

Optimizing the Quantum Dot Lasers for High-Speed Operation: Novel Versus Conventional Designs

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Abstract: Direct modulation bandwidth and optimum dc current maximizing it are discussed for double tunneling-injection quantum dot (QD) lasers and QD lasers with asymmetric barrier layers and compared to those for conventional QD lasers. © 2021 The Author(s)

The dynamic properties of novel and conventional semiconductor quantum dot (QD) lasers are reviewed. In particular, the maximum modulation bandwidth and the optimum dc current maximizing it are discussed and compared for these lasers.

In conventional semiconductor lasers, the charge carriers first appear in the optical confinement layer (OCL) on their way to the low-dimensional active region. The electrons and holes are not spatially separated in the OCL and hence can easily recombine with each other therein. This unwanted electron-hole recombination in the OCL is the main contributor to the temperature dependence of the threshold current in diode lasers [1–3]. In addition, there is a certain delay in the carrier capture from the bulk OCL into the quantum-confined active region. As a result of this delay, the electron and hole densities in the OCL, and hence the parasitic electron-hole recombination rate, do not remain fixed after the lasing starts – they grow with increasing pumping. This leads to sublinearity of the light-current characteristic (LCC) of the laser and limits its useful output optical power [4–6].

To suppress the recombination outside the quantum-confined active region, two design approaches were proposed. One of the approaches [7–13] exploits double tunneling-injection (DTI), i.e., tunneling injection of both electrons and holes into the active region from two separate quantum wells (QWs). In a DTI laser, the quantum-confined active region, located in the central part of the OCL, is clad on each side by a thin barrier and a QW. Electrons and holes are injected into the active region by tunneling from the corresponding QWs. Ideally, there should be no second tunneling step, i.e. out-tunneling from the active region into the ‘foreign’ QWs (electron-injecting QW for holes and hole-injecting QW for electrons).

The other approach [8, 9] is based on independent tailoring of the conduction and valence bandedges by means of the use of two asymmetric barrier layers (ABLs) – one on each side of the active region. The ABL in the electron-injecting side of the structure should ideally prevent holes from entering that side while not hindering the electron-injection into the active region. The ABL in the hole-injecting side should prevent electrons from entering that side while not hindering the hole-injection into the active region. A laser utilizing ABLs was termed a bandedge-engineered laser [8, 9, 14] or an ABL laser [15–17].

In both DTI and ABL lasers, there will ideally be no electrons (holes) in the hole- (electron-) injecting side of the structure, i.e., the bipolar population will be suppressed outside the active region.

Elimination of parasitic recombination would allow to attain close-to-ideal static operating characteristics in DTI and ABL lasers, namely, virtually temperature-insensitive threshold current, close-to-one internal quantum efficiency, and linear LCC.

The dynamic characteristics are also improved in DTI and ABL lasers as compared to conventional lasers [18–21]. Modulation bandwidth is an important parameter describing the speed with which the optical output of diode lasers is varied with altering the input injection current [18]. For the conventional, DTI, and ABL QD lasers, Fig. 1 shows the modulation bandwidth as a function of the dc component of the injection current. Except for the barriers (in the DTI and ABL structures) and injector-QWs (in the DTI structure), the structures are otherwise similar. As seen from the figure, the modulation bandwidth has a maximum at a certain optimum value of the dc component of the injection current. As also seen from the figure, the maximum bandwidth is the same in all the three structures. The point is that the maximum bandwidth is merely controlled by the photon lifetime in the cavity, which is the same in all the three structures as the cavity length is chosen to be the same. However, the optimum dc injection current is considerably different in the structures – it is highest in the conventional laser, noticeably lower in the DTI laser, and significantly lower in the ABL laser. The physics behind this is as follows: in contrast to the maximum modulation bandwidth that is not affected by the differential gain, the optimum current does depend on the differential gain – it decreases with increasing differential gain. Due to the fact that each type of carriers is only present on side of the DTI and ABL lasers, the differential gain is higher there as compared to that in the

conventional laser. Furthermore, the differential gain is higher in the ABL laser as compared to that in the DTI laser as there are no QWs and hence no extra carriers therein in the ABL laser.

In conclusion, it is discussed that the optimum dc current that maximizes the modulation bandwidth is lower in the DTI QD laser as compared to that in the conventional QD laser, and even significantly lower in the ABL QD laser. Hence, while the maximum modulation bandwidth is more easily attainable in the DTI laser as compared to the conventional laser, it is most easily attainable in the ABL laser out of the three lasers considered.

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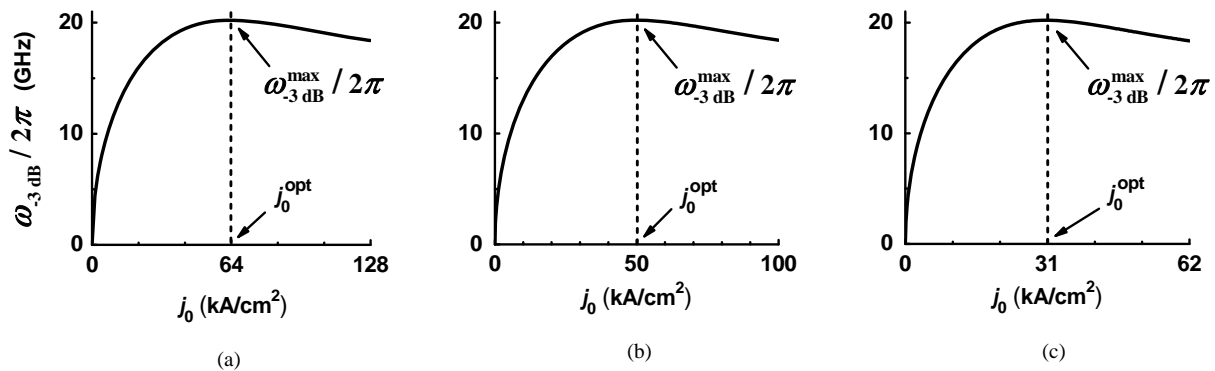


Fig. 1. Modulation bandwidth vs. dc component of injection current density in QD lasers of different designs: (a) conventional, (b) DTI, and (c) ABL.

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