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Research Article

1D Confocal Broad Area Semiconductor Lasers (Confocal BALs) for Fundamental Transverse Mode Selection (TMS#0)

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Previously in this journal we have reported on fundamental transverse mode selection (TMS#0) of broad area semiconductor lasers (BALs) with integrated twice-retracted $4f$ set-up and film-waveguide lens as the Fourier-transform element. *Now* we choose and report on a simpler approach for BAL-TMS#0, i.e., the use of a stable confocal longitudinal BAL resonator of length L with a transverse constriction. The absolute value of the radius R of curvature of both mirror-facets convex in one dimension (1D) is $R = L = 2f$ with focal length f. The round trip length $2L = 4f$ again makes up for a Fourier-optical $4f$ set-up and the constriction resulting in a resonator-internal beam waist stands for a Fourier-optical low-pass spatial frequency filter. Good TMS#0 is achieved, as long as the constriction is tight enough, but filamentation is not completely suppressed.

1. Introduction

Broad area (semiconductor diode) lasers (BALs) are intended to emit high optical output powers (where "high" is relative and depending on the material system). As compared to conventional narrow stripe lasers, the higher power is distributed over a larger transverse cross-section, thus avoiding catastrophic optical mirror damage (COMD). Typical BALs have emitter widths of around 100 μm.

The drawback is the distribution of the high output power over a large number of transverse modes (in cases without countermeasures) limiting the portion of the light power in the fundamental transverse mode (mode #0), which ought to be maximized for the sake of good light focusability.

Thus techniques have to be used to support, prefer, or select the fundamental transverse mode (transverse mode selection TMS#0) by suppression of higher order modes already upon build-up of the laser oscillation.

In many cases reported in the literature, either a BAL facet, the transverse effective refractive index distribution, or the pump current distribution is modified [1–8]. Or an external cavity is employed [7–14]. In all these instances eventually low-pass spatial frequency filtering is performed. Since feedback from an external cavity may also cause self-pulsation due to destabilization of the emission process [15–19], the transverse mode selection set-up might also be *integrated* into the laser resonator [20, 21], a concept which we presented earlier. Moreover, approaches with tapered lasers or amplifiers or similar devices are known [22–25].

Previously in this journal we have also reported on a concept for TMS#0, which has employed a twice-retracted integrated $4f$ set-up with an actual length of $1f$ forming the laser resonator [26]. One facet has incorporated the spatial frequency filter, while the other one has housed a film-waveguide lens as the 1D Fourier-transform element. Experimental results have shown good TMS#0. The best one-dimensional beam quality parameter measured has been $M^2{}_{1D} = 1.47$.

A technological disadvantage of the latter approach has been the sophisticated preparation of the film-waveguide lens with a necessary dry-etch depth precision better than (i.e., below) 20 nm. Here we propose a simpler resonator design.

2. Concept and Laser Design

In this contribution, we propose and report on the realization of a confocal BAL resonator with (in top-view) a bow-tie-shaped beam constriction of minimal width a defining the smallest transverse beam width half-way between the cylindrical facets with Fresnel reflection. These mirror-facets are both convex in 1D (viewed from outside the resonator), giving a stable resonator.

Typically confocal resonators are not employed for semiconductor lasers. An early contribution with a so-called confocal resonator is given in [27]. But one of the mirror-facets had been convex, while the other one had been concave or plane, yielding an unstable resonator. In our case, only mirror-facets, which are convex in 1D (see above) and of equal absolute value for the radius of curvature, are employed.

A confocal resonator is defined by the following equation:

$$R = L = 2f, \tag{1}$$

where R is the absolute value of the radius of curvature of both facets, L the resonator length, $2L$ the round trip length, and f the common (absolute value of the) focal length of the curved mirror-facets.

Both 1D curved mirror-facets perform a 1D spatial Fourier-transform, each from their respective front to their back focal plane. Since the resonator length is $2f$, these focal planes coincide with the plane in the longitudinal middle of the resonator, called the "middle plane" from now on.

Rays with low propagation angles with respect to the optical axis account for low spatial frequencies and thus for the fundamental transverse mode (#0). They are Fresnel-reflected back into the resonator at the cylindrical mirror-facets with a reflectivity of about 31%. Rays with larger propagation angles, which correlate with larger spatial frequencies and higher transverse modes, are blocked by the transverse constriction, the latter thus acting as a 1D low-pass spatial frequency filter, intended to support the fundamental transverse mode.

Figure 1 contains a light microscope image of one of our confocal BAL resonators in top-view with a bow-tie-shaped, dry-etched laser ridge and a constriction with a width of (in this case) 32 μm in the middle plane [28]. The absolute value of the radius of curvature is $R = 1$ mm for both convex facets, identical to the resonator length L. To the best of our knowledge, the spatial resolution of the etch process does not affect the symmetry of the bow-tie shape.

The advantage of using a confocal resonator for Fourier-optical spatial frequency filtering is its ease of design and technological preparation as well as the fact that a relatively wide opening angle of the mirror-facets can be used even for a tide constriction a (beam width on facet $b > a$). That is, the transverse beam width b on the facets is considerably larger than the width a of the constriction (spatial frequency filter) in the middle plane. The latter aspect is schematically illustrated in Figure 2.

The layer sequence of our lasers is based on the AlGaAsSb material system on GaAs substrates. The devices are pn junctions, i.e., laser diodes, edge-emitting with a 450 nm thick active region consisting of eight Stransky-Krastanov-grown

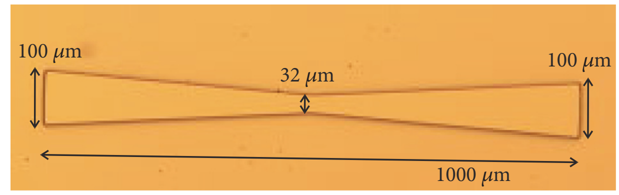

Figure 1: Light microscope image (top-view) of a confocal BAL resonator with a bow-tie-shaped laser ridge and, in this example, a 32 μm wide constriction in the middle plane. The resonator length and the radii of curvature are 1 mm.

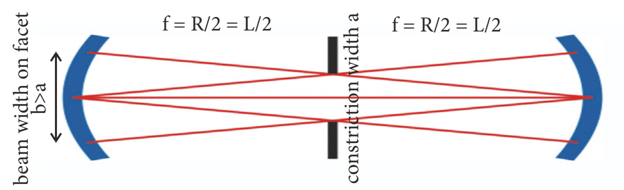

Figure 2: Principal sketch of the confocal resonator with constriction. The transverse beam width b on the facets is considerably larger than the opening width a of the low-pass spatial frequency filter in the middle plane.

GaAsSb quantum dot (QD) layers in-between 50 nm wide GaAs barriers [28]. The lasers emit at wavelengths of ca. 930 nm.

It has to be stressed here that our confocal BAL approach is not restricted to this material system and laser design, but it rather represents a general concept. Even unipolar quantum cascade lasers for the THz emission range might profit from it.

For comparison, we prepared several lasers from the same batch/wafer: with no constriction or constrictions of 64, 48, 32, and 16 μm as the smallest transverse width, respectively. In all cases, the bow-ties were 100 μm wide at the outer edges (see Figure 1 again). The device with a 16 μm wide constriction did not oscillate/lase.

3. Experimental Results and Discussion

Figure 3 gives the laser characteristics for the confocal BAL, e.g., with the 64 μm wide constriction (low-pass spatial frequency filter) to verify that the laser devices are of very good quality, even at continuous wave and room temperature operation. The differential quantum efficiency is 31.5% here.

For later comparison, Figure 4 reveals the results in terms of the near- and far-field intensity distributions for the confocal BAL without any constriction. The device operating temperature has been around 90 K.

And Figure 5 gives false-color plots (intensity coded as colors, black/blue for low intensities, white/red/yellow for large intensities) of the near-field transverse intensity distributions for confocal BALs of the same batch with different smallest widths of the constriction. Actually the uppermost plot is from the confocal BAL without constriction, and the other ones stem from the devices with 64, 48, and 32 μm wide (smallest) constriction, respectively. (Please remember:

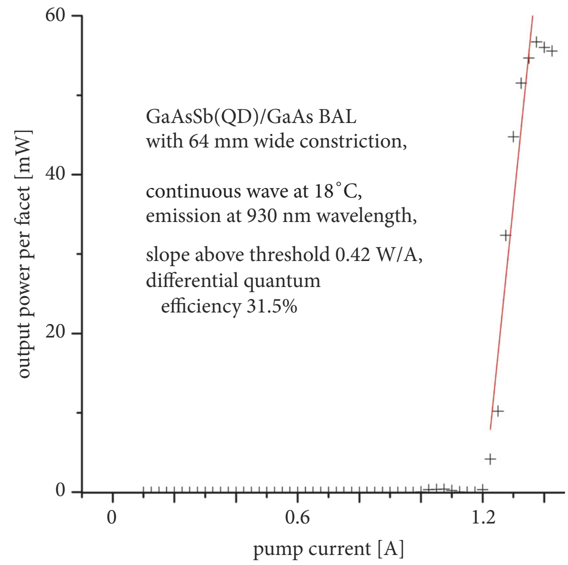

FIGURE 3: Laser characteristics of a confocal BAL with 64 μm wide constriction just to show that the lasers are of very good quality. The laser threshold is at 1.2 A, and the output power per facet shows values around 60 mW for a pump current of about 16% above threshold.

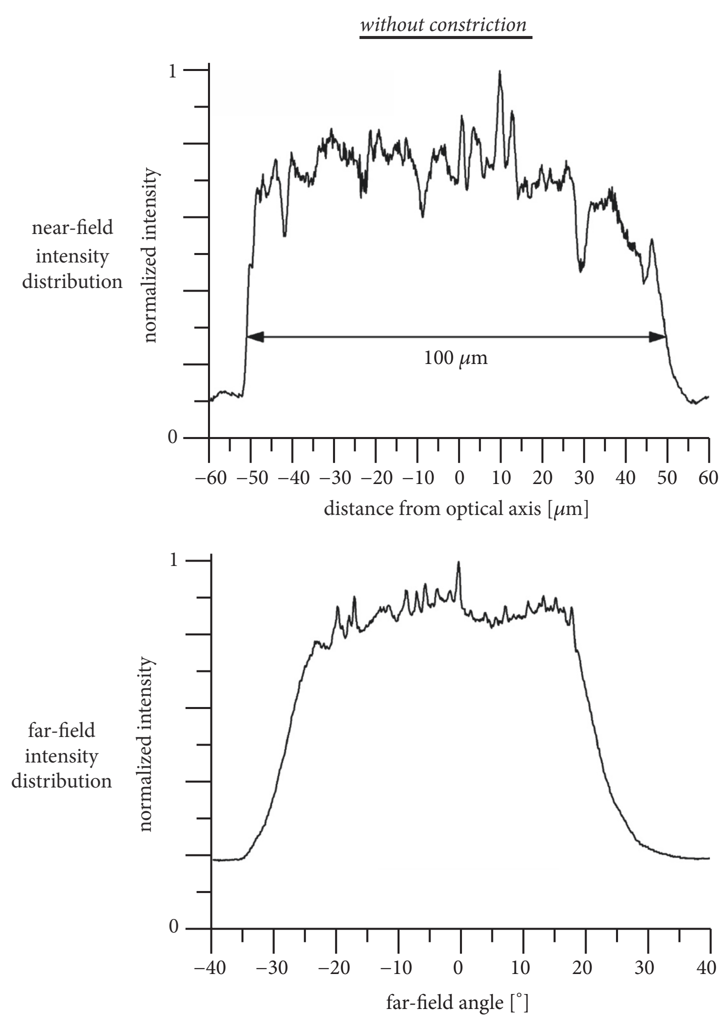

FIGURE 4: Near- and far-field intensity distributions for the confocal BAL without constriction, for comparison. The laser has been operated around 90 K in continuous-wave emission.

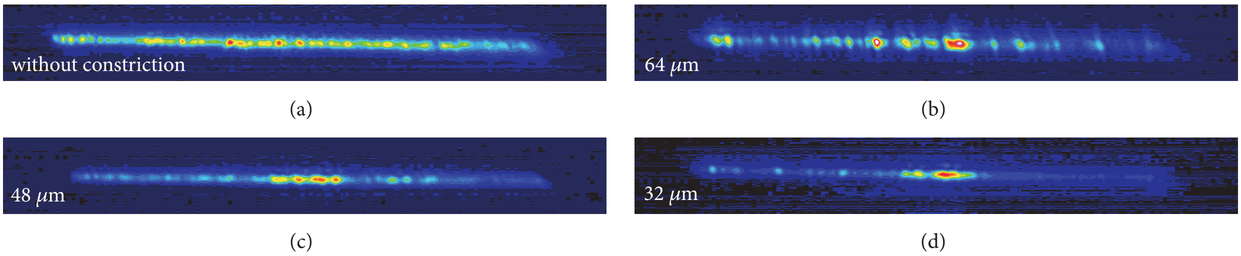

Figure 5: False-color plots of the near-field transverse intensity distributions for confocal BALs of the same batch with different widths of the constriction in the middle plane (i.e., no constriction, 64, 48, and 32 μm wide, respectively). In all cases, the pump current has been around 16% above laser threshold and the lasers have been operated around 90 K in continuous-wave emission.

the device with a 16 μm narrow constriction did not lase!) In all cases the pump current has been around 16% above laser threshold. Again the device operating temperature has been around 90 K.

In the sequence of results in Figure 5, an increasingly stronger confinement of the transverse intensity distribution is obvious, resulting in a near-field intensity distribution similar to that of the desired fundamental transverse mode for a constriction with a width of 32 μm the middle plane. But filamentation is not completely suppressed.

To make a closer inspection possible, Figure 6 (top and middle row) shows both the near- and the far-field intensity distribution for the same operating conditions for the confocal BAL with 32 μm wide constriction in the middle plane. Gaussian fits (red lines) are added as guides to the eye.

Obviously the fundamental transverse mode is supported, but filamentation is not totally suppressed.

Both the near- and the far-field intensity distributions—measured with the help of objective lenses—show an intensity offset. As illustrated in the bottom part of Figure 6 by a side-view sketch and a top-view scanning electron micrograph (SEM), this is due to the fact that the mirror-facets have been dry-etched, resulting in some distance (ca. 36 μm long) between the bow-tie edge and the device/crystal edge. Within this distance, the substrate has been laid bare upon etching, giving a plateau with a roughened surface. Part of the emitted light is diffusely reflected or rather scattered off the plateau. The scattered intensity portion accounts for the offset.

At pump currents, more than 20% above threshold considerable TMS#0 is not observed, a problem which our approach has in common with most TMS concepts.

Comparing devices (from the same wafer) we have not found any significant deviations in differential quantum efficiency within our device and measurement tolerances for different smallest widths of the constriction (except for the fact that the device with 16 μm constriction did not lase/oscillate at all). But the devices *without* any constriction had a worse quantum efficiency, worse by up to a factor of 10. This is an unexpected result, since the TMS#0 via a confocal resonator with constriction should increase the fraction of the total power in the fundamental transverse mode, but not necessarily the overall power. Further investigations have to be pursued on this issue.

As can be seen from the figure captions, the devices have been operated (continuous wave) both at around 90 K and at room-temperature (18°C). In both cases, we did not observe a significant increase in device instability upon a temperature change by a couple of ten degrees Celsius.

The (even in the cases with constriction) still strong filamentation is also an unexpected result, since the bow-tie-shape of the confocal resonator should have restricted the possible longitudinal paths for gain filaments geometrically. On the other hand, light scattering from the roughness of the etched *transverse* bow-tie edges might cause an additional coupling of the gain filaments. Thus an attempt to improve the TMS#0 (i.e., to reduce the filamentation) further should go for a reduction of the mentioned roughness, which has been on the order of 100 to 500 nm (root-mean-square nominally) so far due to the roughness of the structures on the lithographic mask as well as the roughness induced by the reactive ion etching process itself.

In the case with the 32 μm wide constriction in the middle plane, the intensity distributions in Figures 5(d) and 6 with a single-lobed far-field and a full far-field angle of 5.1° (disregarding filamentation for a moment) allow for the extraction of a 1D beam quality parameter of $M_{1D}^2 = 1.71$.

4. Conclusions

A concept for fundamental spatial transverse mode selection (TMS#0) of edge-emitting broad area (semiconductor diode) lasers (BALs) is presented, which employs a 1D confocal resonator with a constriction in the middle plane, i.e., the plane half-way between the equally strongly curved convex mirror-facets. This plane serves both as the front and the back focal plane of the curved facets and, thus, also as the Fourier-transform plane in the sense of a Fourier-optical 4f set-up. A transverse constriction in this plane is employed as a low-pass spatial frequency filter in order to select the fundamental transverse mode (TMS#0).

Several lasers have been prepared from the same batch, differing from one another in the smallest width of the transverse constriction. The lasers are of very good quality, revealed by a differential quantum efficiency of around 30%.

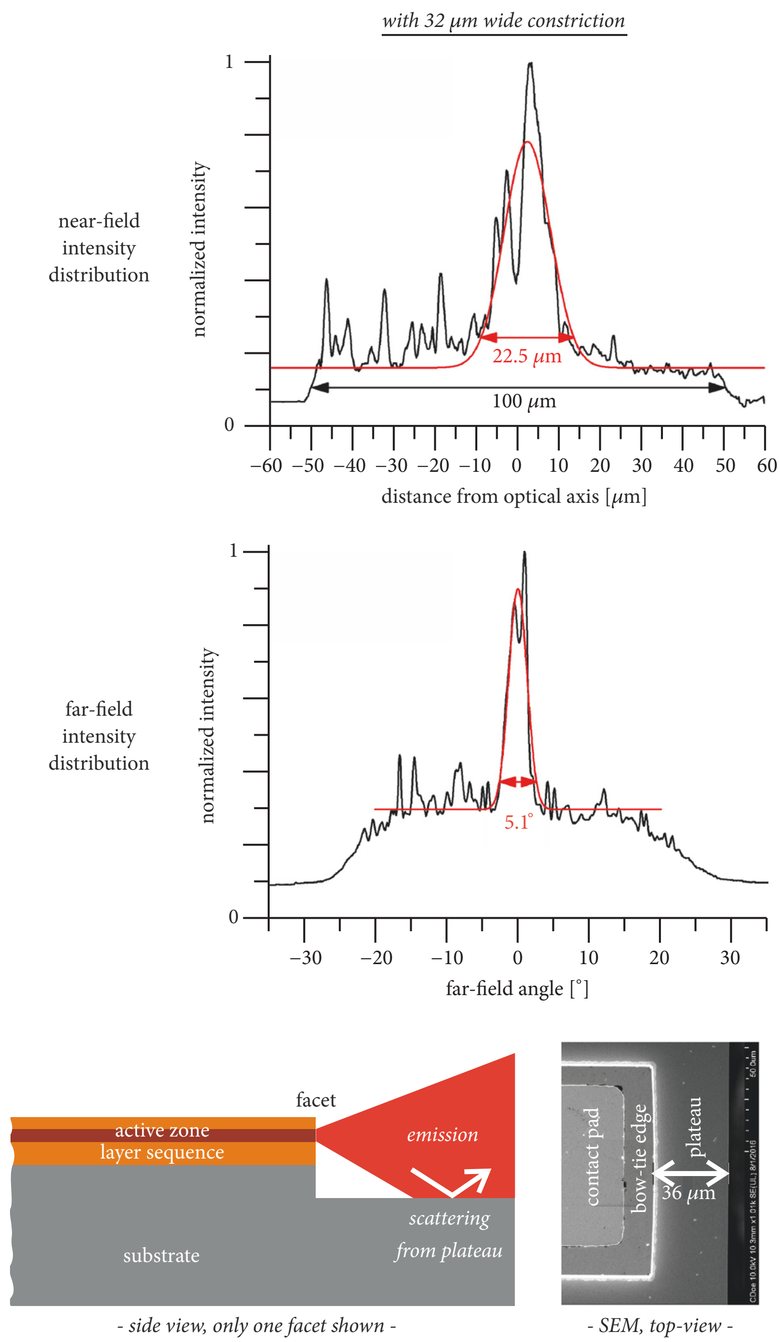

FIGURE 6: Top and middle row: near- and far-field intensity distributions for the confocal BAL with a 32 μm wide constriction in the middle plane. Gaussian fits (red lines) are added for both intensity distributions as guides to the eye. The laser has been operated around 90 K in continuous-wave emission. Bottom: side-view sketch and top-view scanning electron micrograph (SEM) of one of the dry-etched mirror-facets. The radiation is partially diffusely reflected or scattered off the somewhat rough substrate plateau, which has resulted from the dry-etch process to define the mirror-facets.

Transverse mode selection (TMS#0) is indeed achieved via the confocal resonator design, that is for pump currents not larger than 20% above threshold. Filamentation is not completely suppressed.

The best TMS#0 is achieved in case of the 32 μm wide constriction. Here the measured one-dimensional (1D) beam quality parameter is ${M^2}_{1D} = 1.71$.

Data Availability

Most of the experimental data used to support the findings of this study are included within the article. Partially previously reported studies and experimental data were used to support this study. These prior studies and datasets are cited at relevant places within the text as references. Further or more detailed data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper, neither concerning the funding nor for any other reason.

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