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Kink power in weakly index guided semiconductor lasers

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A periodic dependence of kink power on laser length is observed and explained. Weakly index guided high power stripe lasers in the AlGaAs, InGaAlP, and InGaAs–AlGaAs material systems are studied and oscillation periods of 100–350 μm are found. Relative kink power differences exceeding a factor of 4 are observed. Facet coatings lead to differences in the oscillation amplitude but not in the oscillation period. The observations indicate that phase-locked fundamental and first-order modes exist at certain preferred laser lengths. This general model fully explains the oscillatory behavior of the kink power and the correlated changes in lateral far field distributions at the front and rear mirrors. It is concluded that the optimum diffraction limited power output can be obtained by choosing the proper laser length. © 1995 American Institute of Physics.

For many applications it is required that narrow stripe high-power laser diodes emit their power in a stable, diffraction limited far field. The transition from diffraction limited to nondiffraction limited operation is observed as a kink in the light versus current curve. For many laser geometries the kink power level is observed at power levels significantly below the output power at which laser degradation sets in, and therefore the kink becomes a limiting factor in laser performance. In this letter the limits on kink power are investigated for the high power lasers of the AlGaAs, InGaAlP, and InGaAs–AlGaAs material systems emitting at a wavelength of 780, 670, and 980 nm, respectively.

Double heterostructure and separate confinement heterostructure (SCH) double quantum well (DQW) lasers have been fabricated by metalorganic vapor phase epitaxy. For λ=780 nm, a bulk active layer ridge waveguide is fabricated. For λ=670 nm and λ=980 nm, strained layer quantum well buried ridge-type laser structures are studied. At λ=670 nm, the GaAs current blocking layer is strongly light absorbing at the laser wavelength, whereas it is transparent at the laser wavelength of λ=980 nm devices.

For λ=980 nm, buried ridge lasers with a double SCH strained layer DQW structure were used with 4.6 nm strained layer In0.25Ga0.75As quantum well layers, separated by 4.7 nm GaAs barriers and embedded in 19 nm thick GaAs and 40 nm thick Al0.20Ga0.80As SCH layers. The Al0.40Ga0.60As cladding layer has a thickness of 1.3 μm. Ridges with a width of 3.2 μm have been etched into the cladding layers and subsequently selectively buried with lattice matched InGaP current blocking layers. The etch stop is at a distance of 150 nm relative to the active layer. After the removal of the mask the p-type GaAs contact layer has been deposited.

For devices operating at a wavelength of λ=780 nm, 40 nm thick Al0.13Ga0.87As active layers and 1.7 μm thick AlGaAs cladding layers were chosen. Ridge waveguide lasers have been fabricated by etching 3.6 μm wide ridges into the p-type GaAs contact and Al0.50Ga0.50As cladding layers down to a distance of 290 nm from the active layer.

For λ=670 nm, buried ridge SCH strained layer DQW lasers have been fabricated by a three step growth process. The strained layer In0.65Ga0.35P quantum wells have a thickness of 8.5 nm, are separated by a 6 nm wide barrier, and are embedded in 45 nm wide SCH In0.53(Ga0.6Al0.4)0.5P layers, and 1.4 μm thick In0.53(Ga0.3Al0.7)0.5P cladding layers. Ridges with a width of 4.2 μm have been etched through the layer package leaving a p-cladding thickness of 0.5 μm. GaAs current blocking layers have been deposited by a selective regrowth, and subsequently the contact GaAs layers have been grown. Although the designs are quite different, the above waveguide structures can be classified as weakly index guided, with calculated lateral effective index steps ranging from about 0.002 for the 670 nm lasers to 0.007 for the 780 nm lasers and 0.015 for the 980 nm devices.

The output power L, differential efficiency dL/dI, and far field distributions of the fabricated devices are measured under continuous wave (cw) operating conditions at room temperature.

Figure 1(a) gives typical L/I and dL/dI curves of a 780 nm laser. In Fig. 1(b) far field distributions at output powers below and above the kink power level are shown. Above the kink power level the far field is observed to shift.

Figure 2(a) gives the kink power for the 670 nm devices. Clearly a periodic variation of kink power as a function of laser length can be observed with a period of 350 μm. Figure 2(b) gives the kink power as measured for coated (13%–70%) and uncoated 780 nm devices. A kink power variation of the type depicted in Fig. 2(a) is found for both the coated and the uncoated devices. The period is 110 μm and appears to be independent of coating. For the coated devices the kink power is higher as can be attributed to the larger fraction of power coupled out of the cavity at the front, low reflectivity, laser facet. Finally Fig. 2(c) shows similar kink power data for the 980 nm devices, with a 100 μm period. It is found experimentally that above the kink power level shifting and broadening of the far field are observed.

The data in Fig. 2 suggest that the kink mechanism is of the same origin for all laser types. Such systematics and the
corresponding kink mechanism have, up till now, not been reported in the literature.

We propose a new model to explain the kink behavior. This model assumes that a phase-locked, first-order lateral optical mode propagates in a laser that is operated above the kink power level. The combination of fundamental and first order modes results in a hybrid mode $E_h$:

$$E_h(y,z) = \sqrt{1-|\xi|^2} E_0(y)e^{-j\beta_0 z} + \xi E_1(y)e^{-j\beta_1 z}. \quad (1)$$

Here $y$ represents the lateral direction, $z$ represents the longitudinal direction, and $\beta_0$ and $\beta_1$ represent the propagation constants of the fundamental and first-order modes, respectively. The lateral mode shapes of $E_0$ and $E_1$ are shown in Fig. 3(a) for the laser operating at 780 nm. The factor $\xi$ determines the amount of first-order mode power with respect to the fundamental mode power at $z=0$. Figure 3(a) also shows the corresponding near field intensity profile of $E_h$. The corresponding far field distributions for $\xi=0.3$ and $\xi=0.3$ are shown in Fig. 3(b). Apparently the hybrid mode can, depending on the phase relationship between the two composing modes at the mirror, cause a shifted or a broadened far field distribution.

A necessary condition for phase locking of the first-order mode is that both fundamental and first-order modes need to fit into the laser cavity at the same vacuum wavelength while propagating with different propagation constants $\beta_i$. Each mode will have to satisfy the mirror boundary conditions demanding that the modes will be in phase after each roundtrip. The beat length between fundamental and first order mode, given by:

$$L_b = \frac{2\pi}{\beta_0 - \beta_1} \quad (2)$$

will therefore play a decisive role in kink phenomena. A kink in the $L/I$ will occur whenever the laser length $L = mL_b/2$, with $m=1,2,...,N$. For other lengths, a kink will not occur until, due to current injection, $\beta_0 - \beta_1$ has been changed accordingly. This explains the periodical shape of the various kinkpower versus length plots in Fig. 2.

The beat lengths calculated for our laser structures using the as fabricated guiding parameters are found as 130, 85, and 500 $\mu m$ for the 980, 780, and 670 nm wavelength devices, respectively. These beat lengths correspond well to the beat lengths observed in Fig. 2.

The model predicts that the hybrid mode is zigzagging periodically through the laser cavity along the laser length. Thus depending on the number of periods in the cavity the mode patterns at front and rear mirror should subsequently appear as identical or as each other’s mirror image. The lateral far field shift directions at front and rear mirrors must therefore be correlated. The correlation expected from our
model is schematically indicated in Figs. 4(a)–(c) for 0.5, 1, and 1.5 periods along the cavity length by the “eye patterns” indicating the direction of power transport in the laser. The figures correspond to 670 nm lasers of 300, 600, and 950 µm lengths. Laser diodes of these lengths were mounted such that both front and rear mirrors could be observed. In Fig. 4 the experimentally observed lateral far fields below and above the kink power level are given and are seen to confirm the model prediction.

The periodic kink power level as a function of laser length cannot be explained by assuming a fundamental lateral mode instability or a first-order mode kink. These are caused by holeburning which does not have a periodic dependence on the laser length. Also, the holeburning strongly depends on the mirror coating reflectivities while we observe, as shown in Fig. 2(b), that coating does not influence the observed kink power level periodicity significantly.

The proposed hybrid mode kink mechanism explains both the observed length dependence of kink power level and the far field behavior. The hybrid mode kink can occur at relatively low power levels since it is not required that the waveguide properties change strongly as is the case with fundamental mode instabilities. Also the first higher order mode does not have to reach threshold. This can only occur at much higher power levels than have been observed here and would even be more unlikely in the geometry with lossy GaAs current blocking layers.

For a more exact beat length computation several refinements can be made, including factors such as ridge shape and carrier profile that influence the lateral waveguide properties. This is a subject of further study. Also the self-stabilization of the mode locking process, associated with the kink effects, will have to be studied to obtain a further understanding of the kink power level versus the laser length curves.

In conclusion, the kink power of weakly index guided waveguide lasers is found to depend periodically on the laser length. The periodicity is observed in three totally different waveguide systems in different material systems and wavelengths. The kinks are explained by a hybrid mode which preferably propagates at laser lengths determined by the beat length of the propagation constants of fundamental and first higher order mode. This hybrid mode causes both shift kinks and fundamental mode broadening kinks. It follows that optimum diffraction limited output power can only be obtained by the proper choice of the laser length.