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Optimization of phase-locked arrays geometry for high brightness laser systems

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The emitted beam far field (FF) distributions of phase-locked semiconductor laser arrays (PLA) made them an interesting candidate for high-brightness light sources. Variations of geometrical parameters of PLA have great influence on their far-field characteristics. This paper presents a review of FF distribution variations induced by such parameters as width and number of active stripes as well as stripe spacing. We also present a description of predicting an operation mode of designed PLA and some limitations in designed geometry of high-brightness PLA are shown as well.

Keywords: semiconductor laser, phase locked arrays, far-field characteristics.

1. Introduction

Phase-locked arrays (PLAs) of semiconductor laser diodes (LDs) are promising high-brightness light sources. Their unique property is the ability of emitting a single central lobed beam (when the phase shift between optical fields guided in neighbour array stripes $\Delta\varphi = 0°$ – "in-phase" case) or double lobed ($\Delta\varphi = 180°$ – out-of-phase case) [1,2] in the junction plane. In both cases, individual lobes are almost diffraction limited [3–5]. In a stripe-geometry LD, stripe widening is the way to increase the emitted power. In PLA, however, an individual stripe width increasing can drastically decrease the beam quality in some cases. The idea of this paper is to demonstrate how to optimise PLA for high-power and good beam quality. Numerical results have been obtained by using FIMMWAVE (Photon Design) commercial program.

1. Modelling assumptions

The heterostructure used in simulations of PLA is described in Table 1 (layers are numbered in epitaxial growth sequence) and device geometry is schematically shown in Fig. 1.

The parameters describing this structure are: N is the number of array elements (stripes), S is the centre spacing between array elements, d is the stripe width, and h is the etching depth. Active stripes are defined by etching a GaAs contact layer ($h = 0.3$ µm) and then ion implantation which causes current blocking and induces optical loss in the area between stripes (implantation range = 0.4 µm – see Fig. 1).

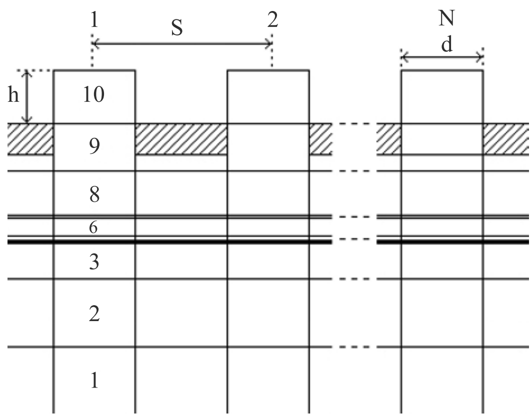

Fig. 1. 2D scheme of device face used to simulate PLA. Grey colour shows quantum well, hatched area and bold-black-line indicate implantation regions and gradient layer, respectively.

The identical elements are assumed in the considered PLA, so the far-field (FF) distribution in the junction plane is given by the equation [1]

$$F(\theta) = \left|E(\theta)\right|^2 I(\theta), \tag{1}$$

where $E(\theta)$ is the FF pattern of individual array stripe, θ is the angle in the junction plane, and $I(\theta)$ is the function characteristics for an array. Actually $\left|E(\theta)\right|^2$ is the "envelope function" superimposed on $I(\theta)$. According to the coupled mode theory, $I(\theta)$ is given by the equation [3]

$$I(\theta, L) = \frac{\sin^2\left[\dfrac{(N+1)(k_0 S\sin\theta + \Delta\varphi)}{2} + \dfrac{L\pi}{2}\right]}{\left[\sin^2\left(\dfrac{k_0 S\sin\theta + \Delta\varphi}{2}\right) - \sin^2\left(\dfrac{L\pi}{2(N+1)}\right)\right]^2}, \tag{2}$$

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Table 1. Description of heterostructure used in simulations.

Layer	Thickness (μm)	x – Al composition	Refractive index	Material loss (1/cm)
10 – GaAs contact layer	0.3	–	3.67	8000
9 – $Al_xGa_{1-x}As$ p – cladding	0.6	0.67	3.221	0 (8000 in hatched area)
8 – $Al_xGa_{1-x}As$ waveguide	0.25	0.38	3.4	0
7 – GaAsP quantum well (QW)	0.016	–	3.58	–1200 in active stripes 8000 between stripes
6 – $Al_xGa_{1-x}As$ waveguide	0.1	0.38	3.4	0
5 – $Al_xGa_{1-x}As$	0.02	0.67	3.221	0
4 – $Al_xGa_{1-x}As$ gradient layer	0.02	0.67 to 0.38	3.221 to 3.4	0
3 – $Al_xGa_{1-x}As$ passive waveguide	0.2	0.38	3.4	0
2 – $Al_xGa_{1-x}As$ n – cladding	4	0.43	3.369	8000
1 – GaAs substrate	0.5	–	3.63	8000

where $k_0 = 2\pi/\lambda$ and λ is the free space wavelength, L is the array supermode number (L = 1, 2 … N), $\Delta\varphi = p\pi$ is the phase shift (p = integer) [4]. Changes in the PLA geometry have similar influence on all supermodes behaviour, so only the first supermode (L = 1) and the out-of-phase case (p = 1) is shown here for brevity.

All presented below FF patterns are cross sections of spherical (centred at the centre of an active region face) projections defined as power flowing through a unit area of the sphere as a function of spherical angle [direction x is in the junction plane θ, direction y is perpendicular to the junction plane] [6]. These FF patterns are one-dimensional (1D) cross sections in junction plane taken at y = 0.

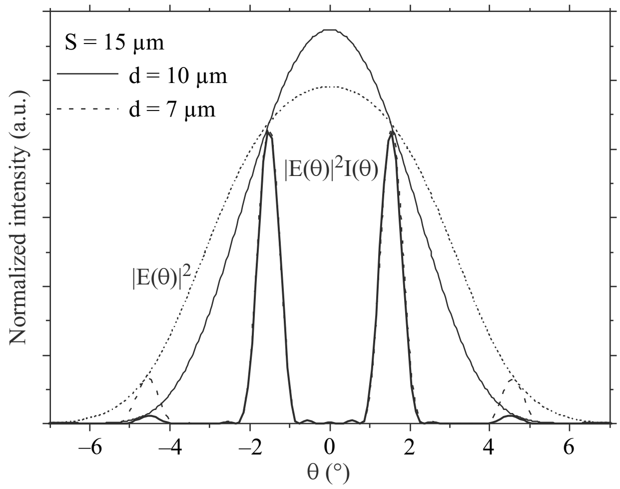

Fig. 2. Far field characteristics of PLA with various active stripe widths.

2. Results and discussions

Geometric parameters of PLA having an influence on the FF distribution can be divided into two groups: variables in $E(\theta)$ and the ones in $I(\theta)$. In the first group, the only one parameter is the width of array element d. Since Eq. (2) is independent from d, it does not have any influence on the position and angular width of lobes. When d increases, the divergence of the beam for a single emitter decreases and a lower number of lobes is contained within the envelope function $E(\theta)$. This is illustrated in Fig. 2 where FF distributions calculated for two structures with different active stripes width d = 7 μm and 10 μm are shown. It is seen that the side lobes are suppressed when d is wider and $E(\theta)$ is narrower. FIMMWAVE program has been employed for these calculations, 2D far-field distributions have been calculated for 2D refractive index distribution (in a mirror plane) shown in Fig. 1 and Table 1 and their cross sections $|E(\theta)|^2\ I(\theta)$ in the junction plane (y = 0) are shown in Fig. 2 and analogously in Figs. 3–6. Additionally, in Fig. 2, the individual stripe $|E(\theta)|^2$ envelopes are shown for an illustration.

In the other group [variables in $I(\theta)$], the influencing parameters are S and N. Figures 3 and 4 show their influence, respectively. In Fig. 3, plots for PLAs with centre spaces of 15 μm and 17 μm are seen. In this case, side lobes in the FF distributions become lower with decreasing S. Simultaneously, as the $I(\theta)$ period changes, the overall beam divergence increases of a smaller S for PLA.

Far field distributions of structures with different active stripe numbers are presented in Fig. 4. Plots are shown with five and nine stripes for the structure. As one can see, the larger N results in a smaller divergence of the lobes. Moreover, higher optical power is expected of higher N from PLA.

In order to obtain high optical power from a single emitter laser, the active stripe widening is necessary. The similar situation is expected in PLA where d and N should be large. As seen above, an array containing more and wider stripes will have better quality of emitted beam. But designing of such a structure is restricted by some limitations.

The most important problem is the higher order lateral modes that are excited in wide stripes. In the case of phase

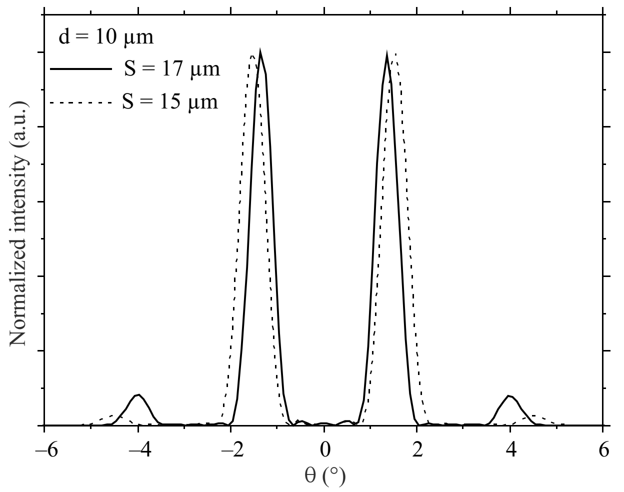

Fig. 3. Far fields characteristics of PLA with various centre spaces of the active stripes.

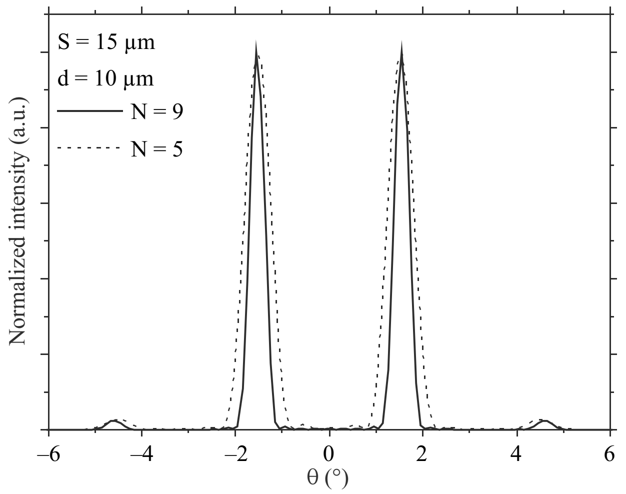

Fig. 4. Far fields characteristics of PLA with various number of active stripes.

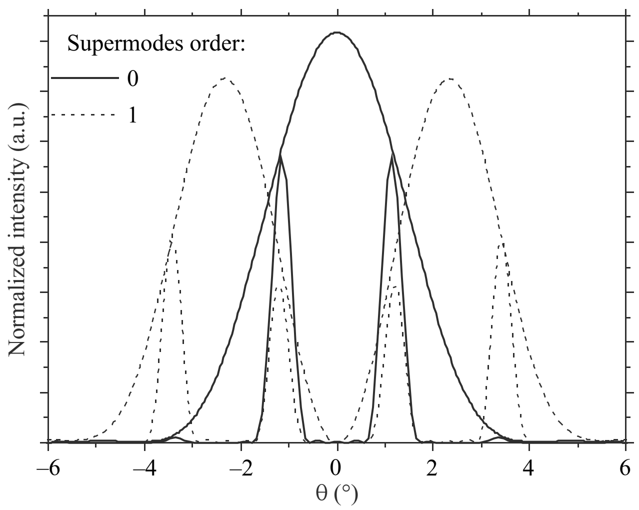

Fig. 5. Far field distributions of zero- and first order supermodes. Thin lines (solid and dash) shows envelope functions (E(θ)), respectively. Supermodes operate with the same phase shift p = π. PLA parameters: N = 5, d = 15 μm, S = 20 μm.

locked arrays, the higher order modes create respective higher order supermodes. These supermodes allow for more lobes (assuming different order supermodes of the same $\Delta\varphi$), because their $E(\theta)$ has more than one maximum. This significantly decreases the beam quality as it can be seen in Fig. 5.

The penetration range outside the "own" stripe of the higher order modes is larger than that the one of the fundamental mode [7]. Thus, the coupling factor of $(n + 1)$ mode disappears for the larger S than that of nth mode. So, elimination of the higher order supermodes cannot be achieved by S-variations.

This indicates that the parameters d and S should be carefully optimized in high-brightness PLAs. Narrow d allows for only the zero-order mode to propagate, but restricts emitted optical power. Small S in turn allows for larger number N of active stripes to be built in the structure, so optical power can be increased.

The S parameter also has another influence on the FF emission pattern. As it was mentioned at the beginning of the paper, the PLA structures can emit a single central lobed or double lobed beam dependent on phase shift between neighbour active stripes, $\Delta\varphi = 0°$ or $\Delta\varphi = 180°$ (no other cases exist, Ref. 4) and this is highly determined by S as it is shown in Fig. 6. The operation mode has a great importance for future application, so it is necessary to optimise PLA structure for the selected phase shift.

The simplest way to predict the operation mode is to plot refractive index profiles of neighbour stripes and their optical field distributions (here TM modes). This is seen in Fig. 7 (to be clear, there is the refraction index distribution only for a reference stripe). If a mode field of a given stripe is falling at the edge of a neighbour stripe, in-phase operation mode is expected (Figs. 6 and 7 shown by solid and dotted lines). In the opposite case, the PLA runs out-of-phase (Figs. 6 and 7 shown by a dashed line). This method

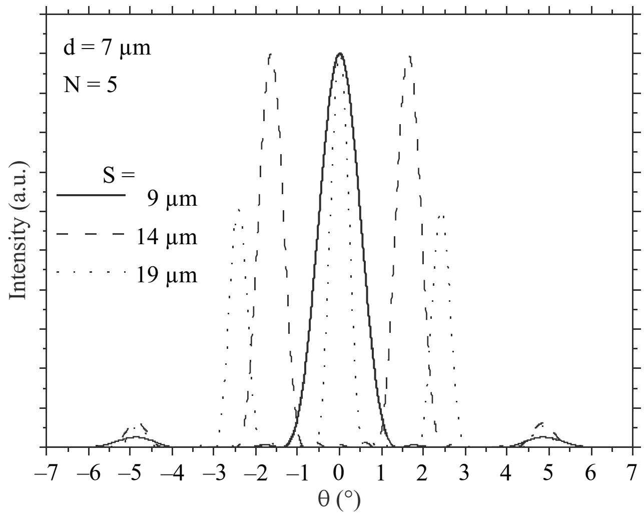

Fig. 6. FF characteristics of PLA structures in various operation modes. Solid and doted lines describe in-phase operation, dashed line – out-of-phase operation.

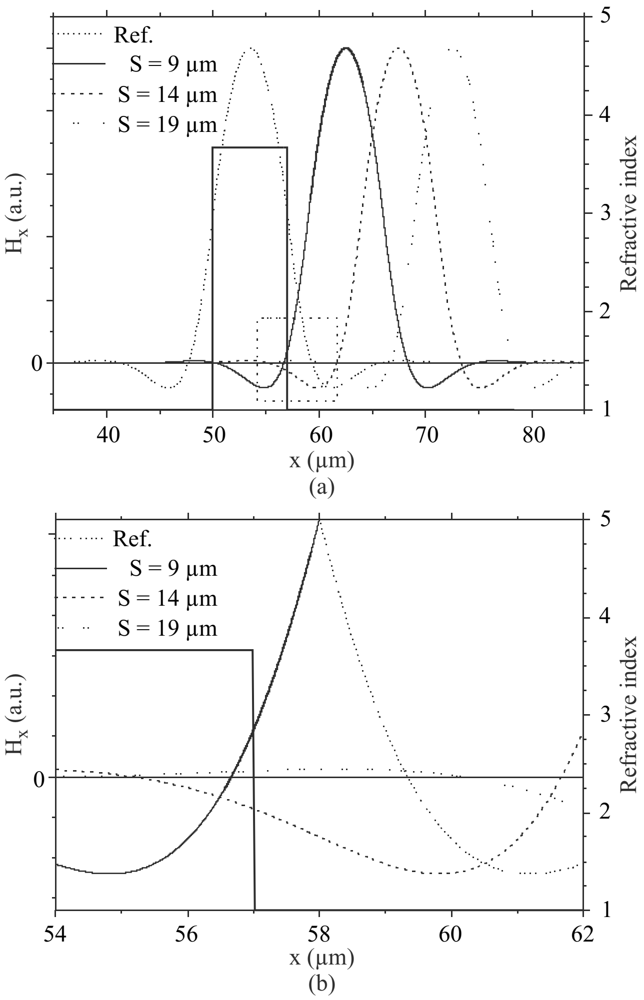

Fig. 7. Method of predicting PLA operation mode: a) shows the mode filed distributions of neighbouring stripes of different centre spacing, b) zoomed part selected from a). Doted line (ref.) is mode distribution of considered active stripe whose index profile is drawn by solid line.

requires high-resolution calculations of the optical field distributions and becomes less effective when at the edge of the neighbour stripe the amplitude of penetrating field is close to its local extreme (maximum or minimum one). Also for broad active stripes ($d > 8$ μm), the precision of the method decreases.

3. Conclusions

In conclusion, the impact of geometrical parameters of the PLA structure on their FF distributions is demonstrated. Number and proportions of the lobs of emitted beam in junction plane can be controlled by width of the active stripes and their centre spaces. Such parameters as a divergence and an angle-distance of lobs also can be controlled by passive areas between stripes and by a number of stripes. For the high-brightness PLA, the active stripes should allow for only zero-order mode to propagate, be as close as possible and the number of active stripes should be high. A simple numerical method has been proposed to predict an operation mode (in-phase or out-of-phase) of the PLA by analysing the optical field of the given stripe at the edge of the neighbour one.

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