# $\mathcal{PT}$ Symmetric Large Area Single Mode DFB Lasers

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**Abstract:** We propose a novel class of large-area single-mode semiconductor lasers in which notions from parity-time symmetry is employed to reliably suppress higher-order modes. The feasibility of our design is investigated in InGaAsP quantum-well arrangements.

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The need for compact high-power single-mode semiconductor lasers has been the driving force behind wide range of innovations in the field of integrated photonics. Yet, despite the intense activity of recent years, the realization of such sources in a fully integrated fashion remains a challenging task to this date. While the three design goals of high output power, single-mode operation and compact integration can be separately accommodated with relative ease, optical nonlinearity and thermal effects inevitably set them in opposition to one another. For instance, the nonlinear phase fluctuations and heat accumulation associated with higher powers could be alleviated by expanding the cross-sectional area of the active region. However, this approach comes at the cost of a deteriorating beam quality, mode instabilities and spectral hole-burning effects as the system becomes multi-moded. Along these lines, various strategies to preferentially encourage lasing in the fundamental mode have been suggested. By means of spatial filtering [1,2], one aims to increase the losses (or at least lower the gain) experienced by the undesirable modes, without unduly influencing the lasing threshold of the fundamental mode. Yet, due to the compromised confinement, the resulting laser devices tend to be significantly more sensitive to longitudinal and lateral perturbations. Quite recently, a new approach has been proposed [3] to resolve these issues by utilizing parity-time ($\mathcal{PT}$) symmetry. When the refractive index of an optical arrangement is described by an even profile, while its gain/loss obeys an anti-symmetric distribution, the corresponding eigenvalue spectrum may be entirely real-valued [4-6]. As a consequence, the modes experience zero net gain or loss, unless $\mathcal{PT}$ symmetry is spontaneously broken. Within the context of large-mode-area lasers, this phase transition can be judiciously tuned to present substantial gain to the fundamental mode, while appearing neutral to all the higher order modes.

Figure 1 illustrates this concept for the example of a distributed feedback (DFB) laser when realized in an InGaAsP multiple quantum-well wafer system. At the operating wavelength of 1550 nm, the conventional DFB structure (Fig. 1(a), top) supports a total of 18 spatial modes. Finite element calculations yield very similar gain values for each of them (bottom). As a result, under these conditions, the system would be entirely incapable of operating in a single-moded fashion. In contrast, the corresponding $\mathcal{PT}$-symmetric arrangement (Fig. 1(b)) exclusively amplifies its fundamental mode.

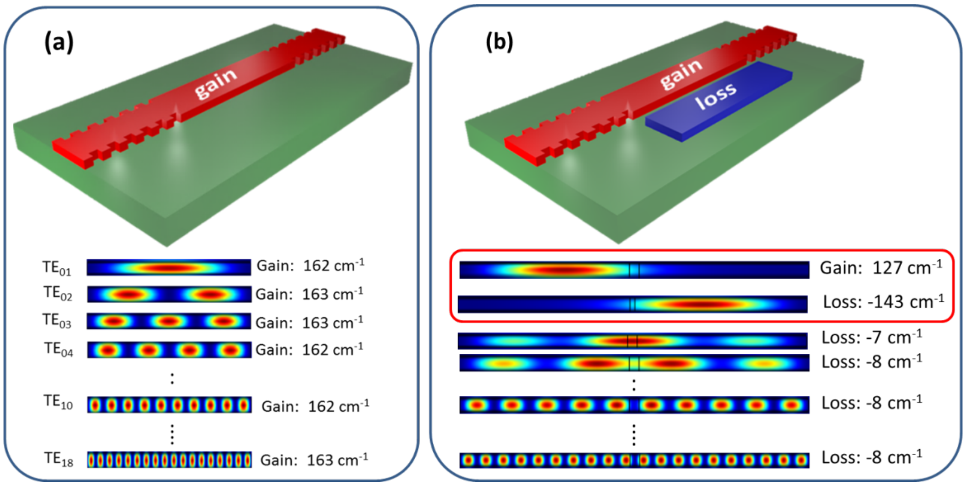

Fig. 1: (a) Conventional large mode area DFB laser (top) supporting up to 18 modes at ~1550 nm (bottom). The active waveguide consists of an InGaAsP multiple quantum-well structure (width 7μm, thickness 220 nm, gain 162 cm$^{-1}$). (b) Corresponding $\mathcal{PT}$ -symmetric design (top). A lossy waveguide with otherwise identical parameters is placed in close proximity. Operating in the broken-symmetry regime, all except the fundamental mode are reliably suppressed (bottom).

In pairing the active waveguide with its lossy counterpart, the number of modes is effectively doubled (to 36 for the example at hand), and the eigenvalues associated with these supermodes depend on the coupling coefficient $\kappa$ between the gain and loss sections. Spontaneous breaking of $\mathcal{PT}$ symmetry occurs when the gain $g$ exceeds $\kappa$. In the process, the previously identical field distributions of a mode pair become distinguishable and reside in the amplifying and lossy region, respectively. As a consequence, their associated propagation constants become complex and assume the values. Given that among all the modes of the $\mathcal{PT}$–symmetric structure, the fundamental mode exhibits the lowest coupling coefficient, it is then possible to tailor the system so as the symmetry breaking occurs exclusively for this mode. In order to ensure that undesirable modes experience a net amount of loss, one may chose the parameters of the lossy structure such that they slightly overcompensate the gain in the active area. In our design (see Fig. 1(b)), the fundamental mode residing in the active region observes a net gain of 127 $\text{cm}^{-1}$. Its counterpart in lossy section is heavily attenuated (loss 143 $\text{cm}^{-1}$), whereas all higher modes feature similar losses on the order of 8 $\text{cm}^{-1}$.

When realizing the closely spaced arrangement of amplifying and attenuating components, particular care must be taken to maintain an even distribution of the real part of the overall refractive index profile. Instead of utilizing different material compositions for the gain and loss waveguide, respectively, we propose to synthesize the desired imaginary index distribution by modulating the pump intensity via an appropriately structured metal cladding. Figure 2(a) depicts a schematic of this configuration. The wafer, containing a 200 nm thick, transversely uniform active layer comprised of six stacked InGaAsP quantum wells, is coated with a 40 nm gold film to selectively shield the active medium from the pump radiation in the lossy regions. The “gain” segment of a $\mathcal{PT}$ arrangement lacks this mask, whereas the area surrounding the component could be rendered semi-transparent by lithographic nanopatterning. Here, the gain induced by the partially transmitted pump would balance the losses, thereby providing a neutral environment (see Fig. 2(b)). In order to avoid unwanted influences on the refractive index profile, a thin spacer layer could be introduced to separate mask and active region. The main challenge in the approach outlined here is the characterization of the dependence between mask geometry and resulting gain distribution in these wavelength-scale arrangements. To this end we have devised a technique to quantify the intrinsic losses of the unpumped quantum-well layer. Our work provides an important first step towards harnessing $\mathcal{PT}$ symmetry to enforce single-mode operation in intense large mode area laser sources.

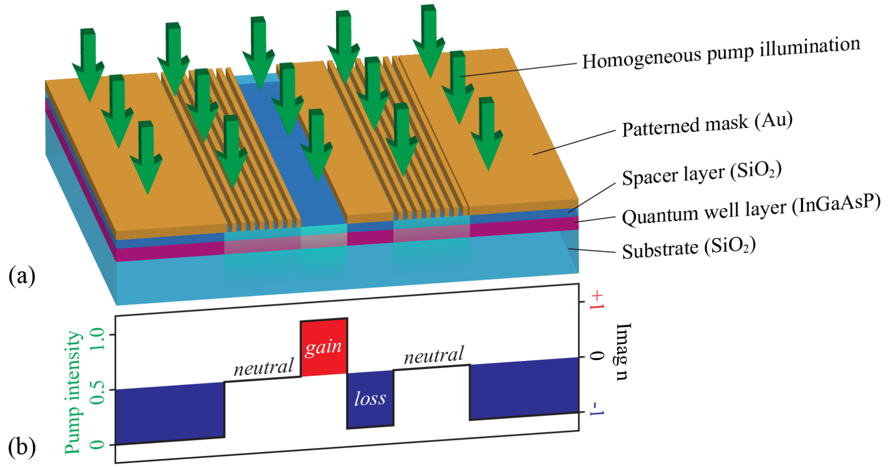

Fig. 2. (a) Schematic of the proposed technique. A thin gold mask serves to selectively block parts of the homogeneous pump beam. (b) The resulting gain distribution depends on the pump intensity distribution, and therefore can be tailored by nanopatterning of the mask layer.

## References

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