Regularization of broad-area lasers by non-Hermitian potentials

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Abstract- It was recently shown that arbitrary non-Hermitian optical potentials based on local Parity-Time (PT-) symmetry may control the flow of light, due to the asymmetric mode coupling. We propose periodic non-Hermitian potentials to efficiently regularize the complex spatial dynamics of broad-area semiconductor (BAS) lasers and Vertical-Cavity Surface-Emitting Lasers (VCSELs). Light generated from the entire active layer is concentrated on the structure axis, confined in an intense central narrow beam opening the path to design compact, bright broad-area lasers.

Semiconductor lasers are compact and efficient coherent light sources yet being generally unstable due to their large aspect ratio and to the lack of a transverse mode control mechanism. Spatial random fluctuations and spatiotemporal instabilities degrade the spatial beam quality and laser coherence [1]. This intrinsic instability gives rise to different nonlinear modal interactions such as filamentation and hole burning, limiting possible applications. Common techniques to control the complex dynamics of BAS and VCSELs semiconductor lasers generally compromise their compactness while reducing the power conversion efficiency.

The present paper proposes a novel solution to the need for a general physical mechanism to stabilize the complex dynamics of semiconductor lasers, while improving the beam quality emission. In recent years, non-Hermitian spatially modulated materials have provided a flexible platform to manipulate light wave dynamics. Simultaneous refractive index and pump modulations have already shown the capability to suppress spatial instabilities in nonlinear optical systems, particularly in BAS and VECSEL devices [2]. A remarkable class of such materials is the one globally holding PT- symmetry [3], which may be regarded as particular class of non-Hermitian systems fulfilling spatial Kramers-Kronig relations [4]. Such materials allow unidirectional light transport arising from the unidirectional mode coupling. In turn, it was shown that local PT-symmetry may lead to light localization and enhancement at a selected point [5] or complex potential may be specially designed using a local Hilbert transform, to control flow of light favoring arbitrary vector fields directionality using periodic, quasiperiodic or random background potentials [6].

We now show how axisymmetric non-Hermitian potentials efficiently regularize VCSELs radiation achieving a stable bright emission, see Figs 1.a-e. Dephased periodic (radial) refractive index and gain-loss modulations accumulate the generated light from the entire active layer and concentrate it around the structure axis to emit narrow beams. We perform a comprehensive analysis to explore the maximum central intensity enhancement and concentration regimes. We observe such lasers can be operated in stationary or pulsating oscillatory regime depending on the relative amplitude and phase of the index and gain-loss modulations. The results indicate stabilization occurs coinciding when the coupling between transverse modes is inwards, while not fulfilling perfect PT-symmetry. We also apply an analogous scheme to control and improve the spatiotemporal dynamics in BAS lasers, see Figs.1e-f. In the proposed modulated BAS devices, the structure in divided into two half-spaces with two symmetric PT-symmetric potentials, by introducing a modulation both in the pump and refractive index. The generated light is directed towards the symmetry axis, see Fig.1g, forming a narrow and bright and temporally stable emitted beam, see Fig.1h.

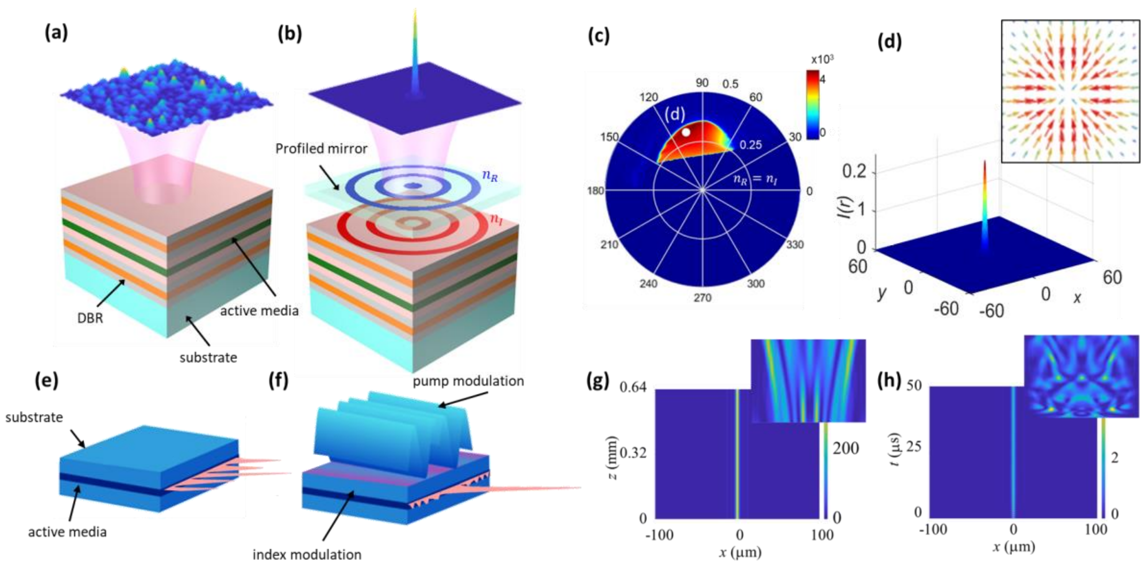

Fig. 1 (a)/b) Complex irregular/bight and narrow beam emission form conventional/structured broad-area VCSELs; (blue, n_R: index, red, n_I: gain-loss); (c) concentration factor C=[I(r=0).Area]/ $\int I(r)dr$ in parameter space (n_I, ϕ); (d) intensity profile in stationary state., and transverse field flow around the center, showing the unidirectional inward radial coupling. (inset) (e)/(f) Complex irregular/bright and narrow emission from conventional/structured BAS lasers; (g) spatial intensity distribution within the BAS laser; (h) temporal evolution of the output intensity profile of the modulated BAS laser and the same intensity profiles for an unstable BAS laser (insets).

The study uncovers rich possibilities for various configurations which could be extended beyond periodic non-Hermitian potentials assuming different random, quasiperiodic complex profiles of the background potential. The reported field regularization effect is universal, and we expect the proposed mechanism to be applicable to regularize the radiation from actual broad aperture lasers and microlasers.

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REFERENCES

1. J. Othsubo, Semiconductor Lasers: Stability, Instability and Chaos (Springer, Heidelberg, 2013).
2. R. Herrero, M. Botey, M. Radziunas, and K. Staliunas, Opt. Lett. 37, 5253 (2012), S. Kumar, R. Herrero, M. Botey, and K. Staliunas, Opt. Lett. 39, 5598 (2014)
3. C. M. Bender and S. Boettcher, Phys. Rev. Lett. 80, 5243 (1998),
4. S. A. R Horsley, M. Artoni, and G. C. La Rocca. Nat. Phot. 9.7, 436 (2015)
5. W. W. Ahmed, R. Herrero, M. Botey, and K. Staliunas, Phys. Rev. A 94, 053819 (2016).
6. W. W. Ahmed, R. Herrero, M. Botey, Z. Hayran, H. Kurt, and K. Staliunas, Phys. Rev. A 97, 033824 (2018).
7. W. W. Ahmed, R. Herrero, M. Botey, Y. Wu and K. Staliunas, arXiv:1902.04915 [physics.optics]