Coherent Beam Combining of Broad-area Blue Laser Diodes Array in a V-shaped External Cavity

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ABSTRACT

Arrays of broad-area lasers are ideal light sources for optical power-demanding applications, but the spectral and beam quality of such arrays can be poor. In this work, we implement an external cavity to phase-lock a large QCW array of broad-area lasers, with multi-W peak power. The theoretical simulations are in good agreement with the experimental results and allow assessing the number of phase-locked emitters in the array. This demonstration paves the way for coherent beam combining of broad-area blue laser diodes.

Keywords: Semiconductor diode array, External optical feedback, phase locking, blue wavelength

1. INTRODUCTION

Lasers have become the light source of choice for a broad range of domains from defense to healthcare, and high-power emission, high spatial beam quality and narrow spectral linewidth are often mandatory. Single semiconductor lasers may not generate sufficient output power, which explains why efforts have focused on beam combining of several lasers. The only technique that encompasses high-power, narrow spectral linewidth and excellent beam quality requirements is coherent beam combining (CBC) of multiple lasers.[1] CBC is achieved by controlling the frequency and relative phases of lasers. Those fundamental requirements introduce significant challenges for large laser arrays,[2–4] especially in the case of passive CBC. A common method to achieve passive CBC is to use external Talbot cavity.[1,5–10] The latter provides self-diffractive coupling to all lasers in the array, which induces mutual phase locking. CBC of laser arrays has mostly been investigated in near infrared regions.[8,11–15] Near perfect diffraction-limited beam emission from phase locking of broad-area diode arrays has been demonstrated[11] employing a V-shaped external cavity design.[12,13] Conversely, phase locking of arrays of lasers in the blue spectral range has received less attention, despite the versatility of blue light for underwater communication,[16] optogenetic activation[17] and harmonic generation in the far-UVC,[18] among others. In this work, we experimentally demonstrate phase locking of a large QCW-operated broad-area diode laser array emitting at blue wavelength, with multi-W peak power. Experimental phase locking is assessed through far-field interferences and is compared with theoretical formula. These two results are compatible with numerical model derived from the Lang-Kobayashi equations,[19,20] and our recent work[21] highlights that the road to phase locking occurs through cluster dynamics,[22–24] meaning groups of lasers synchronizing among uncorrelated lasers. This analysis impacts on the design and development of high-power blue light sources leveraging CBC in broad-area laser arrays.

2. PHASE LOCKING OF AN ARRAY OF HIGH POWER SEMICONDUCTOR LASERS EMITTING IN THE BLUE

Phase locking of laser bars with external cavity is often achieved in a configuration with V-shaped cavities.[12,13] Additionally, filtered optical feedback is provided by a reflection grating. The latter allows selecting a narrow wavelength for the feedback light, which means that the lasers in the bar that receive enough feedback light

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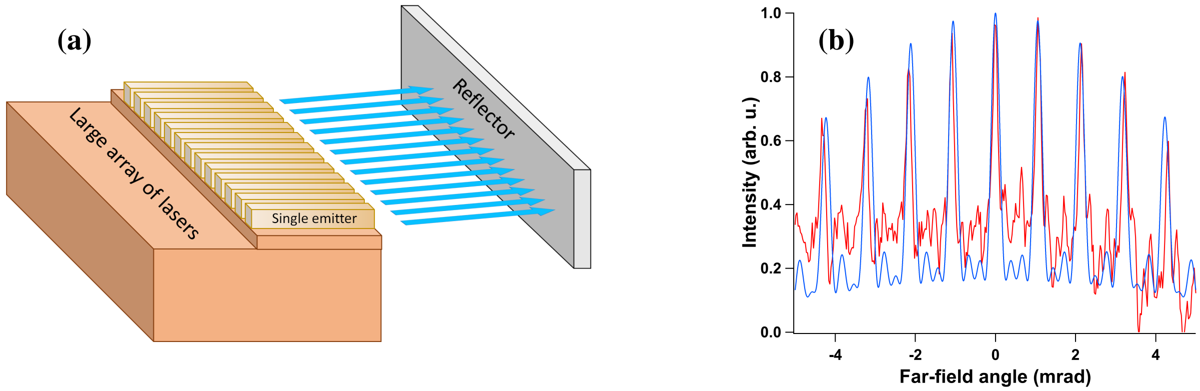

Figure 1. (a) Phase locking of the large array of lasers is achieved with external optical feedback provided by a reflector in a compact linear cavity. (b) Experimental far-field profile (red) for the partially phase-locked array of 12 broad-area blue-wavelength lasers and simulation far-field profile (blue) for 4 ideal, coherent, in-phase lasers in the 12-emitter array.

are forced to emit within this narrow wavelength range. If the feedback roundtrip distance corresponds to a fractional Talbot distance, mutual coupling is observed between several lasers in the array and this leads to phase locking, where several lasers in the array have a common wavelength of emission and a constant phase relationship between them. Leveraging this technique, we were recently able to demonstrate phase locking in a large array of broad-area blue lasers with low anti-reflection coatings and QCW bias.[21] This experimental result allowed achieving peak power in excess of 10 W for the partially coherent blue beam.

Even if the combination of V-shaped external cavity and reflective grating was key to achieve this feat, the experimental setup we previously detailed lacks compactness, and we thus decided to study a more versatile cavity structure, which is depicted in Fig. 1 (a). The reflector is a partially reflective mirror with a reflectivity in the order of 20%, which means that we are in a conventional feedback case, not in a wavelength-selective feedback case as aforementioned. We study phase locking in an array of 12 lasers emitting around 450 nm, and this array was manufactured by BluGlass. The 12-laser array has a pitch of 400 μm and emitter width of 35 μm, which means that the laser diodes are broad-area emitters and the fill factor is 8.75%. Even though they can provide high optical power, which is a very desirable feature for light sources, large arrays of blue semiconductor lasers can rarely be operated CW. In our case, the laser array can be biased CW but this drastically reduces the output power, and we decided to bias the array in QCW mode, with a duty cycle of 4% and a repetition frequency of 80 Hz, corresponding to a QCW pulse length of 500 μs. With this configuration, the peak optical power is in excess of 5 W for a QCW bias current of 18 A. Design optimization of the external cavity yields the experimental far-field pattern in Fig. 1 (b) (red curve) for a bias current of 9 A and the aforementioned QCW bias. The interference pattern shows bright fringes as well as a dense background, meaning that only partial coherence is achieved for this experimental configuration. This background stems from the lack of wavelength selectivity because we use an output coupler instead of a reflective grating. Wavelengths that are not participating in the phase locking process, hindering high visibility. Several characteristics can be retrieved from this far-field pattern, that includes the visibility of the beam profile and the width of bright fringes, corresponding to $\frac{\lambda}{N \times p}$, with λ the wavelength of emission, N the number of coherent lasers in the array and p the pitch of the laser array (space interval between lasers in the structure). With this piece of information, the estimation is that 4 lasers out of 12 are perfectly phase-locked, while 8 lasers out of 12 do not contribute to the coherence process. However, this clear distinction between locked lasers and non-locked lasers is simplistic, and a better explanation would be that the lasers emit at various, distinguishable wavelengths (due to the absence of wavelength selectivity), with some of these wavelengths being phase-locked for several lasers while other wavelength only contribute to the incoherent background. For the sake of simplicity in the computational analysis, we will assume that 4 lasers out of 12 are perfectly phase-locked, while 8 lasers out of 12 only contribute to the incoherent background. We carry out a simulation to derive the theoretical far-field pattern for 4 coherent, in-phase lasers out of an array of 12 emitters, based on the process described in Ref. 21. This yields the blue curve in Fig. 1 (b), with a strong agreement between the experimental trace and the modeled far-field pattern.

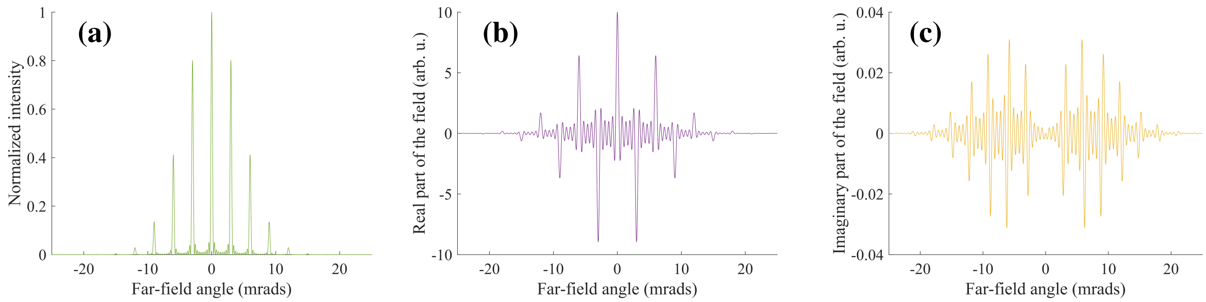

Figure 2. Simulation for an array of 10 phase-locked lasers. (a) Far-field interference pattern with normalized intensity. (b) real part of the combined field of all the phase-locked lasers. (c) imaginary part of the combined field of all the phase-locked lasers.

3. TOWARDS BEAM COMBINING OF PHASE-LOCKED BLUE LASERS

When the lasers in the array are phase-locked, the total optical power emitted by the array is not affected compared to the incoherent case. However, interference fringes can be found in the far-field profile. If the fill factor of the array is large (typically in the order of 50%, as outlined experimentally with an array of broad-area lasers emitting in the near infrared[11]) and all the lasers in the array are phase-locked, then most of the optical power can be found in the central bright fringe of the interference pattern. This configuration is rarely found experimentally because a large fill factor is related to increased thermal burden on the laser array, especially for blue laser arrays relying on GaN technology, and that degrades the quality of phase locking. Based on our recent experimental investigations with blue-laser arrays, high-quality phase locking can be found in conjunction with low fill factors, which in turns leads to an extended far-field profile (as shown in Fig. 1 (b)) with the optical power spread between several interference peaks and not just the central bright fringe. Nevertheless, a high-quality phase locking interference pattern is compatible with coherent beam combining because the phase of the interference fringes can be predicted accurately, and depends on the number of phase-locked lasers: even or odd. These two configurations are described in Fig. 2 and Fig. 3 for 10 phase-locked lasers and 11 phase-locked lasers, respectively. The left panel corresponds to the normalized intensity far-field interference pattern, the central panel corresponds to the real part of the combined field of all the phase-locked lasers, the right panel corresponds to the imaginary part of the combined field of all the phase-locked lasers. For the case with 10 lasers in Fig. 2, the magnitude of the imaginary part of the field is negligible when compared to the magnitude of the real part, for the angular positions of the peaks. With this approximation, the phase of the peaks is either 0 (for instance for the central bright fringe) or π (for instance for the two bright fringes adjacent to the central fringe). For the case with 11 lasers in Fig. 3, the magnitude of the imaginary part of the field is still negligible when compared to the magnitude of the real part. Besides, the phase of all the peaks is now 0. Consequently, if all the lasers in the array are phase-locked, it becomes possible to further combine the interference peaks, as the phase of the latter is known. The results in this work focused on two configurations with 10 lasers and 11

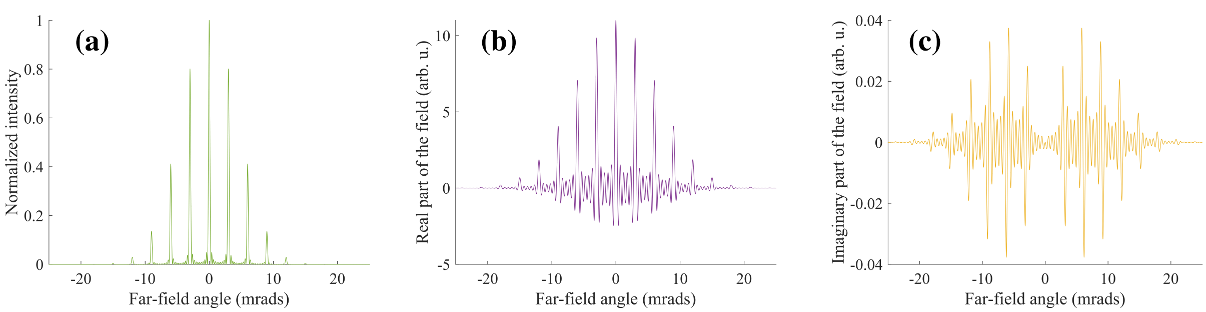

Figure 3. Simulation for an array of 11 phase-locked lasers. (a) Far-field interference pattern with normalized intensity. (b) real part of the combined field of all the phase-locked lasers. (c) imaginary part of the combined field of all the phase-locked lasers.

lasers, but simulations were also carried out for larger numbers of lasers and gave the same conclusions.

4. CONCLUSION

We experimentally demonstrated phase locking of several blue semiconductor lasers in an array of 12 emitters. Contrary to the reflective grating configuration where phase locking is mediated by the wavelength selectivity process, the configuration that we highlight in this work allows spontaneous phase locking of the array, as the feedback light is provided by a partially reflective mirror. Multi-W phase-locked optical power is achieved and the quality of phase locking is determined by the far-field beam profile showing bright interference fringes. This experimental far-field pattern is compared with a theoretical model, that allows estimating the number of phase-locked emitters in an ideal scenario, which does not encompass the framework of multi-wavelength emission. The latter is likely a more realistic description of the partial phase locking that we observed experimentally, but is beyond the scope of this work. Further optimization of the array brightness will be possible with coherent beam combining, as the phases of the interference peaks can be precisely predicted, and depend on the number of phase-locked lasers.

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