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High Brightness Index-Guided Parabolic Bow-Tie Laser Arrays

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***Abstract*—This letter describes a novel 980-nm parabolic bow-tie laser array (PBTLA) that is suitable for high-power and high-brightness operation. Output powers in excess of 2.5 W/facet pulsed in a 1° (lateral) beam, less than twice the diffraction limit, corresponding to 275 $\mathrm{MW \cdot cm^{-2} \cdot sr^{-1}}$ brightness, have been measured without the use of external lenses from uncoated PBTLAs fabricated in-house (top metal contact surface area $\sim 0.1\ \mathrm{mm}^2$). Experimental results presented in this letter indicate that coherence effects are significant in the operation of such devices. Theoretical models based on the simple diffraction theory and on the coupled-mode theory have been used to interpret the experimental results.**

***Index Terms*—High brightness lasers, high power, index-guiding, tapered geometry lasers.**

I. Introduction

HIGH-POWER semiconductor optical sources that are characterized also by high brightness are required for various applications, including lidar, sensing, materials processing, optical pumping, medicine. The challenge in designing high-power high-brightness semiconductor sources resides in overcoming catastrophic optical damage, optical gain saturation, and filamentation. In addition, the output beam profile should be optimized to achieve the desired high brightness. Therefore, to develop semiconductor optical sources with such characteristics it is important to appropriately design both the material epitaxy and the device geometry. Effective device designs for high-power high-brightness sources can be found in the literature, including external cavity-tuned lasers [1], antiresonant reflecting optical waveguide lasers [2], and master oscillator power amplifiers [3]. However, the above designs generally require sophisticated device fabrication to sustain in-phase operation and/or the use of external optics to focus the output beam. Of interest in this letter are index-guiding tapered geometry devices [4]–[6], since they seem to provide an effective and convenient design model to combine the desirable operational characteristics of high power and narrow output beam with simple low-cost device fabrication.

II. Parabolic Bow-Tie Laser Arrays

In the devices presented in this letter, an etched tapered rib provides (weak) lateral optical confinement. Therefore, in such devices the quality of the output beam is determined by the optical cavity design. The array discussed here is a development of a parabolic bow-tie laser (PBTL) designed in-house that was

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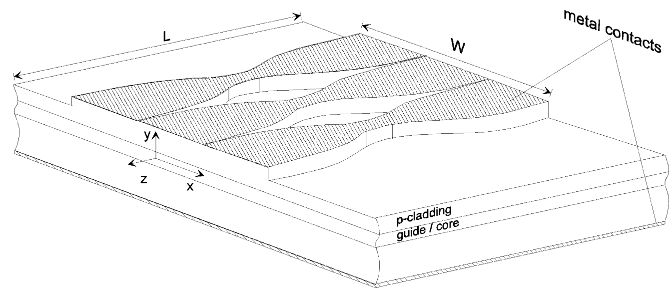

Fig. 1. Schematic of a three-element PBTLA geometry; the main parameters are also specified in the diagram.

demonstrated to be well suited for high-brightness operation with moderately high-power output [4], [5]. However, the output power from a PBTL cannot be increased indefinitely because the device would need to be impractically long to retain the modal properties required for high brightness. Hence, to scale up the output optical power, a number of PBTLs are now driven simultaneously as an array. The schematic of a three-element PBTL array (PBTLA) is illustrated in Fig. 1. Different from the work presented in [7]–[9], the intention here is to achieve phase-locking between the emitters in order to obtain not only high power, but also high brightness. The PBTLAs have been designed to achieve longitudinally nonuniform coupling between the elements with weak coupling along the length of the device and strong coupling at the device facets, to sustain in-phase (array) mode operation. The experimental results, presented in Section III, have been interpreted using results computed with theoretical models based on the simple diffraction theory (SDT) [10], and on the coupled-mode theory (CMT) [11].

III. Experimental Results and Discussion

Experimental results measured from three categories of devices are considered in this letter: stripe lasers (SLs), linearly tapered bow-tie laser arrays (LBTLAs), and PBTLAs. The devices of interest here have been fabricated in-house from a specially designed 980-nm high-power double heterostructure, triple quantum-well (QW) material with three 7-nm-thick InGaAs QWs separated by two 10-nm GaAs barriers [5]. Several arrays have been fabricated with a different number of elements, but all with the same length and the same output facet width (details in figure captions), to compare performance characteristics. The devices are bonded p-side down on temperature stabilized copper mounts; however, at present, thermal management is not optimal and, therefore, the devices are tested in pulsed conditions with 0.1% duty cycle (5-μs pulsewidth).

The pulsed L-J characteristics and wall-plug efficiency for arrays of three, four, and five elements of different geometries

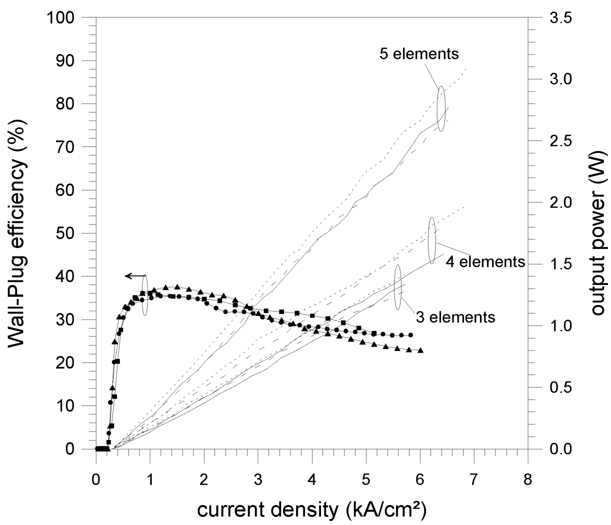

Fig. 2. Optical output power and Wall-Plug efficiency versus pulsed injection current density measured from arrays of three (▲), four (■), and five (●) elements: SL (dotted line); LBTLA (dashed line); and PBTLA (continuous line). All devices are of the same length, $L = 1.05$ mm; the output facet widths are as follows: three-element arrays: $W = 60\ \mu$m; four-element arrays: $W = 80\ \mu$m; five-element arrays: $W = 100\ \mu$m. Intensity filters have been used to take readings at high power levels.

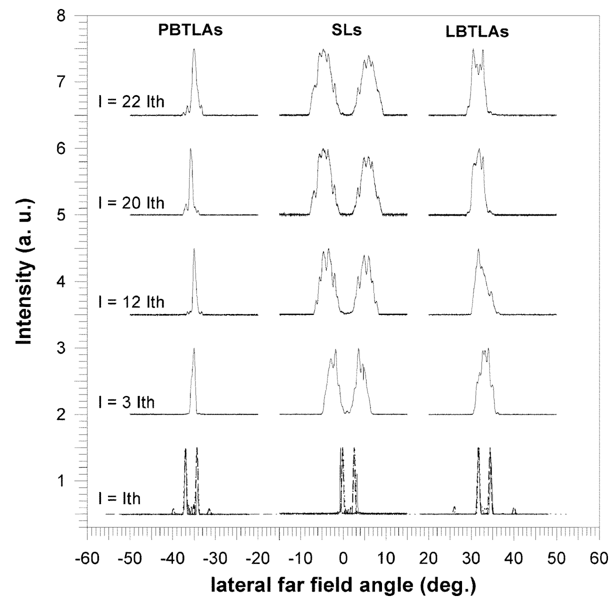

Fig. 3. Far field intensity profiles measured from SLs, LBTLAs, and PBTLAs ($L = 1.05$ mm, $W = 100\ \mu$m) over a wide range of currents (pulsed operation). Theoretical profiles computed with the CMT (dashed line) and with the SDT (dotted line) at threshold are also included.

TABLE I
COMPARISON OF PULSED OPERATIONAL CHARACTERISTICS MEASURED FROM SLs, LBTLAs, AND PBTLAs AT LOW ($I = 3I_{\rm th}$) AND HIGH CURRENTS ($I = 20I_{\rm th}$)

	Output Power ($W/facet$)		Far-Field FWHM (deg.)		Brightness ($MWcm^{-2}sr^{-1}$)	
Device	$I=3I_{th}$	$I=20I_{th}$	$I=3I_{th}$	$I=20I_{th}$	$I=3I_{th}$	$I=20I_{th}$
SL	0.41	3.1	9.1	13.8	5	25
LBTLA	0.23	2.6	2	3.1	8.4	92
PBTLA	0.32	2.8	0.8	1.08	42.4	275

are presented in Fig. 2. The output power is significantly higher for arrays with a larger number of elements (N), but varies little with the geometry of the device for arrays with the same N. The main operational characteristics measured from five-element arrays are summarized in Table I for low ($I = 3I_{\rm th}$) and high current injection levels, $I = 20I_{\rm th}$. For all such arrays, the threshold current is $I_{\rm th} = 160$ mA (corresponding to $J_{\rm th} = 0.2$ k Acm^{-2}); the slope efficiency is ~70%; the maximum wall-plug efficiency considering output power per facet is $\sim 35\%$ at $I = 0.75$ A (pulsed) and optical output power 0.6 W/facet (Fig. 2).

Representative far fields measured without the use of external lenses over a wide range of input currents from five-element arrays are presented in Fig. 3 for comparison (angle resolution of measurements $\sim 0.05°$). Although the output powers from all such devices are comparable, Table I, the quality of the output beam varies enormously depending on the cavity geometry. At threshold, all devices operate in the out-of-phase mode; at higher currents, SLs present a typical double-lobed pattern while both types of tapered laser arrays (LBTLAs and PBTLAs) present essentially a single-lobed beam over a wide range of currents. The latter observation is an indication of the fact that over a wide range of currents, quasi-in-phase-locking is achieved with the tapered optical cavity design. The change in mode operation can be attributed to the effect of carriers on the refractive index and gain spatial hole-burning in the device. In the region near the output facets there is no explicit lateral mode control since the elements merge in a single contact; it is in these regions that the interelement coupling is stronger. In such areas, above threshold, the modal gain in low index regions exceeds that in high index regions because of spatial hole-burning, thereby promoting in-phase operation, as discussed in [12] for arrays of a small number (3–5) of SLs. However, in the arrays of tapered lasers presented in this letter, this effect is associated to the mode filtering effect of the central region (Fig. 1), as demonstrated by the fact that in-phase locking is not observed in SLs.

The narrowest far field full-width at half-maximum (FWHM) has been measured from five-element PBTLAs (FWHM $= 1.08°$) which remains less than twice the estimated diffraction limit $\theta_d = \arcsin(\lambda_o/W) = 0.56°$ for a wide range of currents. Therefore, although all three categories of devices produce high power, the corresponding brightness strongly depends on the geometry of the cavity, with the highest values achieved with PBTLAs (275 MW $\cdot$ cm^{-2} $\cdot$ sr^{-1}), Table I. A further, important observation from the measured experimental results is that the output beam from five-element PBTLAs is considerably narrower than that measured from an individual PBTL element ($\theta_d = 2.8°$) [5], indicating that coherence effects are significant in the operation of the arrays. Similar trends have been observed for arrays of three and four elements of all geometries. Preliminary continuous-wave measurements on five-element PBTLAs have shown that the far field presents two peaks at threshold, but becomes single-lobed at higher currents with FWHM $= 3°$ at $I = 1.2$ A $= 7.5I_{\rm th}$ and output power of 370 mW.

To interpret the above experimental results, theoretical far fields have been computed using the CMT [11], starting from the field of the individual emitters [5] under the assumption that coupling occurs only at the facets. The above results have been

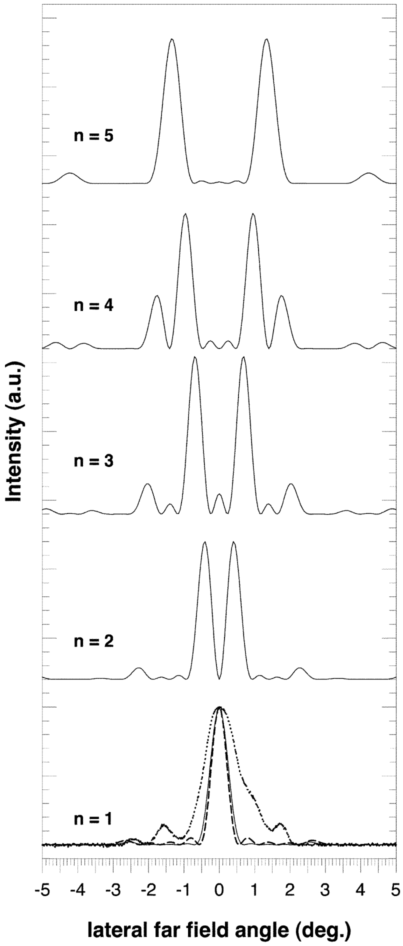

Fig. 4. Far field intensity profiles of the five modes computed with the CMT (solid line) and SDT (dashed line) for five-element PBTLA. The measured profile (at $I = 20I_{\rm th}$) is also included (dotted line).

also compared with those obtained using the SDT [10]. Theoretical results obtained at threshold are presented in Fig. 3. To obtain good agreement between the experimental profiles and those computed with the SDT, it has been necessary to introduce a $\Delta\phi = \pi$ phase-shift between elements at threshold. At higher input currents, the phase relation between individual elements changes and it is found that PBTLAs are quasi-in-phase (fundamental mode operation) while the SLs are always locked in the out-of-phase mode. The far field intensity profiles of all the five PBTLA modes obtained using the CMT are presented in Fig. 4. From the results presented in Fig. 4, it is possible to infer that the far field broadening at higher injection currents is due to the contribution of higher order array modes. At this stage it has not been possible to quantify nor ascertain the presence of beam steering since with the present measurement apparatus the accuracy of the scale is $\sim 0.5^\circ$, which is of the same order of magnitude of reported beam steering [6], [13]. No astigmatism was observed for any device geometry.

IV. Conclusion

This letter presents the characterization of a category of semiconductor index-guided lasers to show that careful cavity design is essential to achieve, simultaneously, high power and high brightness. Comparisons of the operational characteristics measured from several in-house fabricated devices of different geometry have been presented and discussed in detail. Theoretical models based on the SDT and on the CMT have been used to interpret the measured far field intensity profiles. Quasi-in-phase-locking (single-lobe output beam) has been observed over a wide range of currents in tapered laser arrays which operate with longitudinally nonuniform coupling. Specifically, the brightest devices, among those considered here, are arrays of coherently coupled PBTLs (275 $\rm MW \cdot cm^{-2} \cdot sr^{-1}$ brightness). Such devices are simple to fabricate and, thus, represent an attractive option for low-cost applications that require devices with high quality operational characteristics.

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