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Coherent Combination of Slab-Coupled Optical Waveguide Lasers

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ABSTRACT

A long-standing challenge for semiconductor lasers is scaling the optical power and brightness of many diode lasers by coherent beam combination. Because single-mode semiconductor lasers have limited power available from a single element, there is a strong motivation to coherently combine the outputs of many elements for applications including industrial lasers for materials processing, free space optical communications, and defense. Despite the fact that such a coherently-combined source is potentially the most efficient laser, coherent combination of semiconductor lasers is generally considered to be difficult, since precise phase control is required between elements.

We describe our approach to coherent combination of semiconductor lasers. The Slab-Coupled Optical Waveguide Laser (SCOWL), invented at Lincoln Laboratory, is used as the single-mode diode laser element for coherent combination. With a 10-element SCOWL array, coherently combined output power as high as 7 W in continuous wave using an external cavity has been demonstrated, which is the highest output level achieved using a coherent array of semiconductor lasers. We are currently working on a related approach to scale the coherent power up to 100 W.

Keywords: Semiconductor lasers, laser arrays

1. INTRODUCTION

Coherent beam combination (CBC) promises the ideal power and brightness scaling of diode lasers [1]. Implementation, however, has been challenging. The primary difficulty is the requirement to maintain precise (better than $\lambda/10$) control on the optical path difference (OPD) of the diode laser or amplifier elements.

Slab-Coupled Optical Waveguide Lasers (SCOWLs) were used as the diode lasers for coherent combination in this work. Improvements to the SCOWL design have been made, resulting in improved device efficiency and reliability while maintaining the power and brightness of earlier SCOWL devices. Recently, we have increased the peak CW Power Conversion Efficiency (PCE) of a 960-nm GaAs-based SCOWL device to greater than 40%, and improved single-mode performance has been obtained.

Control of the OPD in SCOWL devices is essential for CBC. Our approach for OPD control is individual current adjustment of each SCOWL array element. By direct measurement of the phase shift of a SCOWL-based device under bias, it was determined that $\lambda/10$ phase control can be obtained by direct current adjustment of each device in the array. Therefore, individually addressable (IA-) SCOWL arrays have been constructed, in which the current of each device can be adjusted independently.

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Two distinct approaches to CBC of IA-SCOWL arrays have been taken. In the first approach, an external cavity based on the Talbot self-imaging effect is constructed, in which coupling for the CBC is provided by Fresnel diffraction between neighboring elements in the array. With the Talbot cavity, 7.2 W of coherently combined power in continuous wave (CW) was demonstrated using a 10-element, 100- μm -pitch IA-SCOWL array. This represents, to our knowledge, the highest power that has been coherently combined using a diode laser array.

In the second approach, amplifier arrays are constructed instead of laser arrays. A frequency-stabilized master laser is used to seed the IA-SCOWL-based amplifier array. In-situ monitoring of the device L-I characteristic during the deposition of the AR-facet coating of the amplifier array was developed. This allowed for the reduction of the reflectivity of the output facet in order to minimize chip-mode oscillation. It was an enabling technique allowing for the demonstration of 4.9 W CW from a 10-element SCOWL amplifier array, with a narrow-bandwidth spectrum centered at 960 nm. The amplifier approach is expected to be scalable to larger numbers of elements. Currently, a demonstration to scale the coherent power from a stack of IA-SCOWL amplifier arrays to 100 W CW is in progress.

This paper is organized as follows. In section 2, the SCOWL devices that were used for CBC experiments, as well as the requirements for CBC from the emitter end, are discussed. Recent progress on improving the device performance is also discussed. In section 3, coherent combining experiments with 10-element SCOWL arrays at power levels up to 7 W are described. In section 4, our current work on extending the output power from a phase-locked array to 100 W is discussed.

2. SLAB-COUPLED OPTICAL WAVEGUIDE LASERS

Coherent combining is clearly challenging, and its difficulty stems from the fact that phase control to the level of $\lambda/10$ is required in the optical path difference (OPD) between elements in order to maintain phase coherence [2]. The key to robust phase-locked arrays is therefore having a means to maintain OPD between elements at levels of $<\lambda/10$. Our entire work on coherent combining is based essentially on the observation that SCOWL devices are high brightness semiconductor lasers with the capability of precise phase control by the fine adjustment of the device current.

2.1 Individually addressable SCOWL arrays

For arrays of Slab-Coupled Optical Waveguide Lasers (SCOWLs) [3,4], it was found that control of the device current of each element is sufficient to effect the required phase control. To demonstrate this, the following experiment was performed. A 980-nm probe beam from a seed laser is incident on an input port of a Mach-Zehnder interferometer. A curved channel 980-nm SCOWL amplifier is placed in one arm of the interferometer, and a quarter-wave ($\lambda/4$) plate is placed in the other arm. At the output beam splitter, in-phase (I) and quadrature (Q) outputs are measured with photodiodes. The phase shift ϕ induced by the SCOWL amplifier is determined by using the relation $\phi = -\text{atan}(Q/I)$. By applying current to the SCOWL amplifier, we found that a full-wave rotation of phase in a SCOWL requires ≈ 130 mA at 0.6 A (see Fig. 1). This corresponds to a modest ≈ 13 mA of current adjustment in order to achieve $\lambda/10$ phase control.

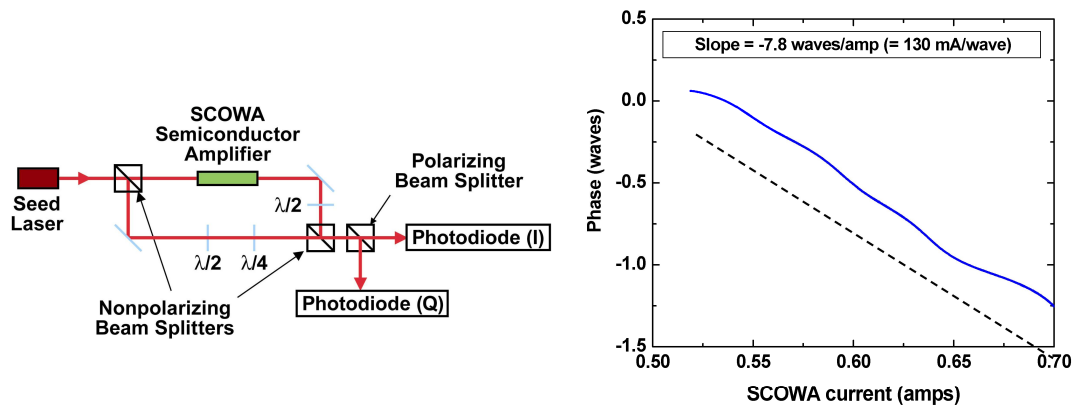


Fig. 1. (Left) Mach-Zehnder interferometer experiment for measurement of phase in SCOWL amplifier. (Right) Phase measurement of SCOWL amplifier as a function of current in device.

It was concluded that $<\lambda/10$ phase control is feasible for SCOWL arrays if one is able to adjust the current for each element, i.e., individually addressable SCOWL arrays are used. Because 13 mA is only a small fraction of the operation current (in the range of 0.5 to 1 A), to a good approximation the current, and therefore the power level, is nearly constant during the current adjustment.

Individually addressable SCOWL (IA-SCOWL) arrays were constructed. The arrays consist of ten elements with 100 μm pitch and cavity lengths of 3 mm to 5 mm. Similar to our previous work on SCOWL arrays [4], thermal management was provided by micro-impingement coolers. Patterned aluminum nitride submounts were used for mounting the arrays junction-side down and making individual electrical contact to each element. In Fig. 2a, a photograph of the IA-SCOWL array in its package is shown. A PC board is used to make electrical contact to the patterned AlN submount. A CuW busbar is used to contact the common cathode of the array. In Fig. 2b, the L-I characteristic of each of the ten elements in the array is shown, indicating that elements in the array can be run independently. Uniform L-I characteristics were observed for this array consisting of ten elements. In Fig. 2c, the L-I characteristic of an IA-SCOWL array run to 10 W CW in output power is shown. This figure indicates that the SCOWLS could be run to 1 W per element on average in the IA-SCOWL array. An inset indicating the near field profile of a device is shown in the graph.

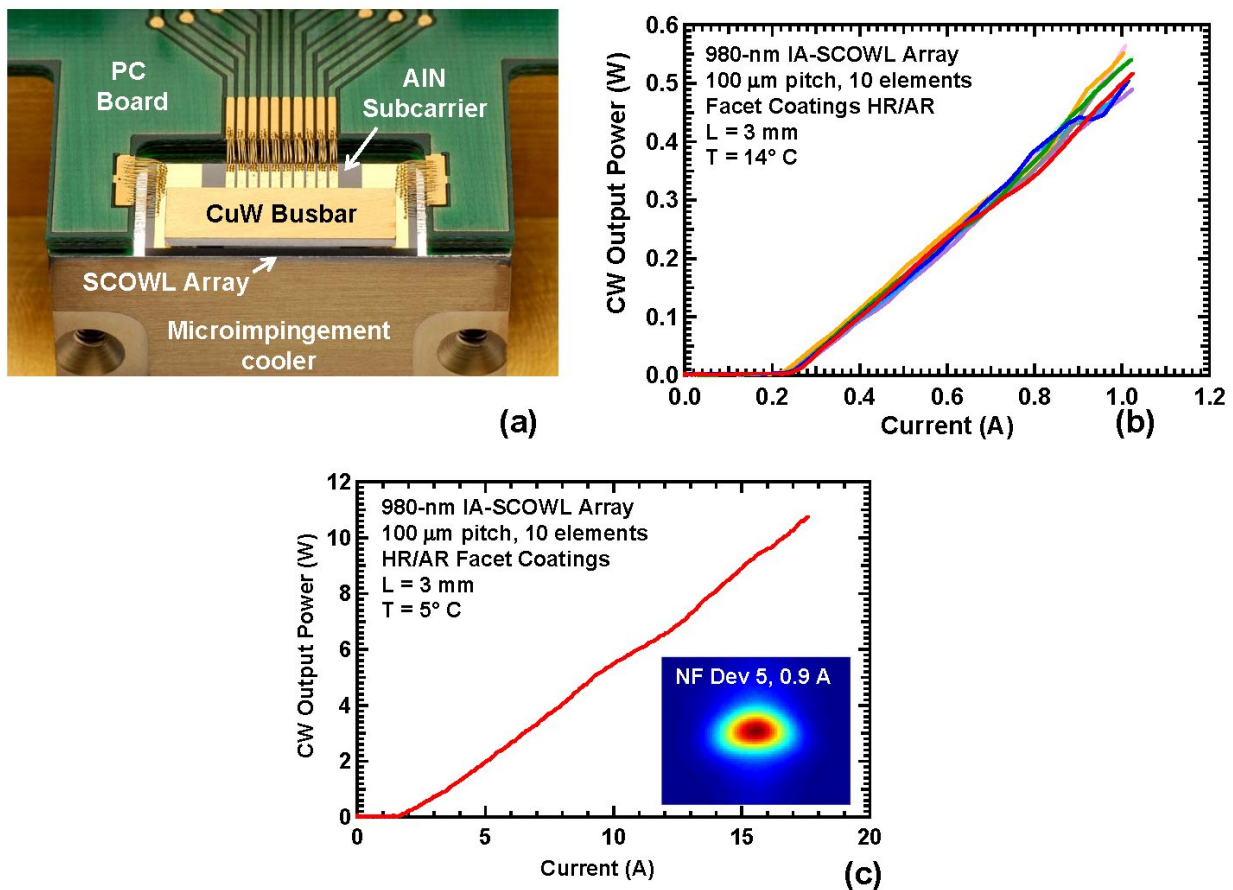


Fig. 2. (a) Photograph of individually addressable (IA) SCOWL array. (b) L-I characteristics of each element in an IA-SCOWL array. (c) 10-W CW output power from 1-mm-wide 980-nm IA SCOWL array. Inset shows near field profile of device 5 in the array.

2.2 Improved SCOWL device

Recent work on improvements to the SCOWL device, with the objective to improve the single-mode performance of these devices, was performed. The device design is similar to that reported previously [5]. With our recent SCOWL devices, greater than 40% electrical-to-optical efficiency from a SCOWL device emitting in a nearly diffraction-limited mode has been obtained. The kink-free operation range of SCOWL devices has been extended, and this is an indication that the devices are operating in the lowest order mode. These improved devices have not yet been used for coherent combination, but similar devices are expected to be used for the 100 W CW demonstration.

In Fig. 3, a CW L-I-V characteristic of an improved SCOWL device lasing at 960 nm is shown. This device has a cavity length of $L = 3$ mm and does not have any facet coatings. The device was mounted junction-side up on a copper

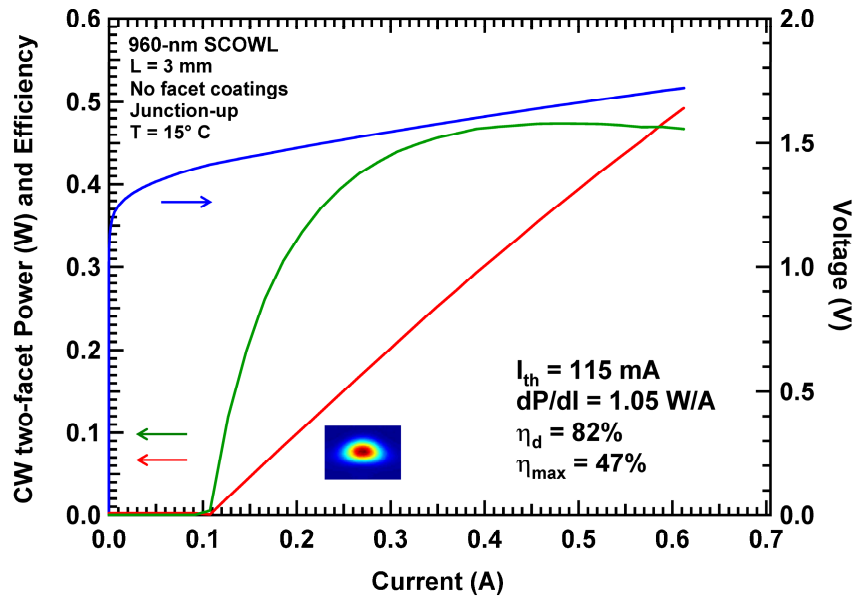


Fig. 3. CW L-I-V characteristic of an improved 960-nm SCOWL device. This device has no facet coating, and has been mounted junction-side up. The inset shows the near field profile of the device.

submount for CW operation. The threshold I_{th} is low, 115 mA, and the slope efficiency dP_0/dI is high, 1.05 W/A, corresponding to a differential quantum efficiency η_d of 82%. This device shows efficient power conversion efficiency (PCE), with a peak value of 47%, when power from both facets is included. The CW operation is essentially kink-free and free of mode-hopping over the range of operation shown. The maximum current is limited since there are no facet coatings on this device.

In Fig. 4, the L-I characteristics of improved SCOWL devices with $L = 1$ cm cavity length are shown. These devices have an HR/AR facet coating. Because these devices were not packaged, they were operated under pulsed operation (200 ns pulse width and 1 kHz repetition rate). These devices feature very high PCE up to 1 W in peak power, with typical PCE exceeding 40% even at the single-ended output power of 1 W. Furthermore, the pulsed L-I characteristics feature kink-free operation over the entire range of device operation. Currently, efforts are underway to obtain similar results under CW operation with junction-side down mounting, so that such devices can be used in coherent combining experiments in the future.

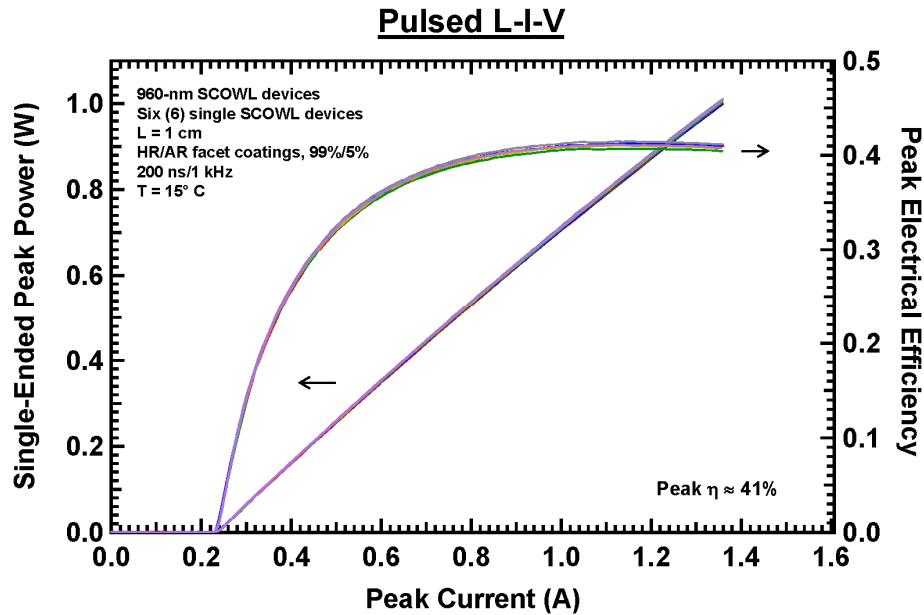


Fig. 4. Pulsed L-I-V characteristic of six (6) improved 960-nm SCOWL devices with cavity length of $L = 1$ cm. These devices have HR/AR facet coatings, and have not been mounted (pulsed measurements shown).

3. COHERENT COMBINING EXPERIMENTS

Two distinct approaches towards coherent beam combination, the Talbot plane approach and the amplifier approach, are utilized. These approaches will be described in the following two sections.

3.1 Talbot plane coherent combination

In the first approach, the external cavity is in the fractional Talbot plane configuration [6]. The Talbot effect, a consequence of Fresnel diffraction, corresponds to the formation of images of a periodic array of coherent emitters at Talbot distances of $z_T = 2d^2/\lambda$, where d is the spacing of elements in the array, and λ is the emitter wavelength. The Talbot effect is commonly used for passive coherent beam combination [1]. In coherent combination using the Talbot effect, an output coupler mirror with a reflectivity that is higher than the residual reflectivity of an anti-reflection-coated periodic array of emitters is typically placed at a distance of half the Talbot distance z_T from the AR-coated emitter array facet. For the fractional Talbot effect, the output coupler is placed at a distance of $z_T/4 \approx 5$ mm away from the array facet, since the image formation at the half Talbot distance ($z_T/2$) back at the facet (one cavity round trip) provides spatial discrimination between the in-phase and out-of-phase modes [6]. In the fractional Talbot approach, the lowest threshold mode is the out-of-phase mode and the in-phase mode has the highest threshold. Discrimination between the in-phase and out-of-phase modes is provided by rotating the output coupler by an angle of λ/d , resulting in the in-phase-mode to have the lowest threshold and the out-of-phase mode to have the highest threshold. The main advantages of the fractional Talbot cavity for coherent beam combination are (1) a spatial filter is not required, and (2) the approach allows for a low edge effect loss. See Fig. 5 for a schematic of the external cavity and the calculated in-phase modes at fractional Talbot distances away from the device facet.

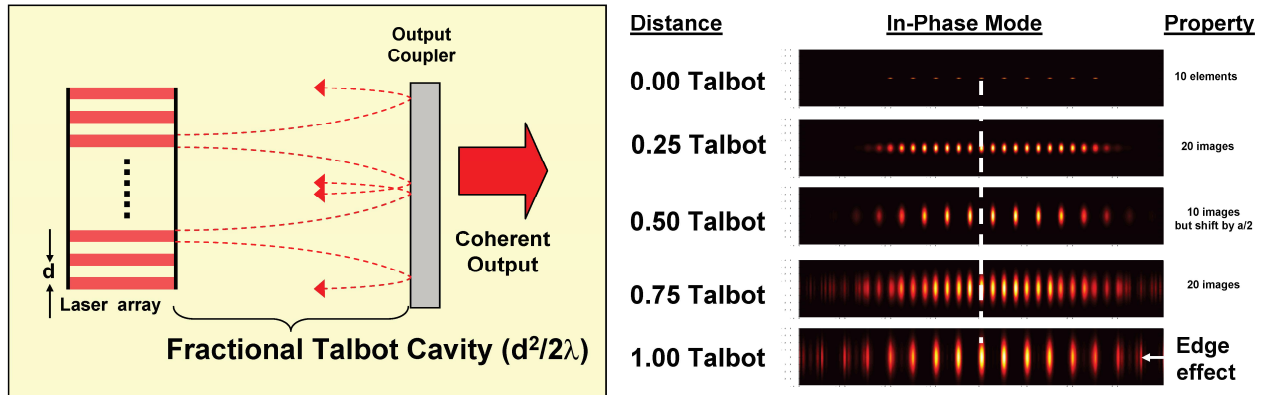


Fig. 5. (Left) External cavity of fractional Talbot effect CBC. (Right) Calculated mode profile as a function of propagation distance from array facet.

Two versions of the fractional Talbot configuration, namely local and global coupling, have been demonstrated. In local coupling, an $f = 120 \mu\text{m}$ (GaP) or $f = 150 \mu\text{m}$ (fused silica) microlens array in front of the facet is used to collimate the beams from the SCOWL array. With collimation, the beams have low divergence and therefore have reduced overlap at the Talbot distance. Indeed, the number of coupled elements is approximately $N \approx 1/\text{FF}$, where FF is the fill factor of the array [1]. In addition, the number far field lobes corresponds to $1/\text{FF}$. In our case, with the microlens array, $\text{FF} \approx 30 \mu\text{m}/100 \mu\text{m} = 0.3$, so that the number of coupled elements is $N \approx 3$, i.e., local coupling for a 10-element array. In Fig. 6, the far field profile of a SCOWL array in a fractional Talbot cavity with local coupling is shown. The clear signature of coherent beam combination is observed, as the visibility $V = (I_{\text{max}} - I_{\text{min}})/(I_{\text{max}} + I_{\text{min}}) \approx 1$, where I_{max} (I_{min}) is the maximum (minimum) intensity in the far field profile. Individual addressability is essential for obtaining high visibility, as evidenced in the relatively large range in the current applied to each device. It was necessary to adjust the currents on each of the ten elements, as indicated in the figure, in order to maximize the visibility of the coherently combined output. The total phase-locked power is 2 W CW, or 200 mW per element on average. The spectrum is multimode, and rather broad. Remarkably, this implies that the external cavity locks each element in the array to this precise spectrum.

By using a bulk cylindrical lens ($f = 1.49 \text{ mm}$) instead of the microlens array, $\text{FF} \approx 5 \mu\text{m}/100 \mu\text{m} \approx 0.05$, so $N \approx 20$. In this case, all ten elements of the array are coupled, i.e., global coupling. The far field profile of the SCOWL array in the fractional Talbot plane configuration with global coupling is shown in Fig. 7. At low power levels, the visibility of coherent combining is nearly unity, and the phase locking is nearly ideal. At high output power levels, the visibility is still high. This represents a coherently combined 10-element semiconductor laser array with coherent power levels of 7.23 W CW, or 723 mW CW per element on average. These are among the higher total and per element power levels ever reported for a phase locked semiconductor laser array. At the highest power levels, the far field lobes broaden. We attribute this broadening to the onset of coherent chip mode lasing, due to the SCOWL array lasing on-chip from an imperfect anti-reflection (AR) facet coating. Work performed on reducing the AR coating reflectivity in order to suppress these coherent chip modes will be discussed in the next section. Similar to the local coupling case, the spectrum at high power levels is multimode and fairly broad, as all ten elements are locked to this spectrum. In both the local and global coupling cases, the SCOWL array in the fractional Talbot plane configuration exhibits extremely stable and robust coherent beam combination, persisting for hours without any electrical or mechanical adjustment. It is important to note that the coherent combination is entirely passive, requiring no active electronic feedback.

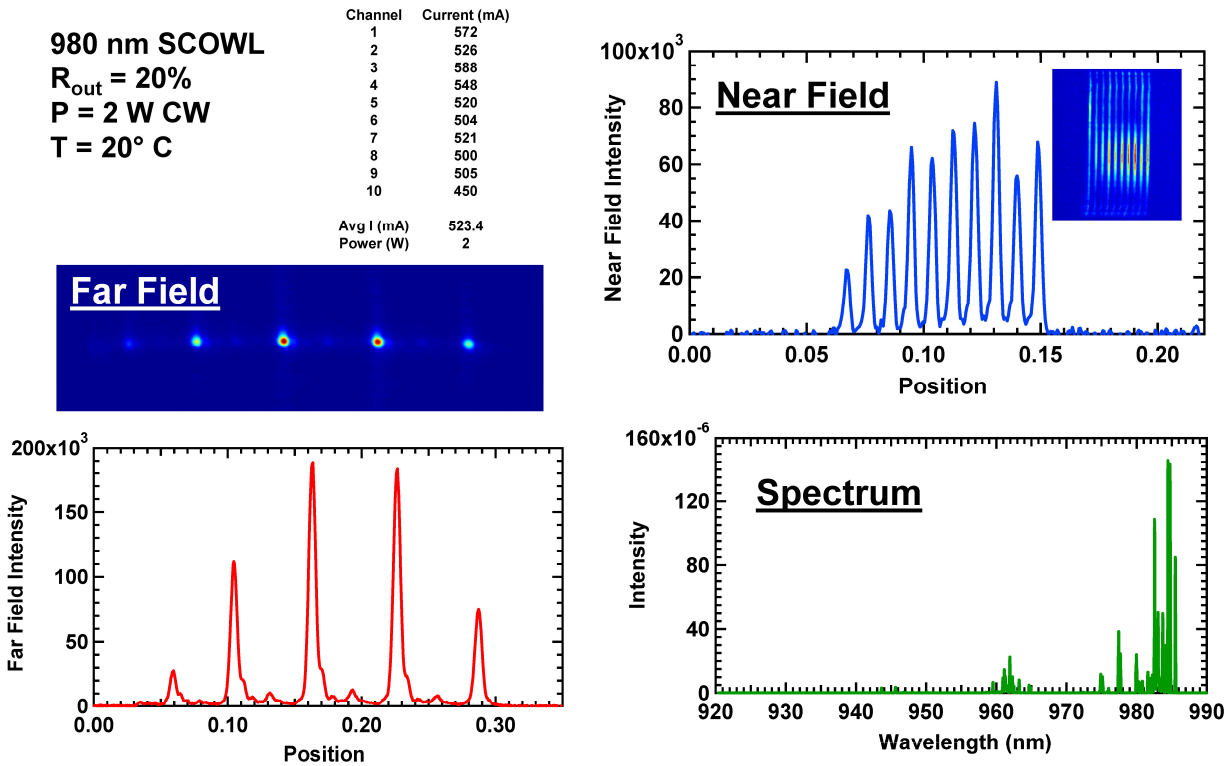


Fig. 6. (Left) Far field profile of coherently combined SCOWL array using the fractional Talbot cavity and local coupling. Experimental conditions are also shown. (Right) Top: near field profile of coherently combined SCOWL array. Bottom: spectrum of coherently combined SCOWL array.

To summarize this section, coherent beam combination of a semiconductor laser array with a phase-locked power of $> 7 \text{ W CW}$ has been demonstrated. While the spatial quality of the coherent beam combination is nearly ideal even at high output power levels, the spectrum is multimode. Nevertheless, this experimental result represents one of the highest passively phase-locked power levels ever reported from a single semiconductor laser array.

3.2 Amplifier coherent combination

For coherent combination, one would like to have the laser output in a narrow spectral bandwidth. In addition, one would like to have a scalable approach that can be extended to large numbers of elements. To address the multimode spectral output observed using the Talbot approach, and also to improve the potential scalability of coherent combination, an approach for coherent beam combination involving amplifiers was selected. Such an approach has been described in Ref. [1].

A key step to accomplish prior to working on the amplifier approach was to decrease the facet reflectivity of the AR-coated facet to as low as possible, ideally, $R < 0.1\%$ or better. The reflectivity of the facet coatings for an IA-SCOWL array was reduced by monitoring the device threshold of a single element in a packaged array in-situ while the evaporated AR-coating was being applied. In this way, a relatively large increase in the device threshold under free-running operation was obtained, which helped to suppress chip-mode lasing when operating the devices as amplifiers. A comparison the L-I characteristic of a device with and without the in-situ-monitored AR facet coating (deposited by ion-assisted deposition, IAD), indicating a large suppression of chip-lasing of the device, is shown in Fig. 8.

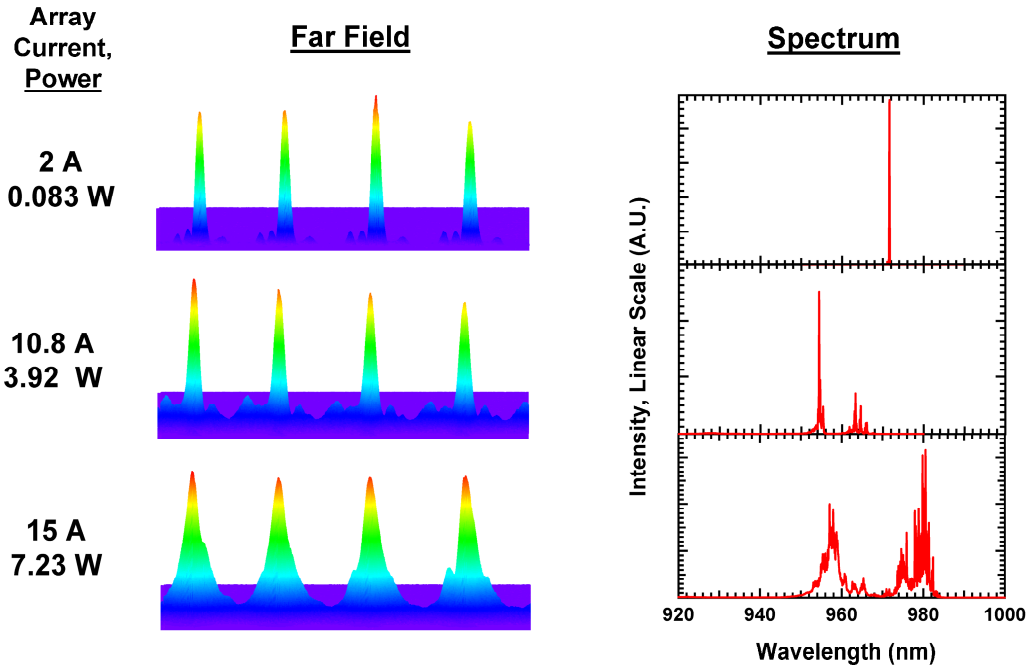


Fig. 7. Coherent beam combining of 10-element, $L = 3$ mm SCOWL array using the fractional Talbot cavity with global coupling. Far field profiles and spectra are shown at power levels of 83 mW, 3.9 W, and 7.2 W CW.

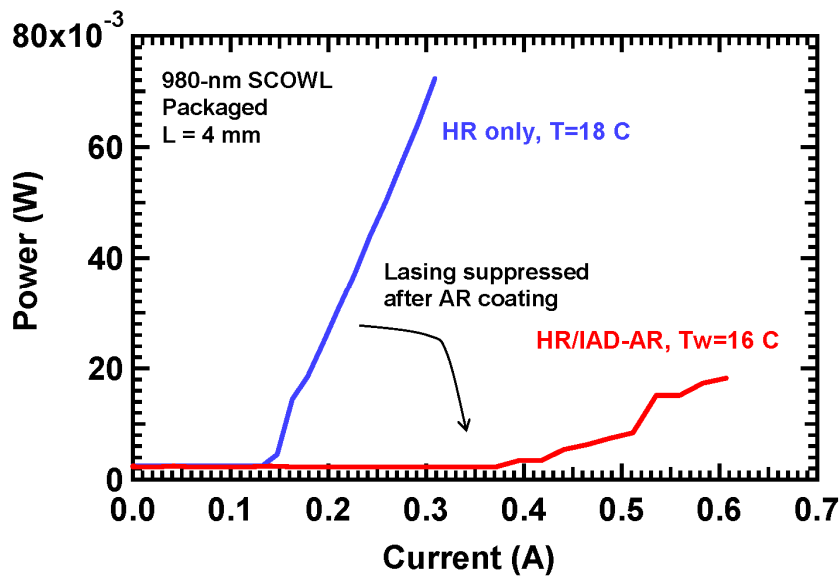


Fig. 8. Comparison of L-I of $L = 4$ mm SCOWL device in IA-SCOWL array before and after application of the in-situ-monitored AR coating (denoted by IAD-AR).

For the amplifier experiment, a master oscillator is used as the seed laser for each amplifier in the array. The beam from the master laser is expanded with a lens, and goes through an isolator. The IA-SCOWL array serves as an amplifier array

in this configuration. The seed laser is used to pump each amplifier in the array, and the coherent output from the amplifier array is extracted through the rejection port in the isolator.

The spectrum and far field profile of the coherently combined amplifier experiment are shown in Figs. 9a and b. The seed laser has been frequency stabilized, so that the spectrum of the combined amplifier array exhibits a narrow bandwidth, even under a logarithmic scale. Furthermore, the far field profile of the combined array exhibits high visibility, similar to that observed before with the Talbot approach. 4.9 W CW was obtained from the coherently combined amplifier array. This approach is believed to be more scalable than the Talbot plane approach, since it does not depend upon nearest-neighbor coupling, which is expected to scale poorly with numbers of elements.

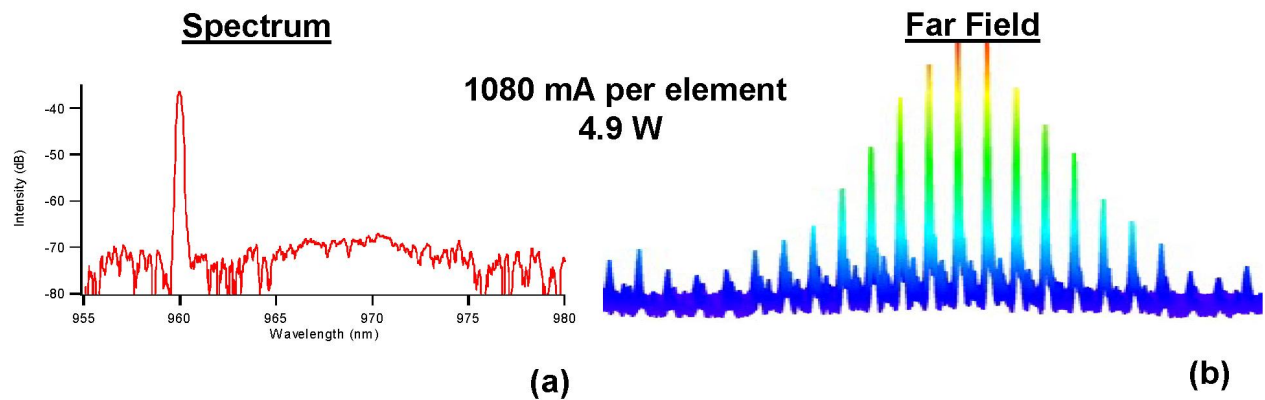


Fig. 9. (a) Spectrum of combined output of amplifier array. (b) Far field profile of combined amplifier array.

4. SCALING OF COHERENT OUTPUT POWER

In this section, current work on scaling the coherent output power in phase-locked semiconductor laser arrays is described. For scalability to higher power levels, an architecture that involves stacks of individually addressable SCOWL arrays operating in amplifier mode is used. To accomplish this objective, a scheme for stacking array elements has been developed. Modifications to the coherent combination architecture have been made so that the entire coherent output of the stack can be converted into a single, nearly diffraction limited spot in the far field.

4.1 Stacking of individually addressable SCOWL arrays

A technique for stacking of individually addressable SCOWL arrays has been developed. A key challenge of stacking IA-SCOWL arrays is to accommodate the need for electrical contact to each device, while maintaining a small stack pitch (approximately 2.5 mm) and maintaining the need for water cooling of the array. To satisfy these requirements, a custom single bar micro-channel cooler, as shown in Fig. 10a, has been designed. As can be seen in the figure, a patterned AlN submount is used, and it is similar to that used with the 10-element arrays described earlier. Electrical connections to the elements of the array are provided by a flex-print cable that is mounted behind the array. The water inlet and outlet ports have been designed so that they do not conflict with the electrical connections. The stacking scheme is illustrated in more detail in Fig. 10 b and c. Our current arrays have been designed to have 21-elements in each bar. The total number of bars in our stack is anticipated to be 11. Therefore, each stack will have a total of 231 elements, each of which can be individually controlled, in a completed IA-SCOWL stack. Our objective for this stack is 100 W CW of output power in a coherently combined output beam.

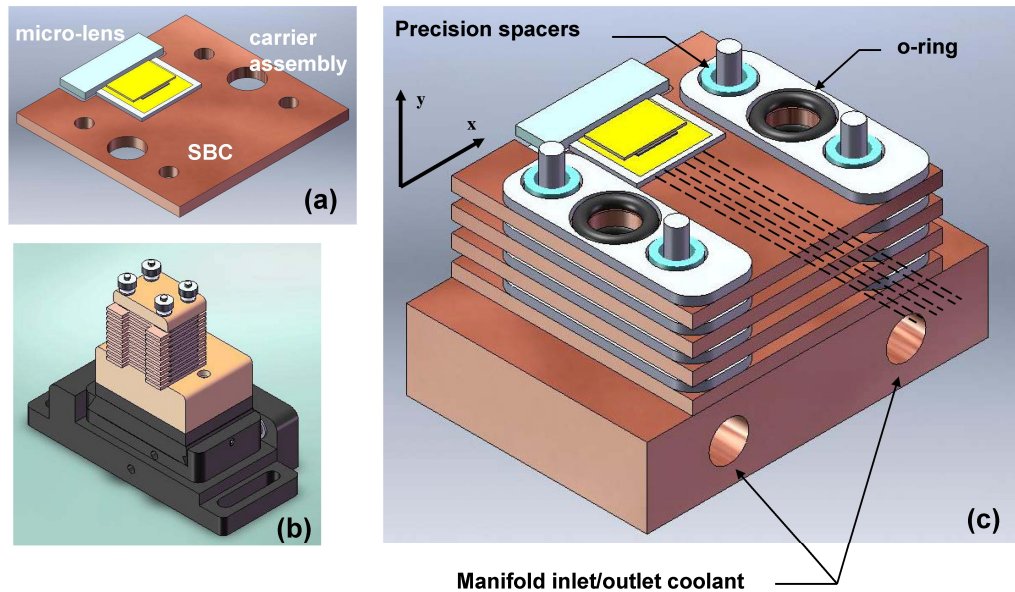


Fig. 10. Design for stack of IA-SCOWL arrays. (a) Single bar micro-channel cooler with array and microlens shown. (b) Graphic showing overview of stacking. (c) Detail of stacking geometry, with electrical connections indicated by dashed lines.

In Fig. 11a, a photograph of a packaged single IA-SCOWL array in the stackable format is shown. In Fig. 11b, the L-I characteristic of a single bar with all elements operating simultaneously is shown. For this 21-element array, 20 W CW of total output power from the array has been obtained. In the inset figure, the measured near field profile of the array is depicted. The emission from each of the 21 elements is clearly observed in this image.

4.2 Architecture for scalable coherent combination

To accomplish the objective of 100 W CW in a coherently combined SCOWL stack, a new architecture for coherent combination has been designed. This scheme is based on the amplifier approach that was discussed in an earlier section. A schematic diagram of the coherent combination architecture is shown in Fig. 12. A grating-stabilized seed diode laser is used as the master oscillator. An intermediate stage consisting of a 10-element amplifier array is used to amplify the seed laser. A 1-D holographic optical element (HOE) is used to combine the beams spatially into a single spot. The Stochastic Parallel Gradient Descent (SPGD) algorithm is used to provide the feedback for phasing the amplifier array coherently [7]. In the final stage, a 2-D IA SCOWL stack is pumped by the amplified seed laser. This stage is similar to the intermediate gain stage, except for the fact that a 2-D HOE is required for the 2-D stack. In addition, a separate SPGD control loop is employed in this stage. The final output of this configuration is expected to be 100 W in a coherent beam with a narrow bandwidth spectrum and also a single spatial spot, since the 2-D HOE is able to combine the multitude of output beams into a single, nearly diffraction-limited spot.

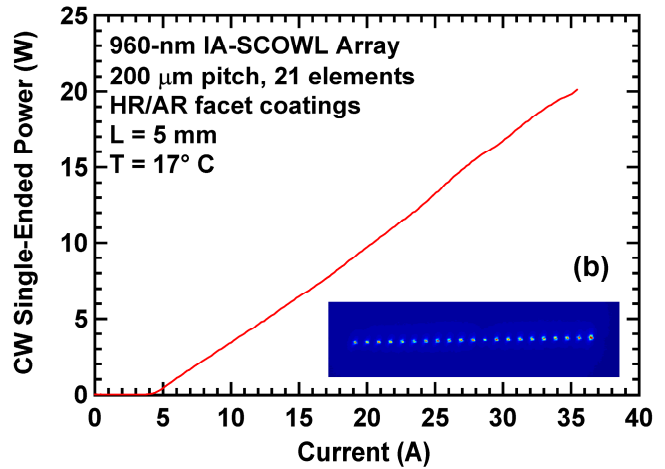
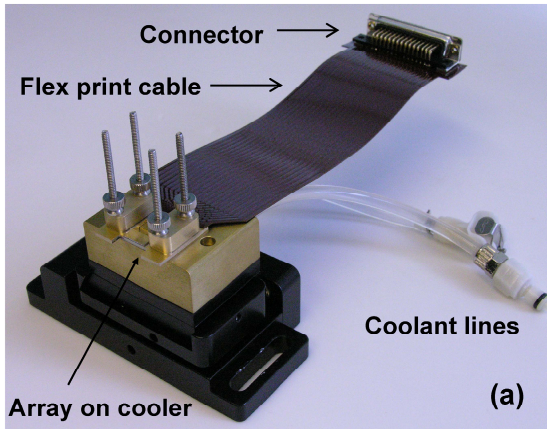


Fig. 11 (a) Photograph of a single IA-SCOWL array in stackable format. (b) CW L-I-V characteristic of 960-nm IA-SCOWL array with 21 elements. 20 W CW output power from the array has been obtained. The near field profile of the array is shown in the inset.

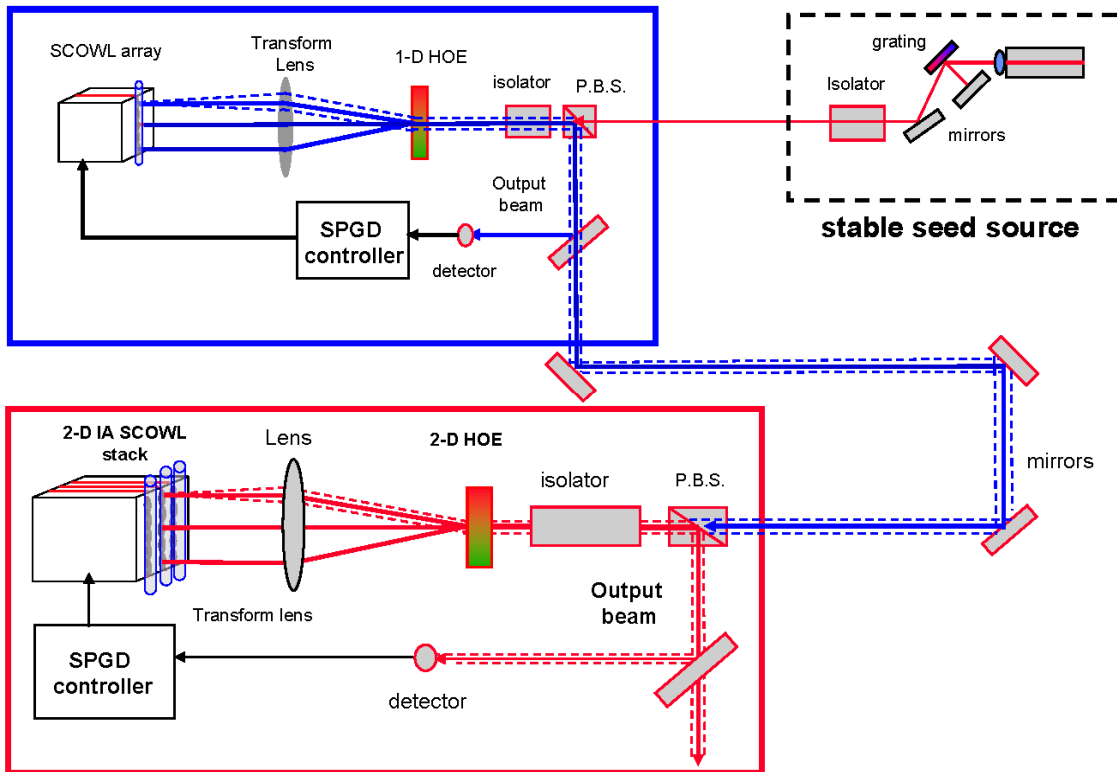


Fig. 12. Architecture for demonstration of 100 W CW coherent beam combination using a two-dimensional IA-SCOWL stack. Components in this architecture include a stable seed source and a pre-amplifier section to generate a seed laser.

5. CONCLUSION

In summary, coherent combination using high brightness semiconductor laser arrays has been demonstrated at multi-Watt levels. SCOWL devices were the semiconductor lasers used, and improvements to the SCOWL have led to 1-W-class, reliable single mode output. Two separate approaches for coherent combination of 10-element IA-SCOWL arrays were used. With the Talbot approach, greater than 7 W CW of coherently combined output power was obtained; using the amplifier approach, nearly 5 W CW of combined power was obtained. We are currently working on the coherent combination of stacks of IA-SCOWL-based amplifier arrays, and expect to be able to scale the output power in the stack arrangement to 100 W CW.

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