the experimental observation.

Note that at P=30 mW, there is strong hole burning at y=0. For a 10 element laser array with element spacing S=3.5 μm, we get the most stable lasing mode and there is no coupling when element spacing are large than approximately 7 μm.

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