Synchronization of semiconductor laser arrays with 2D Bragg structures

V R Baryshev and N S Ginzburg

IAP RAS, 603950, Nizhny Novgorod, Russia

E-mail: baryshev@appl.sci-nnov.ru

Abstract. A model of a planar semiconductor multi-channel laser is developed. In this model two-dimensional (2D) Bragg mirror structures are used for synchronizing radiation of multiple laser channels. Coupling of longitudinal and transverse waves can be mentioned as the distinguishing feature of these structures. Synchronization of 20 laser channels is demonstrated with a semi-classical approach based on Maxwell-Bloch equations.

1. Introduction

Multi-channel laser systems are recognized as a common technique of increasing beam width and power of semiconductor lasers. In those systems the output laser beam is a combination of beams from individual channels. Keeping that combination coherent requires a way of synchronizing the channels. Commonly known methods of synchronization include using external cavities [1], Talbot effect [2] as well as various ways of coupling the channels [3]. In this paper we suggest synchronization of multiple semiconductor heterostructure laser channels with 2D Bragg reflectors. This approach can be effective for planar laser diode arrays and allows integrating the reflectors with the channels on the same substrate as well as using them as an external resonator.

Figure 1 shows the suggested scheme of a multi-channel laser. Active channels with the number of n length of l_z and the width of l_k are separated with air or dielectric lanes with the width of l_d. In the direction of Y axis the channel thickness b_0 is considered sufficient small to allow propagation only one planar waveguide eigenmode, which is typical for distributed feedback (DBF) lasers. Coupling between the channels is provided by special reflectors being planar dielectric waveguides with certain areas covered by 2D Bragg corrugation. The distinguishing feature of those corrugated areas is coupling between longitudinal (Z axis) and transverse (X axis) partial waves [4, 5]. As shown below, this coupling provides mutual synchronization of the laser channels, including channels with slightly different wavelengths.

2. Nonlinear model of a 2D DBF multi-channel laser

A 2D Bragg reflector based on planar dielectric waveguide has rectangular shaped area with the following double periodic sinusoidal modulation of waveguide thickness:

$$b(x,z) = b_0 + b_{1,2}(\cos(\bar{h}(x+z)) + \cos(\bar{h}(x-z)) \quad (1)$$

where $b_{1,2}$ is the modulation amplitudes of the left and right reflectors respectively, $\bar{h} = 2\pi/d$, d is

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.
Published under licence by IOP Publishing Ltd

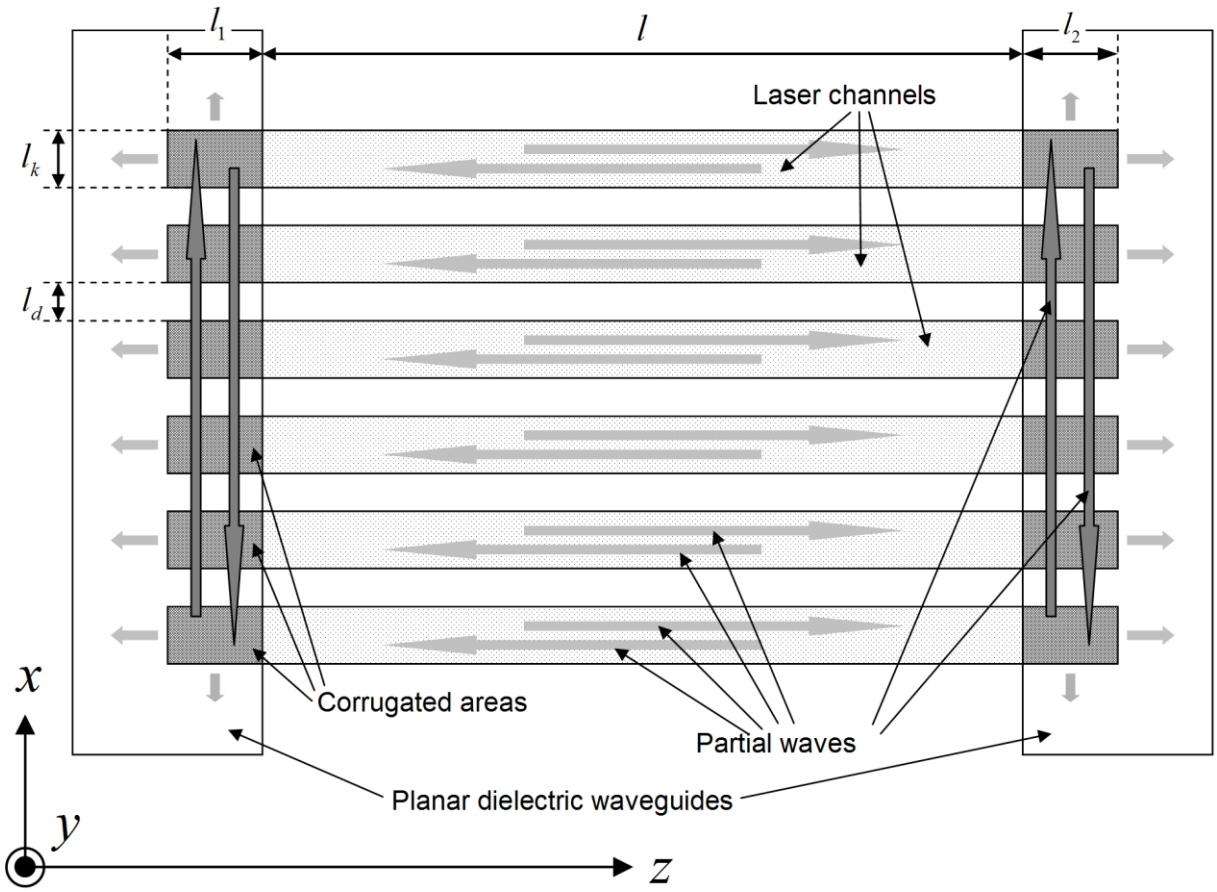


Figure 1. Multi-channel semiconductor laser with 2D Bragg reflectors.

the modulation period along the x- и z- coordinates. Under the Bragg resonance conditions:

$$h \approx \bar{h} \tag{2}$$

those structures provide mutual coupling of the following four partial wave-beams [4, 5]:

$$\vec{A} = \mathrm{Re}\left[\left(\vec{a}_1(y)\left(C_z^+ \mathrm{e}^{-ihz} + C_z^- \mathrm{e}^{ihz}\right) + \vec{a}_2(y)\left(C_x^+ \mathrm{e}^{-ihx} + C_x^- \mathrm{e}^{ihx}\right)\right)e^{i\omega t}\right] \tag{3}$$

where $\vec{a}_{1,2}(y)$ are eigenwaves of a planar dielectric waveguide propagating along x- и z- directions, $C_{x,z}^{\pm}(x,z,t)$ are complex amplitudes of partial waves. Let us mention that $C_z^{\pm}$ waves are amplified when propagate through the laser channels while $C_x^{\pm}$ waves propagate only in the reflectors and are produced by Bragg scattering. We assume that the channels are wide enough in the scale of Fresnel paremeter ($l_k^{\,2}/l_z\lambda >> 1$) to neglect the diffraction and assume $C_z^{\pm} \equiv 0$ at $x \notin (j(l_k+g), j(l_k+g)+l_k)$, where $j = 0 \ldots n-1$, which means that waves $C_z^{\pm}$ exist only in laser channels and the corresponding parts of the reflectors. Similarly, we will consider the transverse waves only inside the reflectors, i.e. $C_x^{\pm} \equiv 0$ at $z \notin (0, l_1)$ and $z \notin (l+l_1, l+l_1+l_2)$. It is important to mention that the sinusoidal modulation (1) can be replaced by a "chessboard" modulation and can also be placed inside the structure on the boundary surface of its waveguide layer.

Mutual Bragg scattering of the longitudinal and transverse wave- beams can be described by the following equations:

$$\left(\pm\frac{\partial}{\partial Z}+\frac{\partial}{\partial\tau}\right)C_z^{\pm}+i\hat{\alpha}_{1,2}\left(C_x^{+}+C_x^{-}\right)=0,$$
$$\left(\pm\frac{\partial}{\partial X}+\frac{\partial}{\partial\tau}\right)C_x^{\pm}+i\hat{\alpha}_{1,2}\left(C_z^{+}+C_z^{-}\right)=0, \tag{4}$$

where $X=x/l_1$, $Z=z/l_1$ and $\tau=tv_g/l_1$ are normalized coordinates. Coupling parameters $\hat{\alpha}_{1,2}$ is given in [5].

Polatization P and inversion ρ of the active media can be represented by components that interact with partial waves $C_z^{\pm}$:

$$P=\mathrm{Re}\left(i\left(P_z^{+}e^{i\bar{h}z}+P_z^{-}e^{-i\bar{h}z}\right)e^{i\omega_0 t}\right),$$
$$\rho=\rho_0+\mathrm{Re}\left(\rho_{2z}e^{2i\bar{h}z}\right), \tag{5}$$

where $\rho_{2z}(x,z,t)$ is the inversion lattice produced by the spatial hole burning effect.

We will use a semi-classical approach [6] in which the lasing process can be described by the following set of equations:

$$\left(\pm\frac{\partial}{\partial Z}+\frac{\partial}{\partial\tau}\right)\hat{C}_z^{\pm}=\hat{P}_z^{\pm},$$
$$\frac{\partial\hat{P}_z^{+}}{\partial\tau}+\frac{\hat{P}_z^{+}}{\hat{T}_2}+i\hat{\delta}_j=\beta\left(2\hat{C}_z^{+}\hat{\rho}_0+\hat{C}_z^{-}\hat{\rho}_{2z}\right),$$
$$\frac{\partial\hat{P}_z^{-}}{\partial\tau}+\frac{\hat{P}_z^{-}}{\hat{T}_2}+i\hat{\delta}_j=\beta\left(2\hat{C}_z^{-}\hat{\rho}_0+\hat{C}_z^{+}\hat{\rho}_{2z}{}^{*}\right), \tag{6}$$
$$\frac{\partial\hat{\rho}_0}{\partial\tau}+\frac{(\hat{\rho}_0-1)}{\hat{T}_1}=-\mathrm{Re}\left(\hat{C}_z^{+}\hat{P}_z^{+*}+\hat{C}_z^{-}\hat{P}_z^{-*}\right),$$
$$\frac{\partial\hat{\rho}_{2z}}{\partial\tau}+\frac{\hat{\rho}_{2z}}{\hat{T}_1}=-\left(\hat{C}_z^{+}\hat{P}_z^{-*}+\hat{C}_z^{-}\hat{P}_z^{+*}\right),$$

Here we use the following normalized variables:

$$\hat{\rho}=\frac{\rho}{\rho_e},\ \hat{P}_z^{\pm}=P_z^{\pm}\left(\frac{\pi b_\rho l_1}{\rho_e\hbar\omega_0 c v_{gr} b_{eff}}\right)^{\frac{1}{2}},\ \hat{C}_{x,z}^{\pm}=C_{x,z}^{\pm}\left(\frac{b_{eff}\omega_0}{\pi\rho_e\hbar c v_{gr} b_\rho}\right)^{\frac{1}{2}},$$

$$\hat{T}_{1,2}=\frac{v_{gr}T_{1,2}}{l_1},\ \beta=\pi\rho_e|\mu|^2 b_\rho l_1 c\big/2\hbar\omega_0 b_{eff}$$

where ρ_e is the equilibrium concentration of inverted active elements (nonequilibrium carriers in semiconductor laser media) without radiation, μ is the dipole element $T_{1,2}$ are the carrier and polarization relaxation times, δ_j is the detuning of the channel number j middle frequency from the Bragg frequency, b_{eff} is the effective waveguide thickness for the TM waveguide waves (given in [7]), v_{gr} is the group velocity of the amplified waves inside the laser channels, b_ρ is the active layer thickness. All of the structure dimensions are also normalized: $L_2=l_2/l_1$, $L=l/l_1$, $L_k=l_k/l_1$, $L_d=l_d/l_1$.

It is important to emphasize that the equations (6) don't use the balance assumption, which neglects the polarization relaxation time. The transverse relaxation time T_2 acts as the reverse linewidth of the laser media. This complication allows us to take possible frequency mismatches between laser channels into account. In our simulations the channel frequencies δ_j were chosen randomly from an interval with the width of δ in the vicinity of the Bragg frequency: $\delta_j \in (-\delta/2, \delta/2)$.

3. Simulation of a multi-channel laser excitation process

Excitation, synchronization and the steady state regime of a multichannel laser with 2D Bragg reflectors is described by equations (4) and (6) and can be studied numerically Simulation results are

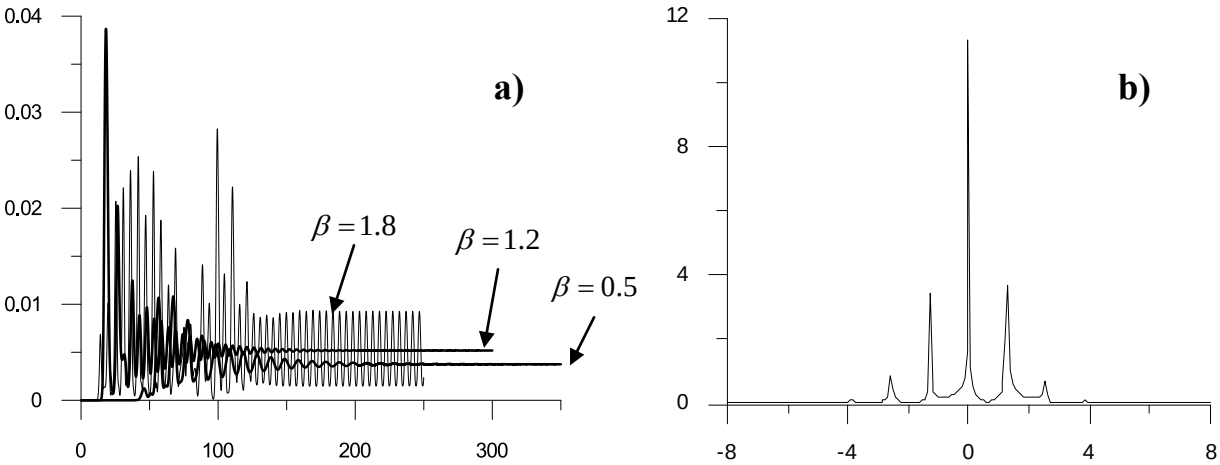


Figure 2. Time dependencies of radiation power at different normalized gain values (a); radiation spectrum in multi-mode regime at $\beta = 1.8$ (b); $n = 20$, $L_2 = 1$, $L = 4$, $L_k = 0.1$, $L_k = 0.05$, $\hat{T}_{1,2} = 1$, $\delta = 1$.

presented in figures 2-4 for the case of 20 laser channels. Establishment of the steady state regime is illustrated in figure 2 by time dependencies of the laser output power. There is a large interval of normalized gain values (parameter β in (6)) where the laser operates in the steady state regime. However, increasing the gain further results in a multimode regime in which the radiation spectrum consist of several longitudinal modes (figure 2b) similar to the Fabry-Perot resonator modes. One can mention that unlike lasers with single section 2D Bragg resonators [4,5], in the considered system single mode excitation can't be provided on the linear stage of the excitation process. The two main reasons for that are presence of multiple longitudinal modes with close quality values and randomness of individual channel frequencies. Accordingly, synchronization of radiation and selection of one longitudinal mode is a result of nonlinear mode interaction.

It is important to emphasize that all four of the partial waves don't have any reflective boundary conditions at the edges of the resonator so the laser radiation goes in all four directions through planar dielectric waveguides (see figure 1). However distribution of the output power between those directions can be made significantly unequal by choosing different length and modulation amplitudes for the left and right reflectors. Stationary distributions of partial waves $C^{\pm}_{x,z}$ are presented in figure 3 for the case where about 80% of radiation power is emitted though $Z = 0$ plane by the C^{-}_{z} partial wave.

Space-time distribution of the main C^{-}_{z} partial wave phase is presented in figure 4. One can notice that phase distribution in the steady state regime is different inside different channels and seems to be

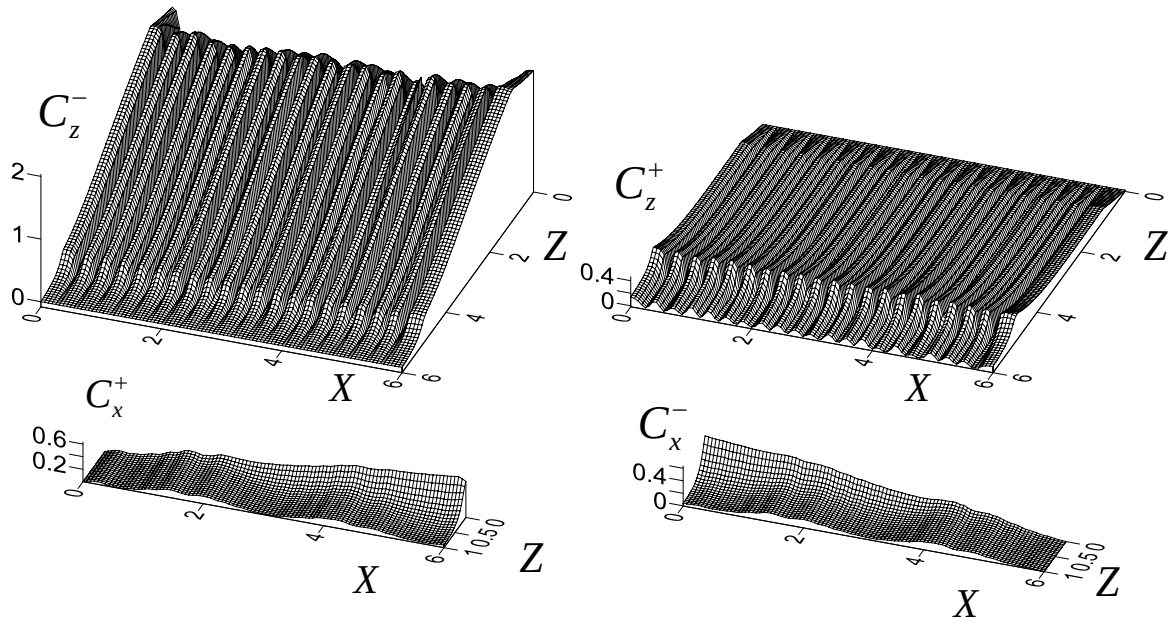


Figure 3. Spatial distributions of partial waves in the steady state regime; $n=20$, $L_2=1$, $L=4$, $L_k=0.1$, $L_k=0.05$, $\hat{T}_{1,2}=1$, $\beta=0.5$, $\delta=1$.

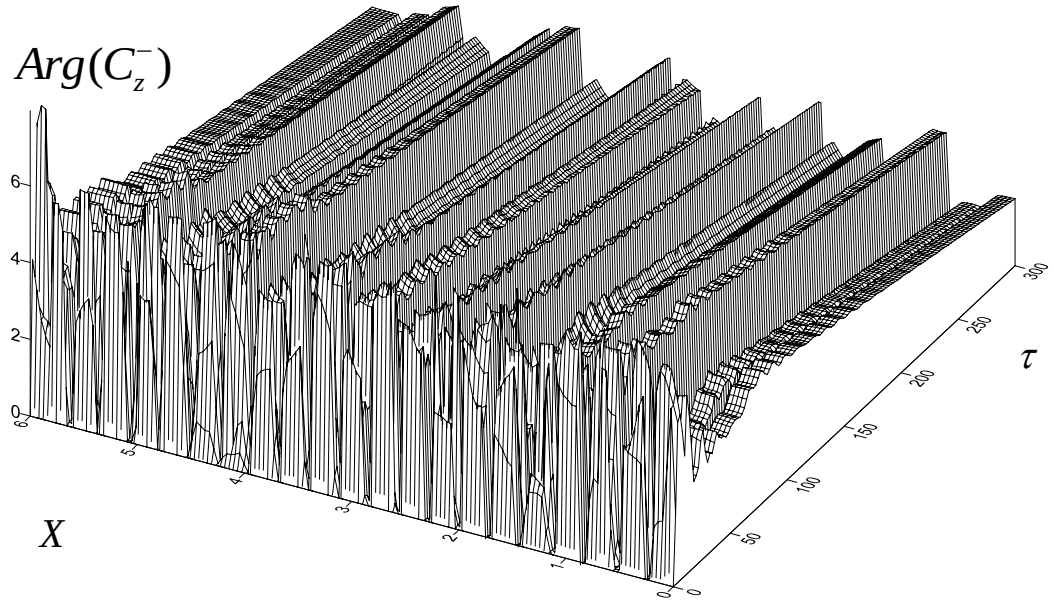


Figure 4. Space-time distribution of the phase of partial wave C_z^- that defines the output radiation structure; $n=20$, $L_2=1$, $L=4$, $L_k=0.1$, $L_k=0.05$, $\hat{T}_{1,2}=1$, $\beta=0.5$, $\delta=1$.

random, which is caused by randomness of the channel frequencies δ_j. In this particular simulation the channel frequencies distribution size δ was comparable to the channel linewidth.

4. Conclusion

2D Bragg structures allow synchronization of multiple semiconductor laser channels when used as external reflectors. Eigenmode spectrum of a resonator with two 2D Bragg structures is located inside the reflection band of the structures. Similarly to a Fabry Perot resonator, the higher quality part of this spectrum consists of equidistant modes with the same transverse but different longitudinal indices. Simulation demonstrates excitation of multiple modes at the initial linear stage of lasing process. At the nonlinear stage the steady state regime establishment corresponding to mutual synchronization of laser array in a wide range of individual channel frequencies and gain values.

Acknowledgements

This work was supported by Competitiveness Program of National Research Nuclear University MEPhI.

References

[1] Lui B *et al* 2014 *Optics Communications* **324** 301
[2] Goldobin I S 1989 *Soviet Journal of Quantum Electronics* **19**(10) 1261
[3] Peleš S, Rogers J L and Wiesenfeld K 2006 *Phys. Rev.* E **73** 026212
[4] Baryshev V R, Ginzburg N S, Malkin A M and Sergeev A S 2009 *Quantim Electron* **39**(12) 1159
[5] Ginzburg N S, Baryshev V R, Sergeev A S and Malkin A M 2015 *Phys. Rev. A* **91** 053806
[6] Andreev A V 1990 *Sov. Phys. Usp.* **33** № 12 997
[7] Kogelnik H and Shank C V 1971 *Appl. Phys. Lett.* **18** № 4 152